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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

Fecha	Duración	Tema	Profesor
Agosto 6	17 a 21 h	EL PANORAMA ENERGETICO MUNDIAL	M. en C. Marcial Portilla Roberton
Agosto 8	17 a 21 h	FUENTE Y CUANTIFICACION	Dr. Everardo Hernández Hernández
Agosto 10	17 a 21 h	SISTEMAS DE CAPTACION	Dr. Gustavo Best Brown
Agosto 13	17 a 21 h	PROCESOS DE CAPTACION	Ing. Rodolfo Martínez Strevel
Agosto 15	17 a 21 h	PROCESOS TERMICOS	M. en C. Roberto Best Brown
Agosto 17	17 a 21 h	APLICACIONES SOLARES A LA VIVIENDA	M. en C. Rodolfo Felix Flores
Agosto 20	17 a 21 h	SISTEMAS FOTOVOLTAICOS	M. en C. Luis Pablo Grijalva López
Agosto 22	17 a 21 h	APLICACIONES	Dr. Gustavo Best Brown
Agosto 24	17 a 19 h	APLICACIONES	" " " "
	19 a 21 h	APLICACIONES	Ing. Rodolfo Martínez Strevel
Agosto 27	19 a 21 h	APLICACIONES	" " " "

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

PROCESOS TERMICOS DE LA ENERGIA SOLAR

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AGOSTO, 1979

PROCESOS TERMICOS DE LA ENERGIA SOLAR

La conversión fototérmica de la energía solar se considera uno de los procesos más prometedores para la utilización de esta fuente energética no convencional.

El área de aplicación de estos procesos térmicos abarca desde el calentamiento de albercas hasta la producción de energía eléctrica; es decir, la conversión fototérmica es capaz de producir cualquier temperatura, desde algunos grados sobre la temperatura ambiente hasta temperaturas del orden de los 4000 grados kelvin.

Los factores principales que determinan las temperaturas de operación son:

- Las propiedades ópticas del absorbedor solar
- El aislamiento térmico
- La densidad de radiación, que puede ser aumentada en forma considerable por concentración óptica.

Los procesos de conversión fototérmica se pueden clasificar entonces, de acuerdo a los rangos de temperatura requeridos y del tipo de captador necesario. (fig. 1 y 2).

El factor de concentración C, se define como la superficie de captación dividida entre el área total del receptor. Utilizando un factor de concentración alto, se logran temperaturas altas con una buena eficiencia debido principalmente a que las pérdidas de calor disminuyen al disminuir a su vez la superficie receptora. (fig.3).

Los captadores de placa plana cubren un rango de temperaturas cercano a los 150°C. Por ello se prefieren para su aplicación en procesos como calentamiento de agua, secado, acondicionamiento de edificios, refrigeración, entre otros.

En este curso, nos concentraremos a estudiar las aplicaciones de la energía solar correspondientes a los sistemas de aire acondicionado y refrigeración.

REFRIGERACION Y AIRE ACONDICIONADO

De todas las aplicaciones térmicas de energía solar a temperaturas intermedias, la que se refiere a enfriamiento (refrigeración y aire acondicionado) es sumamente atractiva, ya que la demanda de enfriamiento va en concordancia con la disponibilidad de energía.

Existen varios sistemas que se han evaluado para la producción de frio con energía solar, tanto para la conservación de productos como para el confort humano, y que podemos clasificar en tres distintos sistemas:

1.- Sistemas de refrigeración por absorción.
2.- Sistemas con un ciclo Rankine acoplados a sistemas de compresión de vapor.
3.- Deshumidificación por medio de materiales absorbentes y adsorbentes.

1.- SISTEMAS DE ABSORCION.- El ciclo de refrigeración por absorción es de los métodos más antiguos de producir frio. A fines del siglo pasado ya existían equipos comerciales operados con vapor de caldera en Europa, que fueron desplazados al desarrollarse los sistemas de compresión y la introducción de los motores eléctricos, aún en procesos en que los sistemas de absorción operaban más eficientemente o cuando existía una fuente térmica disponible. Ahora este sistema se está volviendo a utilizar.

A partir del renovado interés por la utilización de la energía solar en la década de los sesentas, se ha llevado a cabo un análisis sistemático de los ciclos termodinámicos, ciclos básicos, régimen permanente, estado transitorio, tamaño de intercambiadores de calor, circulación de la solución, variación de la temperatura de enfriamiento, temperaturas de evaporación, temperaturas de generación, variación en la capacidad y el efecto de todo lo anterior en la eficiencia. (1,2,3 y 4).

El ciclo básico de la refrigeración por absorción se muestra en la fig.4 . El fluído utilizado es una mezcla de refrigerante-absorbente. Se suministra calor a esta solución en el generador, vaporizando el refrigerante y quedando una solución menos concentrada del mismo, este vapor es condensado a alta presión y ya líquido es pasado a través de la válvula de expansión al evaporador, que se encuentra a baja presión, el refrigerante vaporizado se recombina en el absorbedor con la solución de la cual se obtuvo; la solución ya concentrada es bombeada al generador, cerrándose el ciclo. Las pérdidas de calor se reducen instalando un intercambiador entre la solución caliente proveniente del generador y la solución fria proveniente del absorbedor. Se utiliza un segundo intercambiador entre el condensador y la válvula de expansión para enfriar el refrigerante líquido con el vapor frio que entra al absorbedor, el calor que se desprende del condensador y del absorbedor es removido por circulación de agua de enfriamiento.

El ciclo termodinámico ideal se puede representar en un diagrama P-T-X. (presión, temperatura y concentración. Fig.5). En la abcisa se pueden leer las temperaturas de evaporación, condensación, el rango de temperaturas durante la absorción y la generanifr, las presiones asociadas y las concentraciones.

Mezclas Refrigerantes.- Las mezclas refrigerante-absorbente deben cumplir una serie de registros físico-químicos (5 y 6). No obstante el gran número de mezclas propuestas(6 y7), solamente dos han sido utilizadas hasta ahora en forma comercial:

	Absorbente	Refrigerante
a)	Agua (H_2O)	Amoniaco (NH_3)
b)	Bromuro de Litio (LiBr)	Agua (H_2O)

El sistema agua-amoniaco se utiliza generalmente para aplicaciones que requieren temperaturas menores de 0^oC y el bromuro-de litio-agua para temperaturas superiores a 0^oC (siendo agua el refrigerante).

Eficiencia de los sistemas.- Se define el COP (coeficiente-de operación), como el calor removido en el evaporadorentre el -calor cedido al generador, de acuerdo a la fig. 4, el valor sería:

$$COP = \frac{A}{B}$$

Esta eficiencia es independiente de la fuente térmica. Los-valores relativos del COP en función de la temperatura de generación para los dos sistemas mencionados, se muestran en la fig.6.

Bromuro de Litio-Agua.- Los primeros trabajos de investigación sobre el empleo de estos sistemas con energía solar, se realizaron en la Universidad de Wisconsin y la primera casa que utilizó un prototipo fue la casa solar en Brisbane, en la Universidad de Queensland, Australia. Desde entonces se ha llevado a cabo un avance considerable en el estudio de estos sistemas, en todos aspectos: Termodinámico, diseño de prototipos y pruebas con-instalaciones completas.

Existen dos firmas comerciales que venden estos equipos en EE.UU y el Japón; la ARKLA Americana fue la primera en adaptar equipos de gas para operar con energía solar; la empresa japonesa YAZAKI, ha mejorado el sistema, sobre todo cuando se trabajó en condiciones distintas de las óptimas de diseño.

Amoniaco-Agua.- Este sistema fue propuesto para operarse con energía solar desde 1939 (8); sin embargo, se encuentra en atraso con respecto al $LiBr-H_2O$. Los problemas que se han presentado se relacionan con la adaptación de sistemas convencionales a utilizarse con energía solar, ya que estos sistemas utilizan temperaturas del orden de $150^{o}C$. Se han realizado trabajos en el rediseño del generador (9), el empleo de sistemas intermitentes (10) (11) y sistemas en etapas (12).

En México se han desarrollado una serie de estudios para la adaptación de sistemas amoniaco-agua, operados con energía solar para la operación de bodegas frigoríficas y producción de hielo; se construyen una serie de prototipos para la obtención de datos tanto termodinámicos como de costo de estos equipos.(13-14).

2.- SISTEMAS RANKINE/COMPRESION DE VAPOR.- Existen dos tipos de máquinas térmicas que técnicamente pueden ser usados en sistemas de refrigeración solar.

En el primero, el fluído refrigerante cambia de fase, de líquido a gas y de gas a líquido; la máquina de este tipo que ha sido más utilizada es la que opera en un ciclo Rankine.

En el otro tipo, el fluído de trabajo permanece en el estado gaseoso, las máquinas de este tipo operan en ciclos Stirling y --

Brayton. Para temperaturas de operación bajas menores de 200°C.- las máquinas del ciclo Rankine son superiores a las de ciclo gaseoso. Debido a esto, el mayor esfuerzo se ha canalizado a estos equipos para operarse con energía solar.

En la fig. 7, se muestra el arreglo básico de un sistema --Rankia/Compresión de Vapor.

La mayoría de los sistemas en desarrollo tienen el arreglo-indicado, expansor, motor y compresor. Algunos utilizan un motor generador en lugar de un motor solamente, con la idea de producir electricidad cuando no se requiere enfriamiento.

El ciclo Rankine es una serie secuencial cerrada de procesos termodinámicos que convierten energía calorífica en energía-mecánica. La conversión se realiza por medio de cambio cíclicos-en las condiciones del fluído de trabajo.

El fluído en el estado líquido se bombea a una caldera donde se evapora con energía térmica, el vapor generado en el hervidor es expandido a través de un expansor que puede ser de varios tipos, una turbina, un pistón y un cilindro de aspa rotatoria. -El proceso de expanción disminuye la temperatura y la presión --del vapor, y este efecto produce una converción de energía térmica en trabajo de eje. El fluído en la fase vapor, fluye del expansor al condensador donde se le regresa a la fase líquida al -ceder el calor de condensación al medio ambiente o de agua de --enfriamiento; el líquido es bombeado nuevamente a la caldera repitiéndose el ciclo.

La selección de un fluído decuado para utilizarse en el ciclo Rankine depende principalmente de la temperatura a la cual -el ciclo recibe energía térmica. Para temperaturas en el rango -

de 400^{o} a 600^{o} C, el mejor fluído es agua (utilizada en plantas termoeléctricas comunmente).

Para temperaturas en el rango de 250^{o} a 400^{o}C, ciertos -- fluídos orgánicos como el Tolueno, se han preferido al agua, en base a la eficiencia del ciclo y a algunas otras consideracio-- nes. A temperaturas inferiores algunos otros fluídos orgánicos, como los refrigerantes fluorocarbonados son más apropiados.

El enfriador de compresión de vapor es esencialmente un ciclo Rankine invertido. En algunos sistemas estudiados se utiliza el mismo fluído de trabajo en los dos sistemas, lo que permite emplear un condensador común y la eliminación de sellos para mantener la separación de fluídos en la unidad de expansión-compresión.

El parámetro de mayor importancia en el empleo del ciclo - Rankine, es la eficiencia de conversión de energía. La base primordial para esta conversión, es el ciclo de Carnot, ya que nos proporciona la eficiencia máxima teórica que se puede obtener - en un ciclo termodinámico cerrado.

La serie de procesos que forma el ciclo de Carnot, no se - puede obtener con un fluído real. En los procesos reales se presentan una serie de irreversibilidades que determinan que toda- máquina térmica operando entre dos temperaturas es siempre me-- nos eficiente que el de Carnot a las mismas temperaturas; es decir, la eficiencia de Carnot representa el límite superior inalcanzable del ciclo Rankine.

La eficiencia del ciclo Rankine como la de otros ciclos -- termodinámicos, se incrementa de acuerdo al aumento de temperatura de la fuente térmica de la que recibe el calor y de la medida en que disminuye la temperatura a la que deshecha calor.

En particular el enfriamiento con agua permite deshechar el calor a temperaturas hasta de 15^{0} C menos que con aire de enfriamiento, este efecto es esuncial cuando se habla de temperaturas máximas de 150^{0} C, que sería el límite para captadores que no necesitan concentración.

El enfriamiento por compresión tiene asociada una relación de funcionamiento que es independiente de la fuerza motríz. El COP es del orden de 5 para máquinas enfriadas por agua y de 3 para máquinas enfriadas por aire. El producto de esta relación por la eficiencia del sistema Rankine nos proporciona el COP. Empleado con la eficiencia del colector, el COP nos ofrece una medida del área requerida para cierta carga frigorífica. Fig. 8.

3.- DESHUMIDIFICACION.- En zonas calientes y húmedas, la carga de calor latente debida al gran contenido de humedad en el ambiente, constituye una gran parte de la carga térmica refrigerante. Para el control satisfactorio de la humedad a través de un sistema de aire acondicionado, el aire debe ser sobreenfriado y recalentado para obtener temperaturas de bulbo seco dentro del área de confort.

Con el proceso de humidificación/deshumidificación, se alcanza el control de la humedad por un método más simple y probablemente más económico. En este sistema, el aire del cuarto se seca por contacto con un material absorbente. Si ahora se evapora agua dentro de este aire seco, la extracción del calor latente de evaporación, provoca que el aire se enfríe, al mismo tiempo el contenido de humedad del aire se incrementa. La evaporación del agua se controla de tal forma, que el aire de salida se encuentre en el estado fijado; el material absorbente puede ser un sólido o un líquido, algunos disecantes orgánicos líquidos son: soluciones de cloruro de litio, bromuro de litio, cloruro de calcio, ácido sulfúrico, hidróxido de potasio y sosa caústica. Algunos absorbentes orgánicos líquidos son: glicerol, dietilen-glicol, trietilen-glicol. Los disecantes sólidos más usados son: cloruro de litio, cloruro de calcio, silicagel, alúmina activada, tamices moleculares.

Los sistemas que han sido empleados en procesos convencionales son soluciones de cloruro de litio, trietilen-glicol, silica gel y cloruro de litio sólido.

En la fig. 9, se muestra un sistema hidroscópico líquido comercial que será utilizado para explicar el sistema.

Fijado el contenido de humedad del material absorbente, la presión de vapor en el equilibrio es función de la temperatura.- Para una concentración dada y dependiendo de la temperatura, la presión de vapor en el equilibrio será mayor o menor que la presión de vapor del agua en el aire por acondicionar, por lo general aún en áreas muy húmedas, la presión de equilibrio a la temperatura ambiente es menor que la presión de vapor del agua en la atmósfera, cuando este aire húmedo es pasado a través de un conjunto de serpentines sobre los cuales se rocía la solución concentrada absorbente, transfiriéndose humedad del aire a la solución, el calor latente cedido, debido a la absorción de humedad y el calor de dilución resultante de el aumento en el contenido de agua de la solución provoca un aumento de temperatura, tanto en la solución como en el aire, que es removido por agua que circula por el interior del serpentín.

La temperatura del aire deshumidificado, más alta que la temperatura a la entrada, se puede bajar para llevar el aire den

...de la zona de confort por varios métodos:

1.- Intercambiando calor sensible en un intercambiador de... deshumidificando a aire ambiente. Hay que tomar en cuenta ... se toleran temperaturas más altas a humedades relativas menores.

2.- Si esto no es suficiente, el aire se puede enfriar aún más por evaporación adiabática de agua (enfriamiento evaporativo), que provoca también un aumento en la humedad absoluta.

3.- El aire puede ser enfriado evaporativamente hasta la ... medida para después mezclarse con aire en distintas proporciones hasta alcanzar la condición de confort.

4.- En algunos casos, se requerirá deshumidificar excesivamente para alcanzar condiciones de confort con enfriamiento evaporativo. Para evitar demasiada humedad en el espacio acondicionado, el aire de salida del cuarto enfriado por enfriamiento evaporativo hasta la saturación se utiliza para enfriar el aire deshumidificado sin aumentar la humedad del mismo.

El proceso de deshumidificación provoca un decremento en la concentración del absorbente en la solución por lo que es necesario regenerarlo para mantener constante el contenido de humedad. En el refrigerador, la solución se calienta a temperaturas a las cuales la presión de vapor es mayor que la presión de vapor atmosférica para que la humedad se transfiera al aire, absorbiéndose calor en el proceso.

El principio de operación de los disecantes sólidos es similar, excepto por las restricciones impuestas por la naturaleza física del material. La transferencia del material de la - -

sección deshumidificante a la de deshumidificación, se lleva a cabo empacando el material en camas rotatorias o ruedas, o intercambiando las corrientes de aire en el tiempo apropiado. En la fig.10, se muestra un deshumidificador rotatorio comercial.

Quizá la desventaja termodinámica mayor, en el uso de desecantes sólidos consiste en la estratificación de temperatura y humedad que hace que el proceso no sea isotérmico.

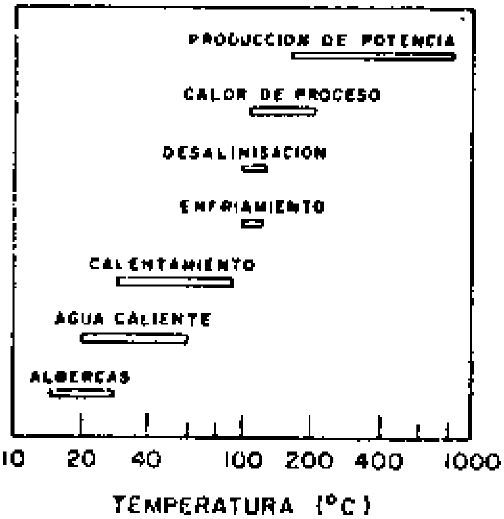


Figura 1

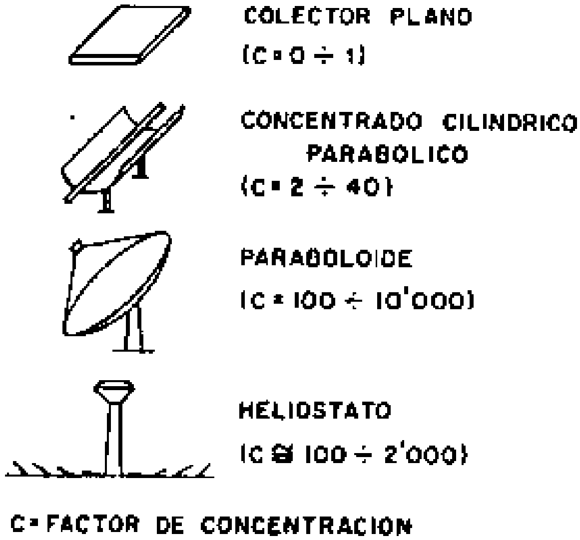


Figura 2

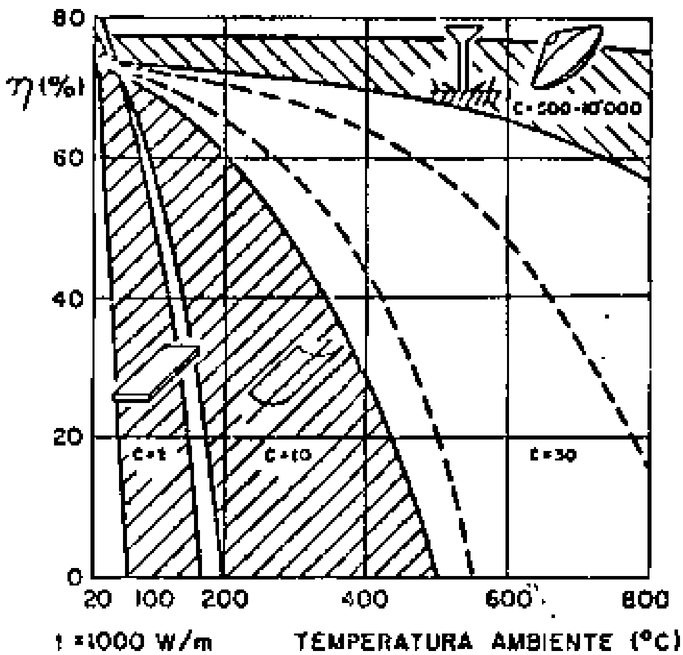


Figura 3

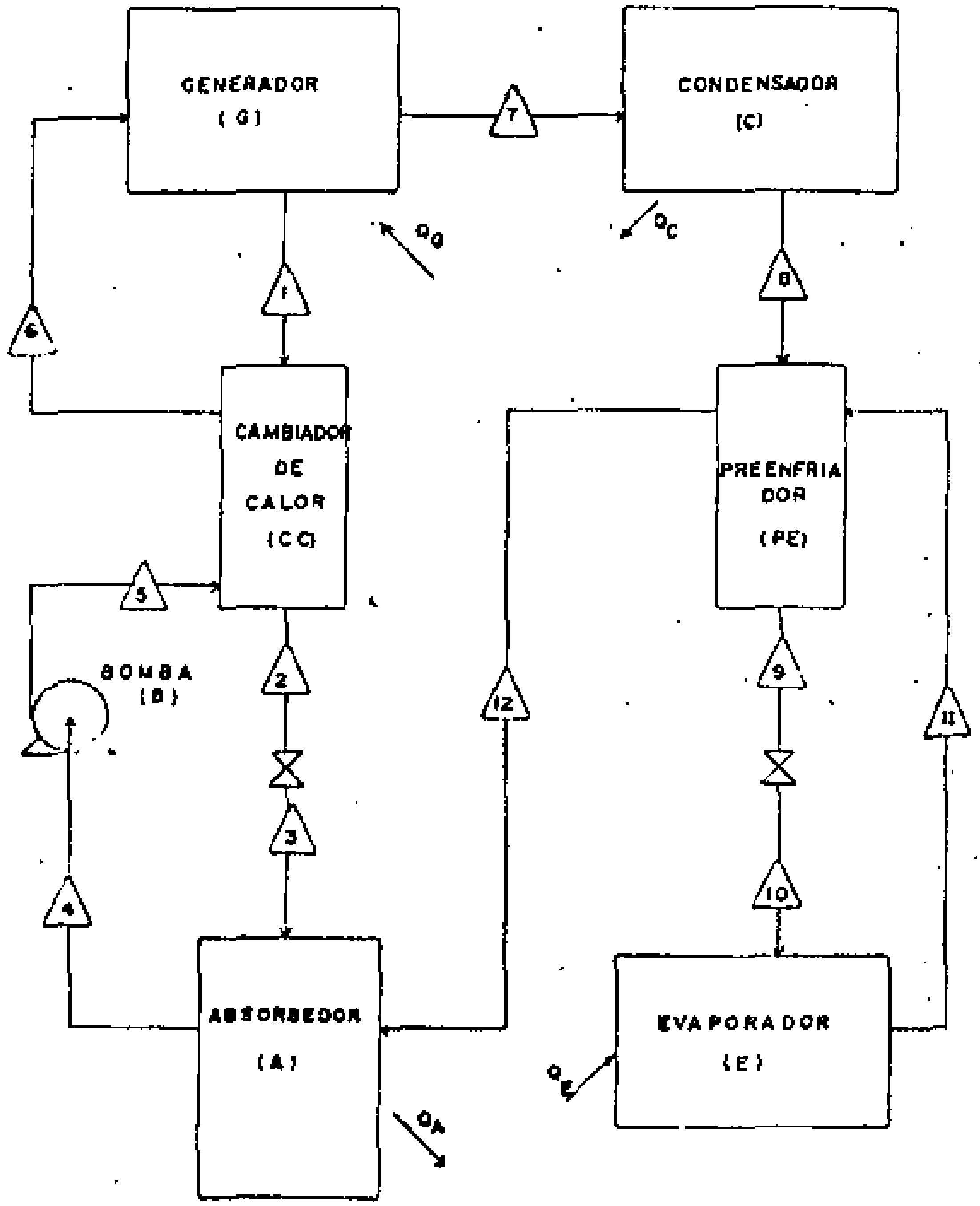


DIAGRAMA ESQUEMATICO DEL PROCESO DE REFRIGERACION POR ABSORCION

Figura 11

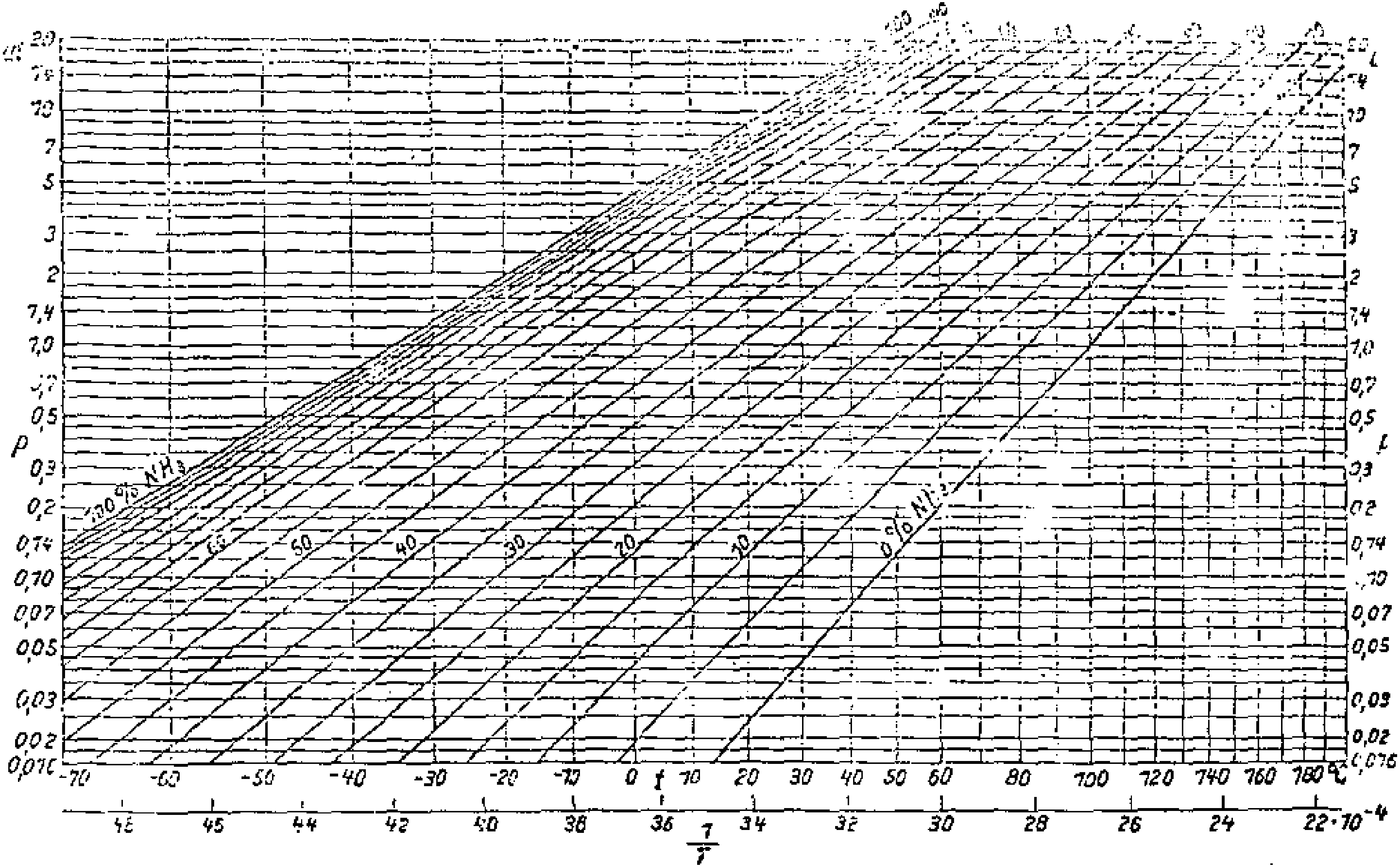


Diagramme $\frac{1}{T}$ log p pour le mélange Eau-Ammoniaque (d'après Bosnjakovic et Wucherer)

Figura 5

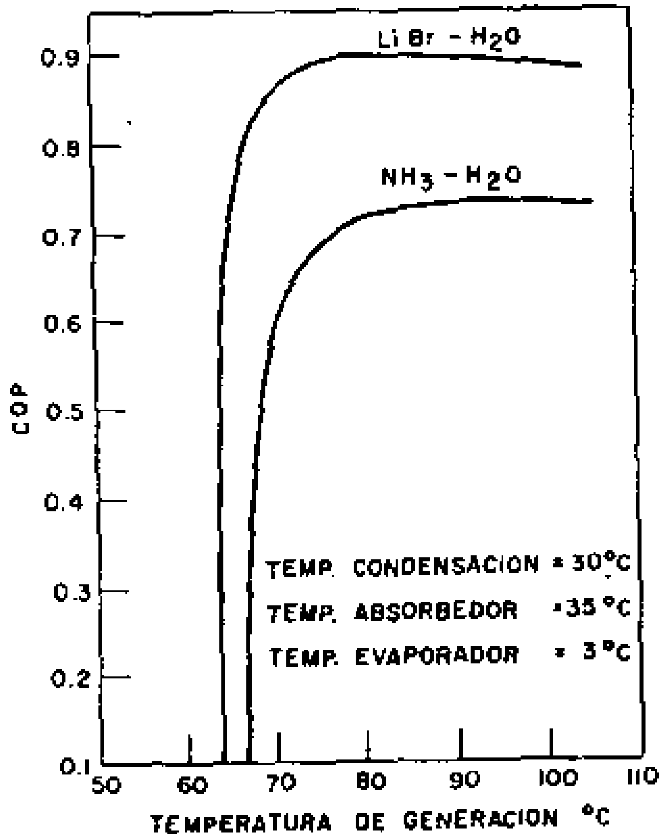


Figura 6

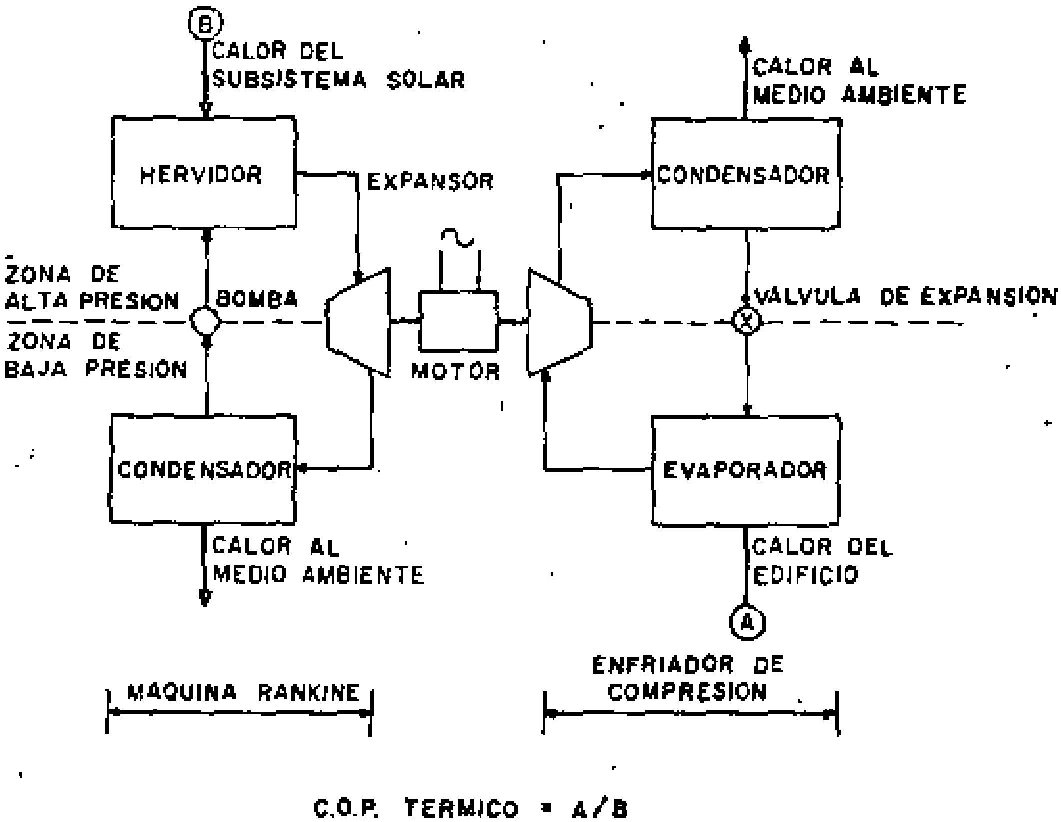


Figura 7

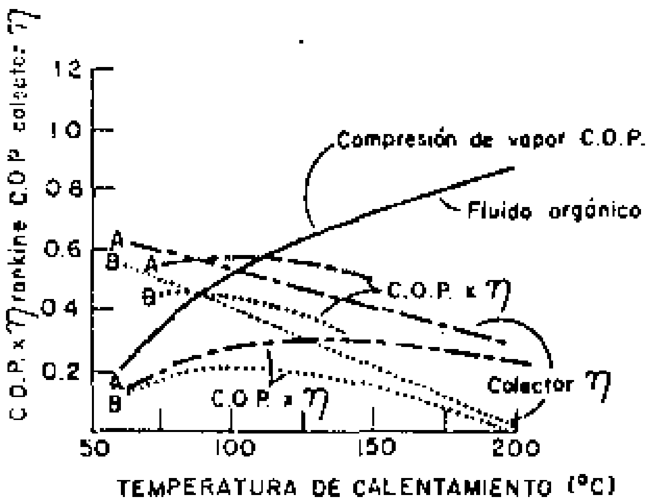


Figura 8

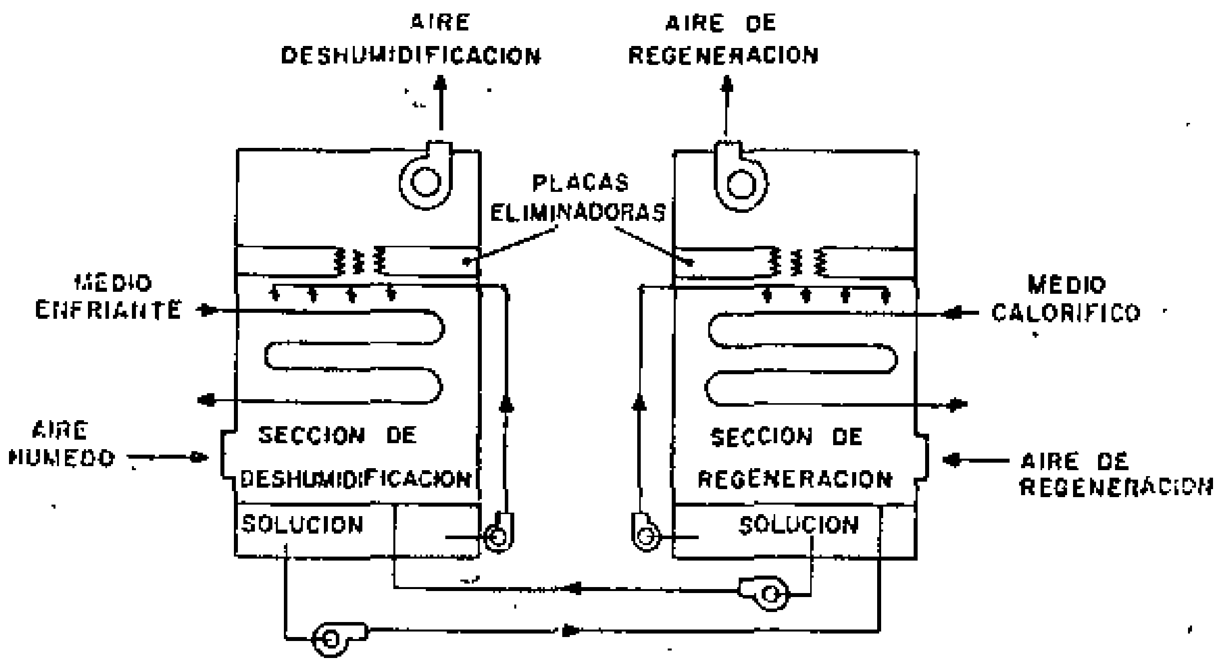
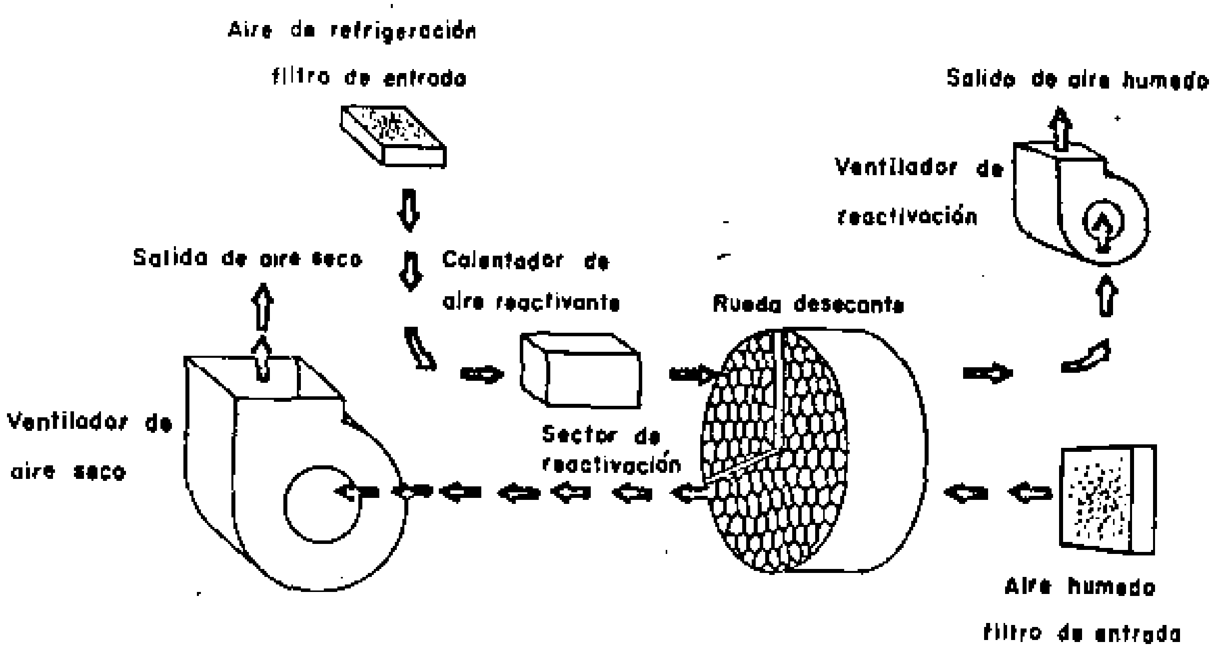


Figura 9



Aire de refrigeración
filtro de entrada
Salida de aire humedo
Ventilador de
reactivación
Salida de aire seco
Calentador de
aire reactivante
Rueda desecante
Ventilador de
aire seco
Sector de
reactivación
Aire humedo
filtro de entrada

Figura 10

BIBLIOGRAFIA

1) Chinnappa, J.C.V.- "Performance of an intermittent refrigerator operated by a flat plate collector", Solar Energy. Vol. 6, No.4 p 143 (1962)

2) Sathyanathan, S. and Kochar, G.S.-"Optimun operating Conditions of NH_3-H_2O absorption refrigeration systems for flat plate solar collector Temperatures". Presented at the 1975 International Solar Energy Congress, Univesity of California, Los Angeles (1975)

3) P.J. Wilbur & C.E. Mitchell.-"Solar Absorption air conditioning alternatives", Solar Energy, 17, 193-199 (1975)

4) D.B. Ward & G.O.G.Lof.-"Design and Construction of a Residential Solar Heating and Cooling System", Solar Energy 17, 13-20. (1975)

5) Hainsworth, W.R., "Refrigerants and Albsorbents" Regrigerating-Engineering, Vol.48, 2, August pp 97-100 (1944)

6) Williams, D.A., Chung, R., Lof, G.O.G. Fester D.A. and Duffie,- J.A.- "Cooling Systems Based on Solar Regeneration", Refrigeration Engineering, 66, pp 34-37 and 64-65 Nov.(1958)

7) Swartman, R.K., Ha, V.H. and Swaminathan, C.-"Comparison of ammonia water and ammonia sodium thiocyanate in a solar refrigeration System", International Solar Energy Society Conference, Paper No. 5. 25, París. (1973)

8) Farber, E.A. et al " Operation and Performance of the University of Florida Solar air Conditioning System", Solar Energy, 10, 91-95 (1966)

9) Simmons, M., Wolgast R. and Wahlig M. "Ammonia-water absorptión Air-Conditioner", extended abstract, ISES. 1975. Congress.pp 400-401 (1975)

10) Chinnappa, J.C.V. & Martin, H.A.- "Dual-mode operation by solar energy of an ammonia-water two-stage cycle: a comparative study". Solar Energy 18, 337-342 (1976)

11) Swartman, R.K.-"Intermitten absorption air-conditioner". Procs. Second ERDA Workshop use of solar energy for the cooling of buildings(Ed. de Winter and de Winter), N.T.I.S., VA 22161, U.S.A. pp.231-237 (1976)

component—the collector—is emphasized. Both approximate and precise methods of collector sizing are given; the former requires only a hand calculator, the latter, a computer.

Design procedures for solar service hot-water heaters are given along with mechanical equipment diagrams and design specifications. A comparison of the advantages and disadvantages of hot-air solar systems indicates that for heating only they are competitive with liquid-cooled collector systems. The limited usage factor of a heating only system diminishes the economic viability of air systems, however.

The economics of solar heating are presented, including the effects of interest rates, inflation, and auxiliary fuel prices. The concepts of life-cycle costing and solar system payout period are developed in tabular and analytical form. Marginal, average, and total costs of solar systems are described and the method of use of each is illustrated by example calculations.

REFERENCES

1. Balcomb, J. D., J. C. Hedstrom, and B. T. Rogers: *Design Considerations of Air Cooled Collector/Rock-bin Storage Solar Heating Systems*, Los Alamos Scientific Laboratory Report LA-UR-75-1334, 8 pp., 1975.
2. Bridgers, F., et al.: Performance of a Solar Heated Office Building, *Heating, Piping and Air Conditioning*, p. 165, November, 1957.
3. Buchberg, H., and J. R. Roulet: Simulation and Optimization of Solar Collection and Storage for House Heating, *Solar Energy*, vol. 12, p. 31, 1968.
4. Butz, L.: *Use of Solar Energy for Residential Heating and Cooling*, Master's thesis, University of Wisconsin, Madison, 1973.
5. Close, D. J.: Solar Air Heaters for Low and Moderate Temperature Applications, *Solar Energy*, vol. 7, p. 117, 1963.
6. Close, D. J.: Rock Pile Thermal Storage for Comfort Air Conditioning, *Mech. Chem. Engrg. Trans. Inst. Eng. (Australia)*, vol. MC-1, p. 11, 1965.
7. Czarnecki, J. T.: Performance of Experimental Solar Water Heaters in Australia, *Solar Energy*, vol. 2, p. 2, 1958.
8. Davey, E. T.: Solar Water Heating, *Building Materials*, vol. 8, p. 57, 1966.
9. Löf, G. O. G., and R. W. Hawley: Unsteady State Heat Transfer Between Air and Loose Solids, *Industr. Engrg. Chem.*, vol. 40, p. 1061, 1948.
10. Löf, G. O. G., and R. A. Tybout: Cost of House Heating with Solar Energy, *Solar Energy*, vol. 14, p. 253, 1973.
11. Speyer, E.: Solar Energy Collection with Evacuated Tubes, *J. Engrg. for Power*, vol. 87, p. 270, July, 1965.
12. Selcuk, K.: Thermal and Economic Analysis of the Overlapped-Glass Plate Solar-Air Collector, *Solar Energy*, vol. 13, p. 165, 1971.

APTER 5

Solar Cooling of Buildings

The real cycle you're working on is a cycle called yourself.

ROBERT PIRSIG

Solar cooling of buildings represents a potentially significant application of solar energy for building air conditioning in most sunny regions of the United States. Solar-cooling technology is presently not as advanced as solar-heating technology, but research work is expected to close the gap between the two by 1980. Several viable, solar-air-conditioning schemes are described in this chapter and methods for tentative system design are presented in detail.

COOLING REQUIREMENTS

The cooling load of a building is the rate at which heat must be removed to maintain the air in a building at a given temperature. It is usually calculated on the basis of the peak load expected during the cooling season. For a given building the cooling load primarily depends on

1. Design inside and outside dry-bulb temperatures
2. Design inside and outside relative humidities
3. Solar radiation heat load
4. Wind speed

A method of cooling-load calculation is presented in detail in the *ASHRAE Handbook of Fundamentals*.

The steps in calculating the cooling loads of a building are

1. Specify the building characteristics:
   Wall area, type of construction, and surface characteristics
   Roof area, type of construction, and surface characteristics
   Window area, setback, and glass type
   Building location and orientation
2. Specify the outside and inside wet- and dry-bulb temperatures.
3. Specify the solar heat load and wind speed

[illegible] building cooling loads due to

- Heat transfer through windows
- Heat transfer through walls
- Heat transfer through roof
- Sensible heat gains due to infiltration and exfiltration
- Latent heat gains (water vapor)
- Internal heat sources, such as people, lights, etc.

Equations (5.1) through (5.7) may be used to calculate the various cooling loads for a building; cooling loads due to lights, building occupants, etc. may be estimated from the *ASHRAE Handbook of Fundamentals*. For unshaded or partially shaded windows, the load is

$$Q_{wi} = A_{wi}\left[F_{sh}\bar{\tau}_{b,wi}I_{h,b}\frac{\cos i}{\sin\alpha} + \bar{\tau}_{d,wi}I_{h,d} + \bar{\tau}_{r,wi}I_r + U_{wi}(T_{out} - T_{in})\right] \quad (5.1)$$

For shaded windows the load (neglecting diffuse sky radiation) is

$$Q_{wi,sh} = A_{wi,sh}U_{wi}(T_{out} - T_{in}) \quad (5.2)$$

For unshaded walls the load is

$$Q_{wa} = A_{wa}\left[\bar{\alpha}_{s,wa}\left(I_r + I_{h,d} + I_{h,b}\frac{\cos i}{\sin\alpha}\right) + U_{wa}(T_{out} - T_{in})\right] \quad (5.3)$$

For shaded walls the load (neglecting diffuse sky radiation) is

$$Q_{wa,sh} = A_{wa,sh}[U_{wa}(T_{out} - T_{in})] \quad (5.4)$$

For the roof the load is

$$Q_{rf} = A_{rf}\left[\bar{\alpha}_{s,rf}\left(I_{h,d} + I_{h,b}\frac{\cos i}{\sin\alpha}\right) + U_{rf}(T_{out} - T_{in})\right] \quad (5.5)$$

For sensible heat infiltration and exfiltration the load is

$$Q_i = \dot{m}_a(h_{a,out} - h_{a,in}) \quad (5.6)$$

For moisture infiltration and exfiltration the load is

$$Q_w = \dot{m}_a(W_{out} - W_{in})\lambda_w \quad (5.7)$$

where

Q_{wi} = heat flow through unshaded windows of area A_{wi}, Btu/hr

$Q_{wi,sh}$ = heat flow through shaded windows of area $A_{wi,sh}$, Btu/hr

Q_{wa} = heat flow through unshaded walls of area A_{wa}, Btu/hr

$Q_{wa,sh}$ = heat flow through shaded walls of area $A_{wa,sh}$, Btu/hr

Q_{rf} = heat flow through roof of area A_{rf}, Btu/hr

Q_i = heat load due to infiltration/exfiltration, Btu/hr

Q_w = latent heat load, Btu/hr

$I_{h,b}$ = beam component of insolation on horizontal surface, Btu/(hr)(ft^2)

$I_{h,d}$ = diffuse component of insolation on horizontal surface, Btu/(hr)(ft^2)

I_r = ground-reflected component of insolation, Btu/(hr)(ft^2) (direct plus diffuse)

W_{out}, W_{in} = outside and inside humidity ratios, lb$_m$ H_2O/(lb$_m$ dry air)

U_{wi}, U_{wa}, U_{rf} = over-all heat-transfer coefficients for windows, walls, and roof, including radiation, Btu/(hr)(ft^2)(°F)

$\dot{m}_a$ = net infiltration and exfiltration of dry air, lb$_m$/hr

T_{out} = outside dry-bulb temperature, °F

T_{in} = indoor dry-bulb temperature, °F

F_{sh} = shading factor (1.0 = unshaded, 0.0 = fully shaded)

$\bar{\alpha}_{s,wa}$ = wall solar absorptance

$\bar{\alpha}_{s,rf}$ = roof solar absorptance

i = solar-incidence angle on walls, windows, and roof, deg

$h_{a,out}, h_{a,in}$ = outside and inside air enthalpy, Btu/lb$_m$

α = solar altitude angle, deg

λ_w = latent heat of water vapor, Btu/lb$_m$

$\bar{\tau}_{b,wi}$ = window transmittance for beam (direct) insolation

$\bar{\tau}_{d,wi}$ = window transmittance for diffuse insolation

$\bar{\tau}_{r,wi}$ = window transmittance for ground-reflected insolation

EXAMPLE

Determine the cooling load for a building in Phoenix, Arizona with the specifications tabulated below.

Factor	Description or specification
Building characteristics:	
Roof:	
Type of roof	Flat, shaded
Area $A_{rf,sh}$, ft²	1,700
Walls (painted white):	
Size, north and south, ft	8 × 60 (two)
Size, east and west, ft	8 × 40 (two)
Area A_{wa}, north and south walls, ft²	$480 - A_{wi} = 480 - 40 = 440$ (two)
Area A_{wa}, east and west walls, ft²	$320 - A_{wi} = 320 - 40 = 280$ (two)
Absorptance $\bar{\alpha}_{s,wa}$ of white paint	0.12
Windows:	
Size, north and south, ft	4 × 5 (two)
Size, east and west, ft	4 × 5 (two)
Shading factor F_{sh}	0.20
Insolation transmittance	$\bar{\tau}_{b,wi} = 0.60$; $\bar{\tau}_{d,wi} = 0.81$; $\bar{\tau}_{r,wi} = 0.60$
Location and latitude	Phoenix, Ariz.; 33°N
Date	August 1
Time and local-solar-hour angle H_s	Noon; $H_s = 0$
Solar declination δ_s, deg	18°14′
Wall surface tilt from horizontal β	90°
Temperature, outside and inside, °F	$T_{out} = 100$; $T_{in} = 75$
Insolation I, Btu/(hr)(ft²)	$I_{h,b} = 185$; $I_{h,d} = 80$; $I_r = 70$
U factor for walls, windows, and roof	$U_{wa} = 0.19$; $U_{wi} = 1.09$; $U_{rf} = 0.061$
Infiltration, lb_m dry air/hr	Neglect
Exfiltration, lb_m dry air/hr	Neglect
Internal loads	Neglect
Latent heat load Q_{wl}, %	30% of wall sensible heat load*

*Approximate rule of thumb for Phoenix.

SOLUTION

To determine the cooling load for the building just described, calculate the following factors in the order listed.

1. Incidence angle for the south wall i

$$\cos i = \cos \delta_s \cos (L - \beta) + \sin \delta_s \sin (L - \beta) = 0.257$$

2. Solar altitude α

$$\sin \alpha = \sin \delta_s \sin L + \cos \delta_s \cos L \cos H_s$$
$$= \cos (L - \delta_s) \approx \cos 15° = 0.96$$

3. South-window load (from Eq. (5.1))

$$Q_{wi} = 40 \left\{(0.2 \times 0.6)\left(185 \frac{0.257}{0.96}\right) + (0.81 \times 80) + (0.60 \times 70) + [1.09(100° - 75°)]\right\}$$
$$= 5{,}600 \text{ Btu/hr}$$

4. Shaded-window load (from Eq. (5.2))

$$Q_{wi,sh} = (3 \times 40)[1.09(100° - 75°)] = 3{,}270 \text{ Btu/hr}$$

5. South-wall load (from Eq. (5.3))

$$Q_{wa} = (480 - 40) \left\{.12 \left[70 + 80 + \left(185 \frac{0.257}{0.96}\right)\right] + 0.19(100° - 75°)\right\} = 12{,}610 \text{ Btu/hr}$$

6. Shaded-wall load (from Eq. 5.4))

$$Q_{wa,sh} = [(480 + 320 + 320) - (3 \times 40)][0.19(100° - 75°)] = 4{,}750 \text{ Btu/hr}$$

7. Roof load (from Eq. 5.5))

$$Q_{rf} = 1{,}700[\bar{\alpha}_{s,rf} \times 0 + 0.061(100° - 75°)] = 2{,}600 \text{ Btu/hr}$$

8. Latent-heat load (30 percent of sensible wall load)

$$Q_{wl} = 0.3[(480 + 480 + 320 + 320) - (4 \times 40)][0.19(100° - 75°)] = 2{,}050 \text{ Btu/hr}$$

9. Infiltration/exfiltration load

$$Q_i = 0$$

10. Total cooling load for the building described in the example.

$$Q_{tot} = Q_{wi} + Q_{wi,sh} + Q_{wa} + Q_{wa,sh} + Q_{rf} + Q_{w} + Q_i$$

$$Q_{tot} = 30{,}880 \text{ Btu/hr} \sim 2.5 \text{ tons air conditioning}$$

This example is simplified for illustrative purposes. Heat loads must be calculated each hour of a design day to determine the maximum load. The maximum cooling load occurs usually between 3 and 4 P.M.

DESIGN OF A COLLECTOR FOR A SOLAR-COOLED BUILDING

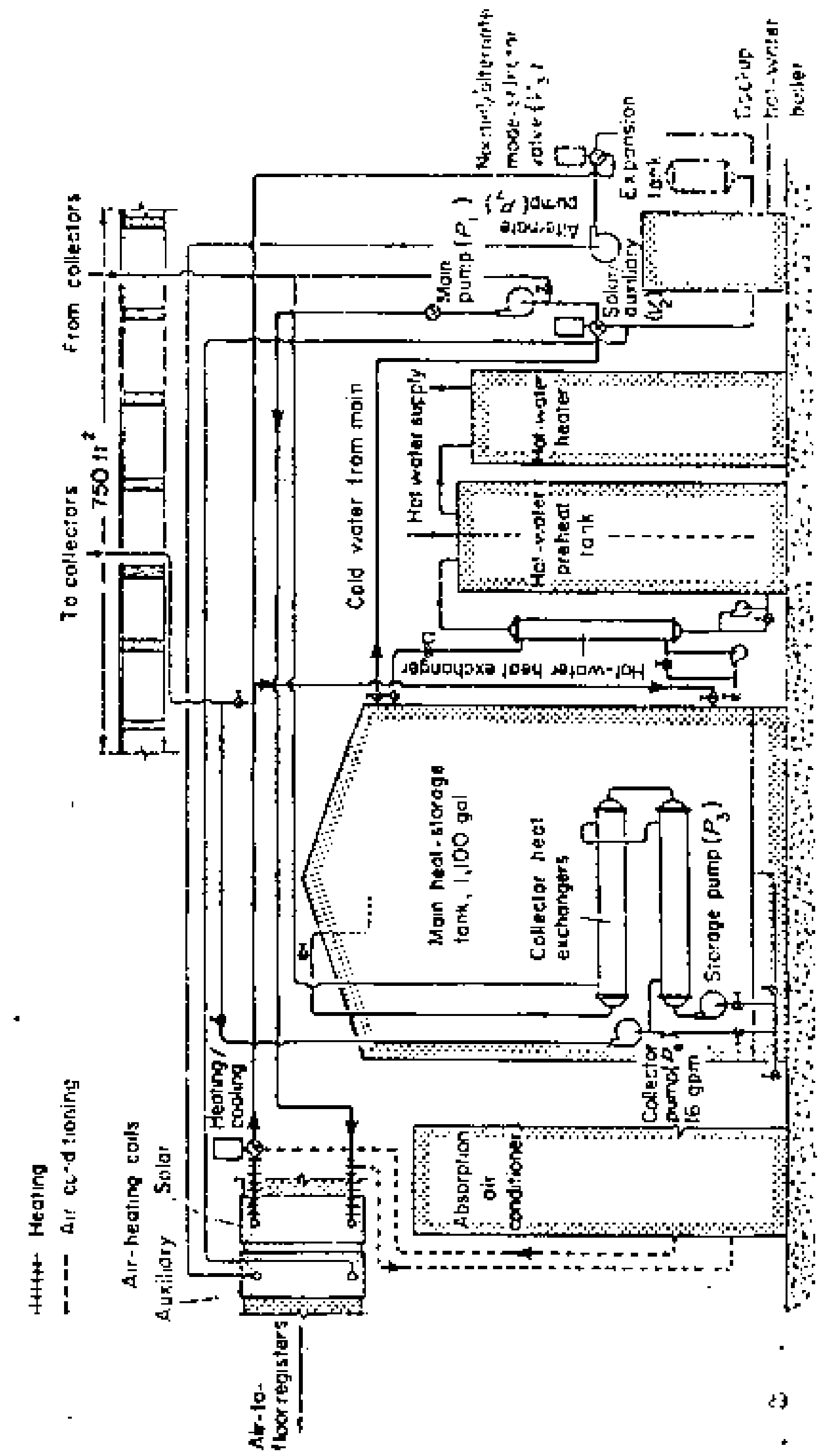
Solar energy can be an economical source of energy for building temperature control in areas where the local climate requires both air conditioning and heating, because use of solar energy for heating and air conditioning increases the system usage factor. The combined system shown in Fig. 5.1 is presently installed in the Solar Energy Applications Laboratory, Colorado State University, Fort Collins, Colo. The same solar collector and storage system can be used for combined, year-round heating and cooling operation. Löf and Tybout* performed an optimization study of combined systems for the same geographical locations as their solar-heating study referenced earlier.* The general conclusions pertinent to collector design for combined systems used in climates with hot summers are

1. Optimal collector tilt β is equal to latitude L (except in the South where $\beta = L - 10°$).
2. Optimal collector area is always greater than that needed for heating only.
3. Three glass covers are desirable due to higher temperature needs of air conditioning systems; in subtropical steppe climate, e.g., Albuquerque, two are optimal.

The Löf-Tybout study modeled a flat-plate collector and lithium-bromide (LiBr) absorption air conditioner with price based on assumed mass production costs for both. The results are the only guide to solar air-conditioning design presently available. More information on the economics of solar air conditioning is given later in this chapter in "The Economics of Solar Air Conditioning."

The results of work and experience on solar air conditioning to date have not yet culminated in a reliable, inexpensive solar air-conditioning unit, and no system can be recommended for wide use at this time.

*G. O. G. Löf and R. A. Tybout, Cost of House Heating with Solar Energy, *Solar Energy*, vol. 14, 1973.



STORAGE OF ENERGY AT HIGH AND LOW TEMPERATURES

For a detailed description of high-temperature storage of energy the reader may refer to Chap. 4, "Storage of Energy." In an air-conditioning system it is also possible to cool a tank of water or other storage medium if excess cooling capacity is available during operational hours. One of the attractions of this approach is that the temperature difference between cold storage (say, 45°F at the coldest) and building temperature (~70°F) is less than the temperature difference between hot-storage and room temperature. As a result, less cooling effect is lost from cold storage than from hot storage. Moreover, cold storage is preferable to hot storage because losses from hot storage in a building add to the summer air-conditioning load.

In addition, 1 Btu of cold storage is 1 Btu of cooling; 1 Btu of hot storage is equivalent to less than 1 Btu of cooling since the air conditioner is not 100 percent efficient. These advantages of cold storage are offset by the additional cost and upkeep required to install and maintain a second storage unit and the associated plumbing and ducting.

The decision to use hot, cold, or combined storage depends on the building location. In Phoenix one should design for cold storage since the investment in hot-storage is uneconomical in a climate where heating loads are small (only 1,500 degree-days per year). In Bemidji, Minn. on the other hand one should design for hot storage since the cooling load is small. Recent test results from the CSU house (Fig. 5.1) have indicated that a small amount of cold buffer storage can improve solar-cooling-system performance significantly.

VAPOR-COMPRESSION SYSTEMS AND HEAT PUMPS

Introduction

As mentioned previously, the periodicity and intermittence of solar energy incident on a collector require the use of a conventional backup (auxiliary) system. The size and cost of the total system depend not only on the Btu's collected but also on storage facilities; any concept that can reduce the collection and storage requirements can improve the economics of solar-energy use. One attractive method to achieve a fuller use factor is to utilize a solar-assisted heat pump-air conditioner for all-year climate control. From an energy standpoint the efficiency of a conventional heat-pump system operating in a northern climate is reduced as a result of low ambient

temperatures; owing to the reduced efficiency of the heat pump, reliance of the system of electric-resistance heating is necessary. However, solar energy can be used at low ambient temperatures to reduce or often eliminate the need for supplemental resistance heating in such systems.

A *heat pump* may be defined as a system that absorbs energy at low temperature and delivers energy at higher temperature through a vapor-compression or absorption cycle. However, no absorption-cycle heat pumps are presently available. Available heat-pumps use a standard vapor-compression refrigeration cycle operated in reverse: the evaporator is usually placed outdoors and the condenser indoors. The mechanical energy input to the compressor during vapor compression raises the internal energy absorbed at low ambient temperatures to a temperature level useful for space heating. The quantity of heat extracted from such a system can be several times larger than the energy required by the compressor. The basic advantage of a heat pump is this "heating multiplication."

In a solar-assisted heat-pump system designed both to heat and to cool a building, two general modes of operation are possible. As shown in Fig. 5.2(*a*), the solar heating system and the heat-pump system may be separate. In Fig. 5.2(*b*) the two cycles are shown connected, and a solar collector assists in reducing the amount of heat that must be supplied by the compressor when heating the building. Obviously, the second arrangement is more efficient.

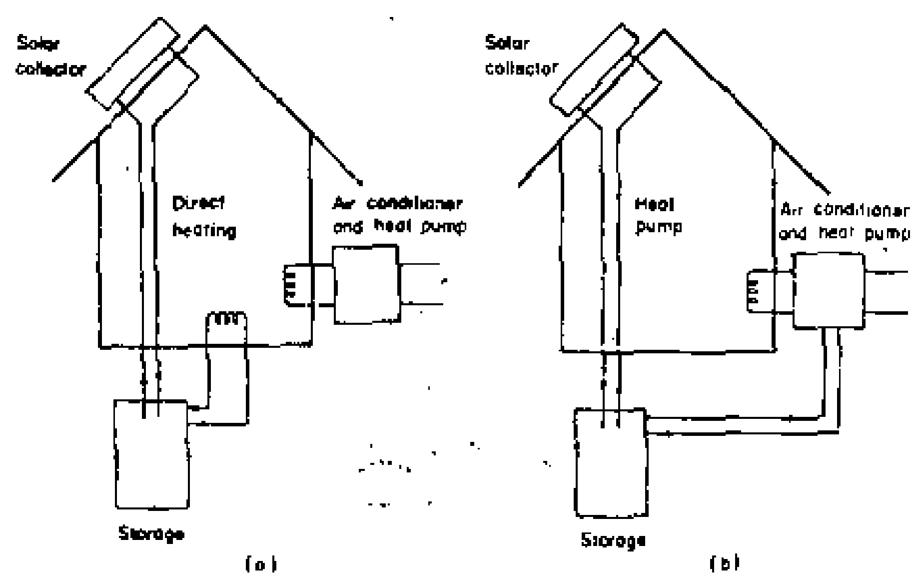


FIG. 5.2 (*a*) Direct solar heating system; (*b*) solar-assisted heat pump.

Solar-Powered Heat-pump Cycle

The heat pump can theoretically be used with any thermodynamic cooling cycle, such as an absorption, a jet compression, and a mechanical vapor compression cycle. Figure 5.3 illustrates the basic heat flows in a conceptual solar-powered heat pump system in which the sun's energy directly provides shaft work instead of acting as a booster as in Fig. 5.2. Q_4 is the amount of heat removed from the environment during the heating mode. A heat balance of the cycle in Fig. 5.3 gives

$$Q_1 + Q_4 = Q_2 + Q_3 \tag{5.8}$$

where Q_1 = solar heat input
Q_2 = heat rejected in the power cycle
Q_3 = heat rejected in the cooling cycle

The efficiency $\eta_{C,hp}$ of the system when the system acts as a heat pump is given by

$$\eta_{C,hp} = \frac{Q_2 + Q_3}{Q_1} \tag{5.9}$$

The efficiency in cooling, i.e., the heat transferred from a building divided by the energy required to drive the system, is called the *coefficient of performance* (COP) and is given as

$$\text{COP} = \frac{\text{cooling effect}}{\text{heat input}} = \frac{Q_4}{Q_1} \tag{5.10}$$

When the system is acting as a heat pump to heat a building, Q_2 and Q_3, the so-called heat rejected are rejected into the building and serve to heat the interior. When the system is acting as an air conditioner, the refrigerant flow is reversed, and heat is removed from the building and rejected to the environment.

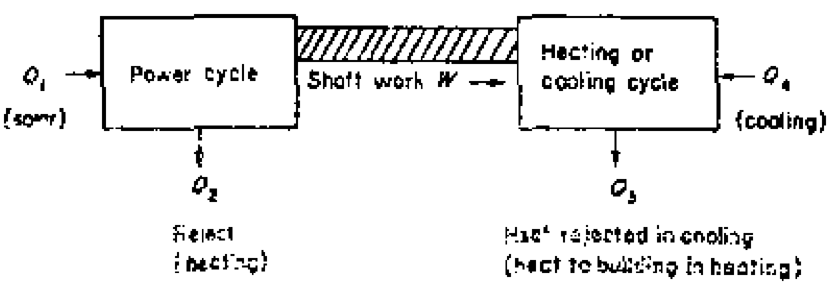


FIG. 5.3 Solar-powered heat-pump system.

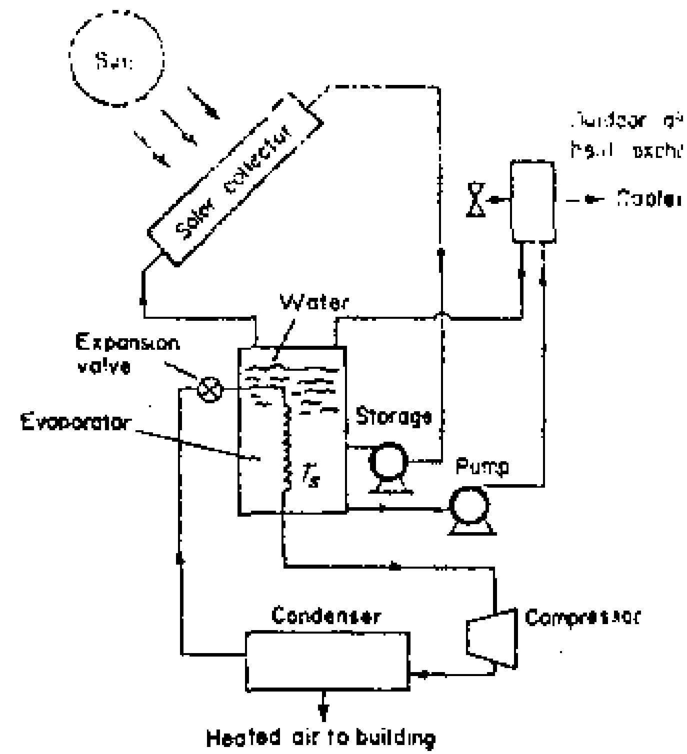


FIG. 5.4 Solar-assisted heat pump system concept using a liquid-to-... pump cycle showing the heating mode.

Solar-assisted, Conventional Heat Pump

A possible system in which solar energy augments a heat ... is shown in Fig. 5.4. In this system, thermal energy is stored ... form of sensible heat and is used as the energy source ... liquid-to-air heat pump. During the heating cycle, solar energy i... to increase the temperature of the storage, and therefore the a... of compression work necessary to increase the temperature ... working fluid is reduced. The energy that could be saved in a ty... single-family residence in the northeastern portion of the U... States is shown in Fig. 5.5. From September to November as ... from March through April, solar energy is sufficient to supp... entire heat demand. Between November and March, the work ... to the compressor is reduced by approximately 50 percent ... coefficient of performance, i.e., the energy delivered to the ... divided by the electrical energy to drive the system, sho... appreciable reduction in energy power consumption for the ... assisted system. Less power is consumed be... the average ...

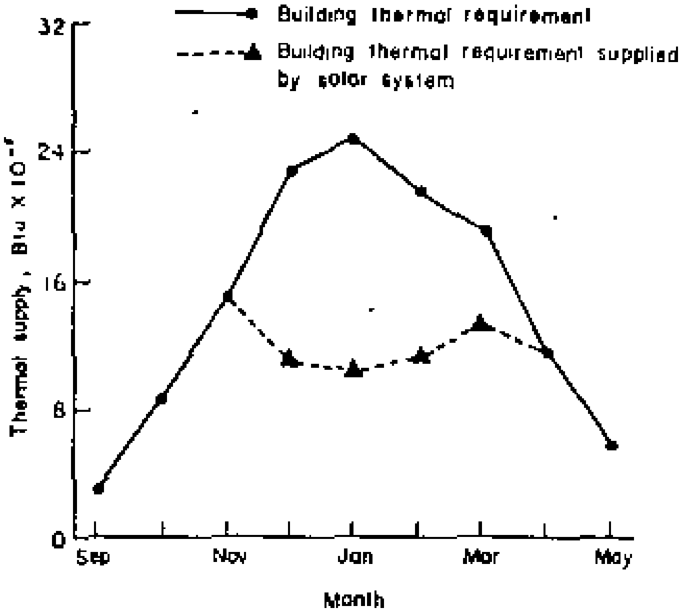


FIG. 5.5 Thermal supply by heating months for solar assisted heat pump concept.

coefficient of performance for a solar-activated system is on the order of 3 in contrast to the yearly coefficient of performance for a conventional heat pump, which is approximately 2. Greater improvements could be expected if concentrator solar collectors were used.

A solar-assisted heat pump (without the fan loop) of the type shown in Fig. 5.4 has been operating successfully in a house constructed in 1974 in Colorado Springs, Colo. The North Campus of the Community College of Denver, the second-largest solar heating system in the world—300,000-ft² heated floor area, 36,000-ft² of collector—uses this same concept.

The Rankine Power Cycle

Many power cycles could be considered for a solar-assisted heat pump. One practical, recommended system is based on the Rankine cycle, illustrated in Fig. 5.6. The components are shown schematically on the left-hand side, and on the right-hand side a pressure-enthalpy diagram for the working fluid is presented.

The working fluid starts at state point 1 (P_1) and is pumped to the pressure in the boiler, state point 2 (P_2), where heat is added until the working fluid arrives at state point 3 (P_3) in a superheated

form. The working fluid is then expanded at constant entropy to state point 4 (P_4), and heat is rejected at constant pressure in a condenser between points 4 and 1.

The magnitude of the efficiency of a Rankine cycle may be estimated by the so-called *Carnot efficiency* of the cycle, which is the highest efficiency that can be attained between the maximum and minimum temperatures available. The Carnot efficiency η_c, is equal to

$$\eta_c = \frac{T_3 - T_1}{T_3} = 1 - \frac{T_1}{T_3} \tag{5.11}$$

where T_3 is the maximum temperature attainable, and T_1 is the lowest, or sink, temperature. Equation (5.11) clearly shows the advantages of a concentrating collector that could increase the temperature T_3. T_1 is not readily maneuverable since it is, in general, dictated by the outside temperature for a power cycle. Figure 5.7 shows the effect of sink temperature and maximum temperature on the Carnot efficiency.

Any real power cycle can achieve only a fraction of the Carnot efficiency owing to the thermodynamic irreversibility of heat additions and other cycle losses. The efficiency for a real cycle, which can be obtained by examination of Fig. 5.6, is given by

$$\eta = \frac{h_3 - h_4}{h_3 - h_1} \tag{5.12}$$

where h is the enthalpy at the condition indicated by the subscript. The work required by the feed pump is usually small and can be neglected.

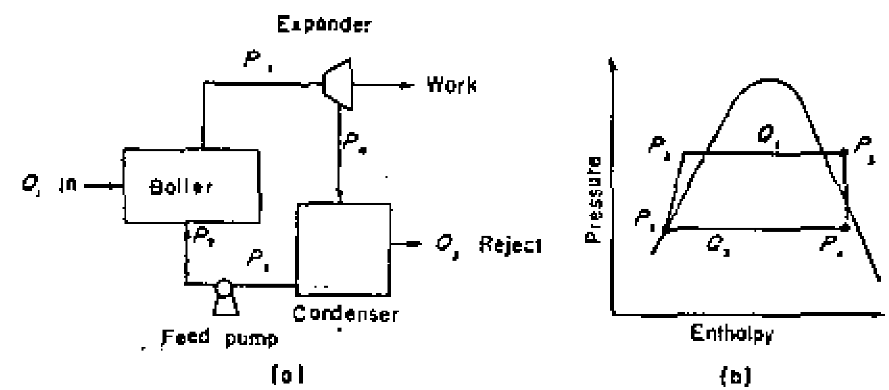


FIG. 5.6 Simple Rankine cycle. (*a*) Components; (*b*) pressure-enthalpy diagram.

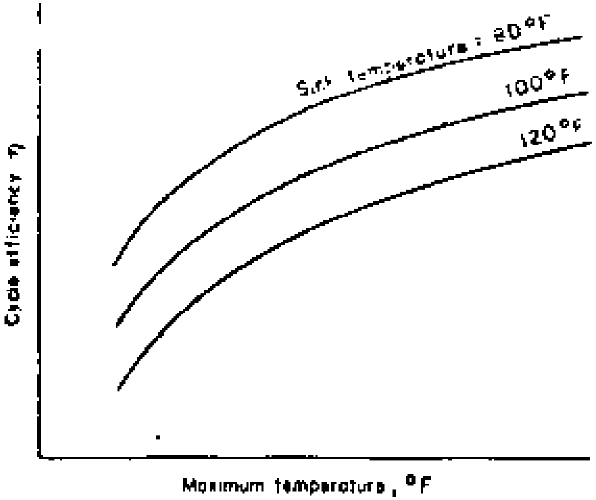


FIG. 5.7 Ideal Carnot-cycle efficiencies as a function of sink temperature and maximum cycle temperature.

The Vapor-compression Cooling Cycle

Figure 5.9 shows a vapor-compression cooling system that is most commonly used for cooling and air conditioning. The only major alternative at the present time is an absorption-cycle cooling system, which will be discussed subsequently.

The Carnot COP for the vapor-compression cycle is given by

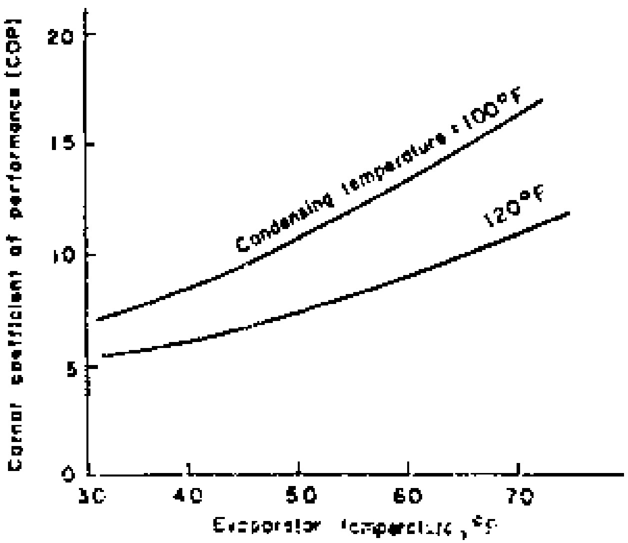


FIG. 5.8 Ideal Carnot refrigeration cycle coefficient of performance as a function of evaporator and condenser temperatures.

$$COP_C = \frac{T_2}{T_1 - T_2} \qquad (5.$$

where T_2 = lowest temperature level of the working fluid at wh[ich] heat from the interior of the house is absorbed

T_1 = upper temperature of the working fluid in the c[on]denser, at which heat is rejected to the atmosphere.

Figure 5.8 shows some typical numbers for Carnot cooling cycles [it] can be seen that the COP is greater than unity; i.e., more coolin[g is] accomplished than the shaft work required to drive the system.

Figure 5.9 shows the hardware for the vapor-compression cy[cle] schematically as well as a pressure-enthalpy diagram for the work[ing] fluid. It can be seen that the heat absorbed (equal to Q_4 in Fig. 5

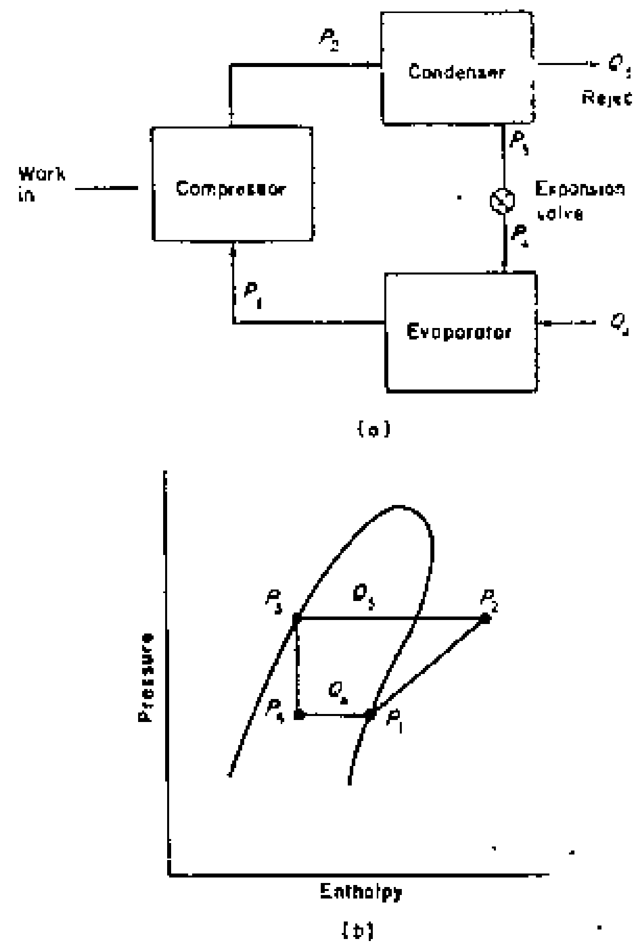


FIG. 5.9 Vapor-compression cooling cycle. (a) Components; (b) pressure enthalpy diagram.

is given by $h_1 - h_4$, and the heat rejected (Q_3 in Fig. 5.3) is given by $h_2 - h_3$. The compression work necessary to increase the temperature to the level required by h_2 is given by $h_2 - h_1$. Thus the COP of the vapor-compression cycle is given by

$$\text{COP} = \frac{\text{cooling effect}}{\text{work input}} = \frac{h_1 - h_4}{h_2 - h_1} \tag{5.14}$$

In summary, the heat-pump-air conditioner is a climate control system that employs a vapor-compression cycle both to heat and cool a building. Typically, the heat sink as well as the heat source for such a system is ambient air, although the ground or ground water can be used. The heat pump is simply a heat transformer, which, by the introduction of mechanical work into the cycle, increases the temperature of the working fluid to a level where it can be used as a source for heating the home.

The heat pump is composed of the same components that are used in standard vapor-compression air-conditioning systems, as shown in Fig. 5.10. The only additions in a heat pump are a four-way valve to permit cycle reversal when the heating mode changes to the cooling mode and an expansion device designed specifically for the particular operational (heating or cooling) refrigerant-flow condition. The basic cycle can be designed to operate in many configurations, as discussed in standard texts on air conditioning.

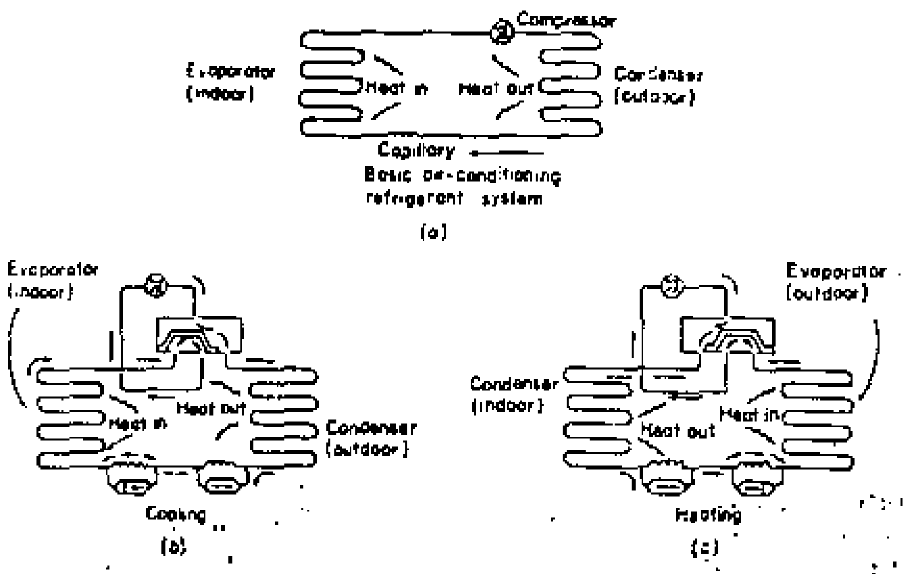


FIG. 5.10 Vapor-compression cycle in (a) basic air-conditioning mode, (b) heat pump cooling mode, and (c) heat pump heating mode.

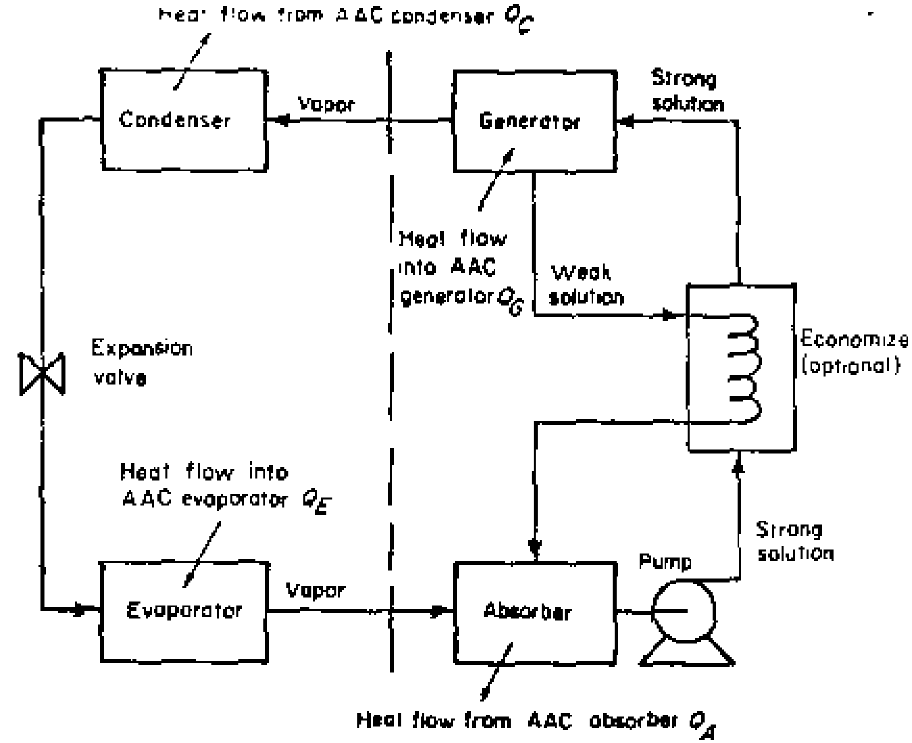


FIG. 5.11 Absorption-air-conditioner heat and fluid flow diagram with economizer.

ABSORPTION AIR CONDITIONING

Absorption air conditioning is the only air conditioning system compatible with the upper collection-temperature limits imposed by currently available flat-plate collectors. Home-sized absorption air conditioning units are more expensive than vapor-compression air conditioning units, but to date only absorption air conditioning has been operated successfully in a full-scale installation.

Presently, two types of absorption air conditioning systems are widely marketed in the United States: the lithium-bromide-water ($LiBr-H_2O$) system and the ammonia-water (NH_3-H_2O) system. The absorption air conditioning system is shown in Fig. 5.11. Absorption air conditioning differs from vapor-compression air conditioning only in the positive pressure gradient stage (right of the dashed line in Fig. 5.11). In absorption air conditioning systems, the pressurization is accomplished by first dissolving the refrigerant in a liquid (the absorbent) in the *absorber section*, then pumping the solution to a high pressure with an ordinary liquid pump. The low-boiling refrigerant is then driven from solution by the addition of heat in the generator. By this means the refrigerant vapor is compressed without the large input of high-grade shaft work the vapor-compression air conditioning demands. The remainder of the system consists of a condenser, expansion valve, and evaporator, identical in function to those used in a vapor-compression air conditioning system.

Of the two common absorption air conditioning systems, the $LiBr-H_2O$ is simpler since a rectifying column is not needed: in the NH_3-H_2O system a rectifying column assures that no water vapor, mixed with NH_3, enters the evaporator where it could freeze. In the $LiBr-H_2O$ system water vapor is the refrigerant. In addition, the NH_3-H_2O system requires higher generator temperatures (250 to 300°F) than a flat-plate solar collector can provide without special techniques. The $LiBr-H_2O$ system operates satisfactorily at a generator temperature of 190 to 200°F, achievable by a flat-plate collector; also, the $LiBr-H_2O$ system has a larger COP than the NH_3-H_2O system. The disadvantage of $LiBr-H_2O$ systems is that evaporators cannot operate at temperatures much below 40°F since the refrigerant is water vapor.

The effective performance of an absorption cycle depends on the two materials that comprise the refrigerant-absorbent pair. Desirable characteristics for the refrigerant-absorbent pair are

1. The absence of a solid-phase absorbent
2. A refrigerant more volatile than the absorbent in order to be separated from the absorbent easily in the generator
3. An absorbent that has a small affinity for the refrigerant
4. A high degree of stability for long-term operations
5. A refrigerant that has a large latent heat so that the circulation rate can be kept at the minimum
6. A low corrosion rate and nontoxicity for safety reasons

The only disadvantage of the $LiBr-H_2O$ pair is the possible problem with crystallization in the generator.

Absorption air conditioners are manufactured by many of the large air conditioning manufacturers in the United States—Carrier, Trane, York, Singer, Arkla-Servel, etc. No manufacturer currently makes a residential-sized (3 to 5 ton) $LiBr-H_2O$ unit. These units are NH_3-H_2O systems. In the past, Arkla-Servel manufactured a smaller residential $LiBr-H_2O$ unit. The line was discontinued some years ago but is being revived because of the recent interest in solar-assisted air conditioning systems. The present trade name of the Arkla-Servel system* is Sol-aire.™

*[illegible] by Arkla Industries, [illegible]ville, Inc.

[illegible]

The COP of an absorption air conditioner can be calc[illegible] from Fig. 5.11.

$$\mathrm{COP} = \frac{\text{cooling effect}}{\text{heat input}}$$

$$\mathrm{COP} = \frac{Q_E}{Q_G} \quad ($$

The pump work has been neglected since it is quite small; in so[illegible] and 5-ton units the pump can even be eliminated entirely [illegible] percolation principle employed instead.

The COP values for absorption air conditioning range [illegible] 0.5 for a small, single-stage unit to 0.85 for a double-s[illegible] steam-fired unit. These values are about 15 percent of the COP [illegible] that can be achieved by a vapor-compression air condition[illegible] incorrect to compare the COP of an absorption air conditioner [illegible] that of a vapor-compression air conditioner, however, because [illegible] efficiency of electric power generation or transmission is [illegible] included in the vapor-compression air conditioning COP. If the [illegible] of the mechanical system is multiplied by the thermal efficien[illegible] the power plant and the efficiency of the transmission networ[illegible] can be shown that the vapor-compression air conditioner has [illegible] or no thermal performance advantage over the absorptio[illegible] conditioning system.

EXAMPLE

A water-lithium-bromide, absorption-refrigeration syst[illegible] such as that shown in Fig. 5.12 is to be analyzed for the follow[illegible] requirements:

1. The machine is to provide 100 tons of refrigeration with [illegible] evaporator temperature of 40°F, an absorber outlet temp[illegible]ture of 90°F, and a condenser temperature of 110°F.
2. The approach at the low-temperature end of the liquid h[illegible] exchanger is to be 10°F.
3. The generator is heated by a flat-plate solar collector capabl[illegible] providing a temperature level of 192°F for the evaporation [illegible] the refrigerant.

Determine the COP, absorbent and refrigerant flow rates, [illegible] heat input required for a 100-ton unit.

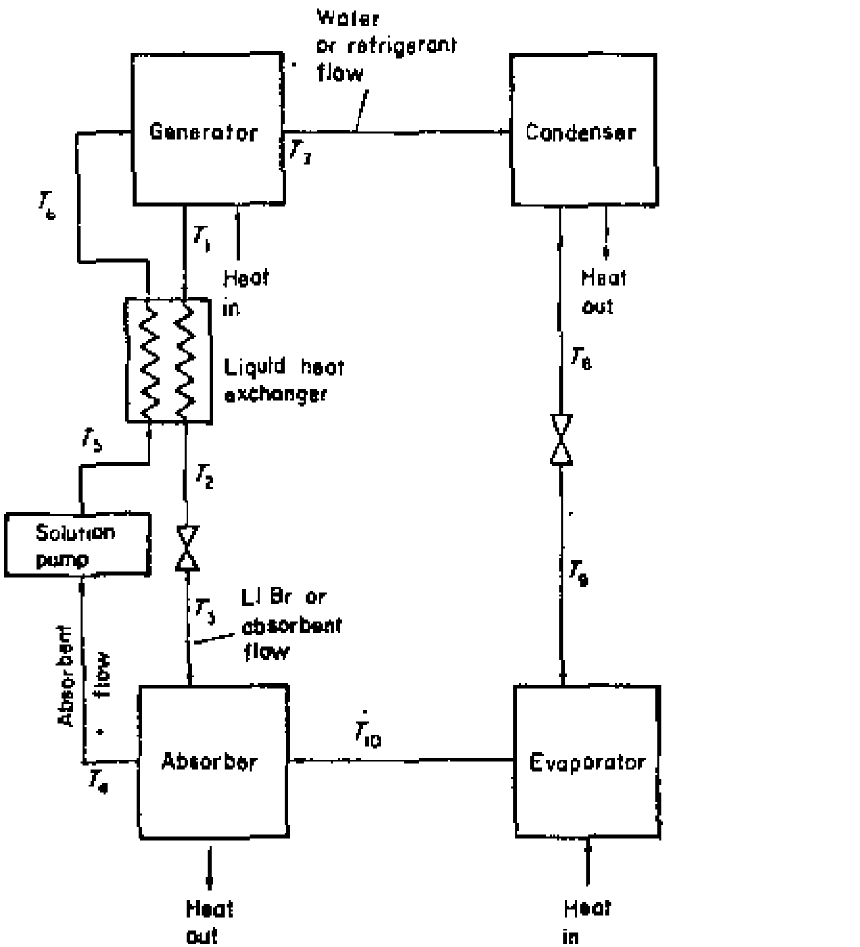


FIG. 5.12 Lithium-bromide-water, absorption-refrigeration cycle (see Table 5.1).

SOLUTION

Analytical evaluation of the LiBr-H_2O cycle requires that several simplifying factors be assumed, for example,

1. At those points in the cycle for which temperatures are specified, the refrigerant and absorbent phases are in equilibrium
2. With the exception of pressure reductions across the expansion device between points 8 and 9 in Fig. 5.12, pressure reductions in the lines and heat exchangers are neglected.
3. The temperature difference at the inlet to the liquid heat exchanger is 10°F.

4. Pressures at the evaporator and condenser are equal to the vapor pressure of the refrigerant, i.e., water, as found in steam tables.
5. Enthalpies for LiBr-H_2O mixtures are given in Fig. 5.13.

As the first step in solving the problem, set up a table similar to Table 5.1; enter values of pressure in the appropriate table columns, enthalpy, and weight fraction for which sufficient information is available. For example, at point 8 the temperature is 110°F, and the vapor pressure of steam corresponding to this pressure in the condenser is 1.28 psia, or 66 mm of Hg.

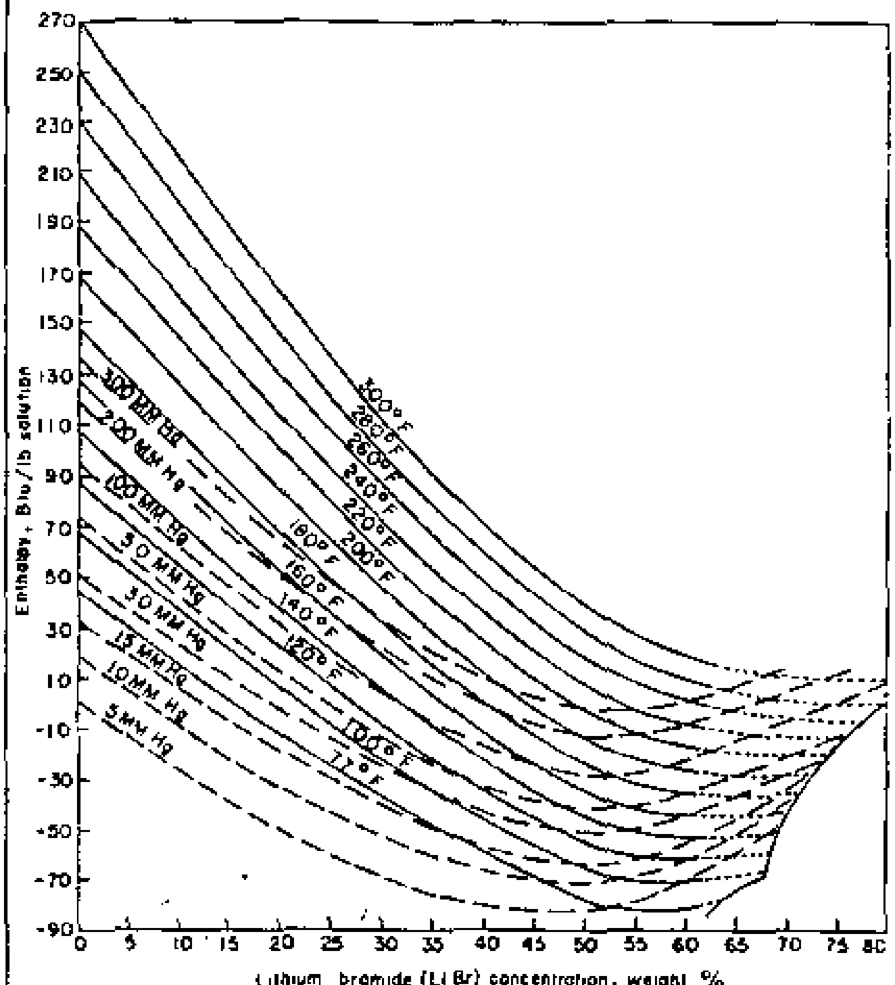


FIG. 5.13 Enthalpy-concentration diagram for lithium-bromide-water combination.

TABLE 5.1 Thermodynamic Properties of Refrigerant and Absorbent for Fig. 5.12

Condition no. in fig. 5.12	Temperature, °F	Pressure, mm Hg	LiBr weight fraction, %	Flow, lb/lb H_2O	Enthalpy, Btu/lb
T_1	192	66.0	0.61	11.2	−30
T_2	100	66.0	0.61	11.2	−70
T_3	100	6.3	0.61	11.2	−70
T_4	90	6.3	0.56	12.2	−75
T_5	90	66.0	0.56	12.2	−75
T_6	163	66.0	0.56	12.2	−38.2
T_7	192	66.0	0	1.0	1147
T_8	110	66.0*	0	1.0	78
T_9	40	6.3*	0	1.0	78
T_{10}	40	6.3	0	1.0	1079

*These values were derived from Joseph H. Keenan and Frederick G. Keyes, "Thermodynamic Properties of Steam," John Wiley & Sons, New York, 1936.

Mass balance equations

Relative flow rates for the absorbent (LiBr) and the refrigerant (H_2O) are obtained from material balances. A total material balance on the generator gives

$$\dot m_6 = \dot m_1 + \dot m_7$$

while a LiBr balance gives

$$\dot m_6 X_r = \dot m_1 X_{ab}$$

where X_{ab} = concentration of LiBr in absorbent, lb/lb of solution
X_r = concentration of LiBr in refrigerant, lb/lb of solution

Substituting $(\dot m_1 + \dot m_7)$ for $\dot m_6$ gives

$$\dot m_1 X_r + \dot m_7 X_r = \dot m_1 X_{ab}$$

Since the fluid entering the condenser is pure refrigerant, i.e., water, $\dot m_7$ is the same as the flow rate of the refrigerant $\dot m_r$:

$$\frac{\dot m_1}{\dot m_7} = \frac{X_r}{X_{ab} - X_r} = \frac{\dot m_{ab}}{\dot m_r}$$

where $\dot m_{ab}$ = flow rate of absorbent, lb/hr
$\dot m_r$ = flow rate of refrigerant, lb/hr

Substituting for X_r and X_{ab} from the table gives the ratio of absorbent-to-refrigerant flow rate

$$\frac{\dot m_{ab}}{\dot m_r} = \frac{0.56}{0.61 - 0.56} = 11.2$$

The ratio of the refrigerant-absorbent solution flow rate $\dot m_s$ to the refrigerant-solution flow rate $\dot m_r$ is

$$\frac{\dot m_s}{\dot m_r} = \frac{\dot m_{ab} + \dot m_r}{\dot m_r} = 11.2 + 1 = 12.2$$

Energy balance equations

The enthalpy of the refrigerant-absorbent solution leaving the liquid heat exchanger at point 6 is obtained from an over-all energy balance on the unit, or

$$\dot m_s h_5 + \dot m_{ab} h_1 = \dot m_{ab} h_2 + \dot m_s h_6$$

Hence, $h_6 = h_5 + \left[\frac{\dot m_{ab}}{\dot m_s}(h_1 - h_2)\right]$

$$= -75 + \frac{11.2}{12.2}[-30-(-70)] = -38.2 \text{ Btu/lb of solution}$$

The temperature corresponding to this value of enthalpy and a pressure of 66 mm Hg is found from Fig. 5.13 to be 163°F.

The flow rate of refrigerant required to produce the desired 100 tons of refrigeration (equivalent to 1,200,000 Btu/hr) is obtained from an energy balance about the evaporator,

$$q_{refrig} = \dot m_r (h_9 - h_{10})$$

where q_{refrig} is the cooling effect supplied the refrigeration unit, and

$$\dot m_r = \frac{1,200,000}{1,079 - 78} = 1,200 \text{ lb/hr}$$

The flow rate of the absorbent is

$$\dot m_{ab} = \frac{\dot m_{ab}}{\dot m_r}\dot m_r = 11.2 \times 1,200 = 13,400 \text{ lb/h}$$

while the flow rate of the solution is

$$\dot{m}_s = \dot{m}_{ab} + \dot{m}_r = 13{,}400 + 1{,}200 = 14{,}600 \text{ lb/hr}$$

The rate at which heat must be supplied to the generator q_{sup} is obtained from the heat balance

$$\begin{aligned} q_{sup} &= \dot{m}_r h_7 + \dot{m}_{ab} h_1 - \dot{m}_{ab} h_6 \\ &= [(1{,}200 \times 1{,}147) + (13{,}400 \times -30)] - (14{,}600 \times -38.2) \\ &= 1{,}540{,}000 \text{ Btu/hr} \end{aligned}$$

This requirement, which determines the size of the solar collector, likely represents the maximum heat load the refrigeration unit must supply during the hottest part of the day.

The coefficient of performance, COP, is

$$\text{COP} = \frac{q_{refrig}}{q_{sup}} = \frac{1{,}200{,}000}{1{,}540{,}000} = 0.78$$

The rate of heat transfer in the other three heat-exchanger units—the liquid heat exchanger, the water condenser, and the generator—is obtained from heat balances. For the liquid heat exchanger this gives

$$\begin{aligned} q_{1-2} &= \dot{m}_{ab}(h_1 - h_2) \\ &= 13{,}400[(-30) - (-70)] = 540{,}000 \text{ Btu/hr} \end{aligned}$$

where q_{1-2} is heat transferred from the absorbent stream to the refrigerant/absorbent stream. For the water condenser the rate of heat transfer q_{7-8} rejected to the environment is

$$\begin{aligned} q_{7-8} &= \dot{m}_r(h_7 - h_8) \\ &= 1{,}200(1{,}147 - 78) = 1{,}280{,}000 \text{ Btu/hr}\,. \end{aligned}$$

The rate of heat removal from the absorber can be calculated from an over-all heat balance on this system:

$$\begin{aligned} Q_A &= q_{7-8} - q_{sup} - q_{refrig} \\ &= 1{,}280{,}000 - 1{,}540{,}000 - 1{,}200{,}000 \\ &= -1{,}460{,}000 \text{ Btu/hr} \end{aligned}$$

Explicit procedures to [illegible] the mass transfer and heat transfer [illegible] as well as the sizing of the heat exchangers are presented in standard heat transfer texts. In large commercial units it may be possible to use higher concentrations of LiBr, operate at a higher absorber temperature, and thus save on heat-exchanger cost. In a solar-driven unit this approach would require a concentrator-type absorber because flat-plate solar collectors cannot achieve a sufficiently high temperature to raise the temperature level in the absorber of an absorption air conditioner much above 190°F.

COMPARISON OF MECHANICAL AND ABSORPTION REFRIGERATION SYSTEMS

Absorption-refrigeration systems operate on cycles in which the primary fluid, a gaseous refrigerant, which has been vaporized in an evaporator, is absorbed by a secondary fluid, called the absorbent. Absorption-refrigeration cycles can be viewed thermodynamically as a combination of a heat-engine cycle and a vapor-compression refrigeration cycle, which are also the two components of a mechanical-refrigeration system. Simplified diagrams for the two methods of providing refrigeration are shown in Figs. 5.14 and 5.15,

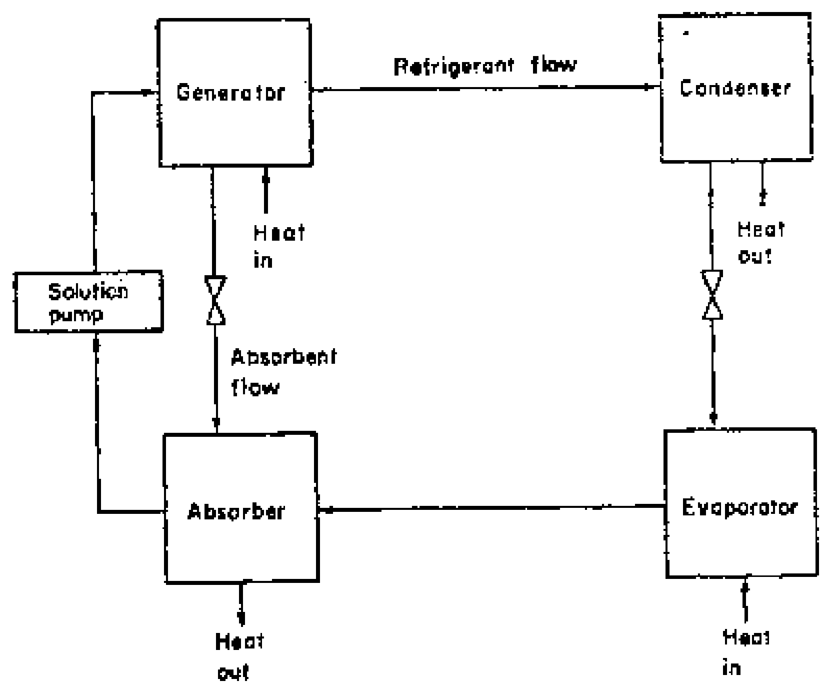


FIG. 5.14 Basic absorption-refrigeration cycle without economizer.

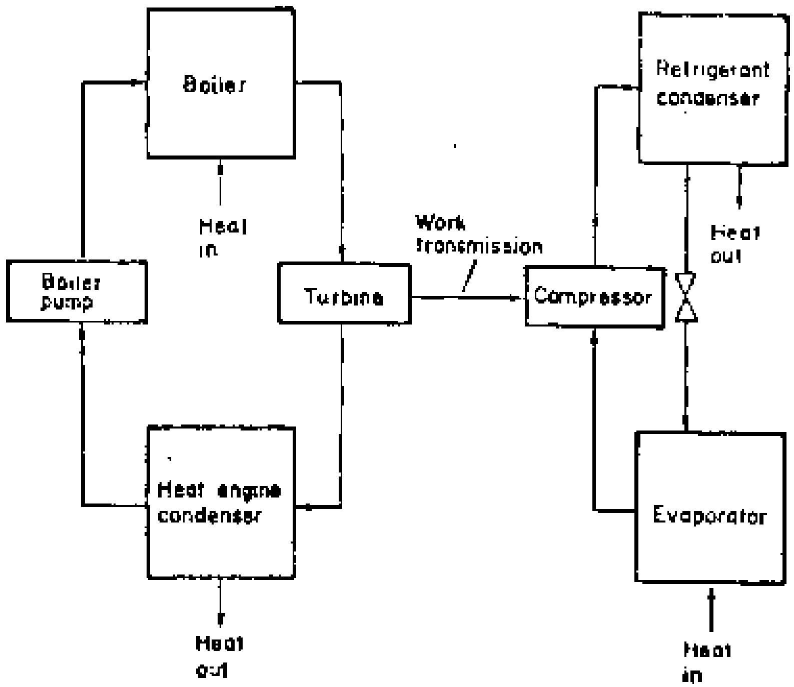


FIG. 5.15 Combination of heat-engine cycle and mechanical-refrigeration cycle.

respectively. A comparison between these two schematic diagrams indicates similarities between the main components in the absorption cycle and the components in a heat-engine cycle driving a mechanical-refrigeration cycle.

In both cycles, heat from a high-temperature source is transferred in a heat exchanger to obtain a relatively high-pressure vapor. In the absorption cycle, the heat input occurs in a generator, from which streams of refrigerant and absorbent emanate. In the heat-engine cycle, the heat input occurs at the boiler, from which a vapor is produced that drives a turbine. The condenser in the absorption cycle is equivalent to the refrigerant condenser in the mechanical-refrigeration cycle. In both heat exchanges, heat is transferred from the refrigerant at relatively high pressures.

In both methods of refrigeration, the high-pressure refrigerant (from which heat has been removed in the condenser) is passed through an expansion valve that reduces the temperature and pressure of the refrigerant before it enters the evaporator. In both methods, heat is transferred to the refrigerant in the evaporator, where as a result of this heat transfer, the refrigerant is vaporized at relatively low pressures. It is the evaporator which absorbs the heat and provides the refrigeration effect in both methods.

The absorber in the absorption-refrigeration cycle corresponds to the heat-engine condenser in the mechanical-refrigeration cycle. Heat is transferred out of the absorber in the absorption cycle, and out of the heat-engine condenser in the combination method, to an intermediate temperature sink to facilitate the conversion of relatively low-pressure vapor to the liquid state. In the absorption method, the absorbent is mixed with the refrigerant in the absorber. The final similarity between the two systems is the solution pump and the boiler pump. In both systems a small amount of work is necessary to increase the pressure of the liquid before entering the boiler or generator of the cycle.

The turbine, which extracts heat energy from the high temperature vapor from the boiler in the combination cycle thereby transforming heat into work to drive a compressor, does not have a counterpart in the absorption method. In the absorption method, the energy input occurs in the form of heat into the generator, and hence the generator can operate at a temperature of less than 200°F. In some absorption cycles, the heat supply can be provided by flat-plate solar collectors. On the other hand, in the combination heat-engine and mechanical-refrigeration cycle, the turbine drive requires a relatively high-temperature vapor for efficient operation and it is difficult to obtain good performance with a flat-plate solar collector and a concentrator type is required.

The relationship between work and heat for an ideal heat-engine operating on a Carnot cycle is

$$W = q_g \frac{T_h - T_{hs}}{T_h} \tag{5.16}$$

where W = work output rate,
q_g = heat input rate,
T_h = temperature of heat source, and
T_{hs} = temperature of heat sink

The relationship between the work required and the refrigeration load for an ideal mechanical-refrigeration machine operating on the reverse Carnot cycle is

$$-W = q_e \frac{T_{hs} - T_1}{T_1} \tag{5.17}$$

where $-W$ = work input rate,
q_e = rate of refrigeration
T_1 = temperature of the refrigeration load
T_{hs} = temperature of the heat sink

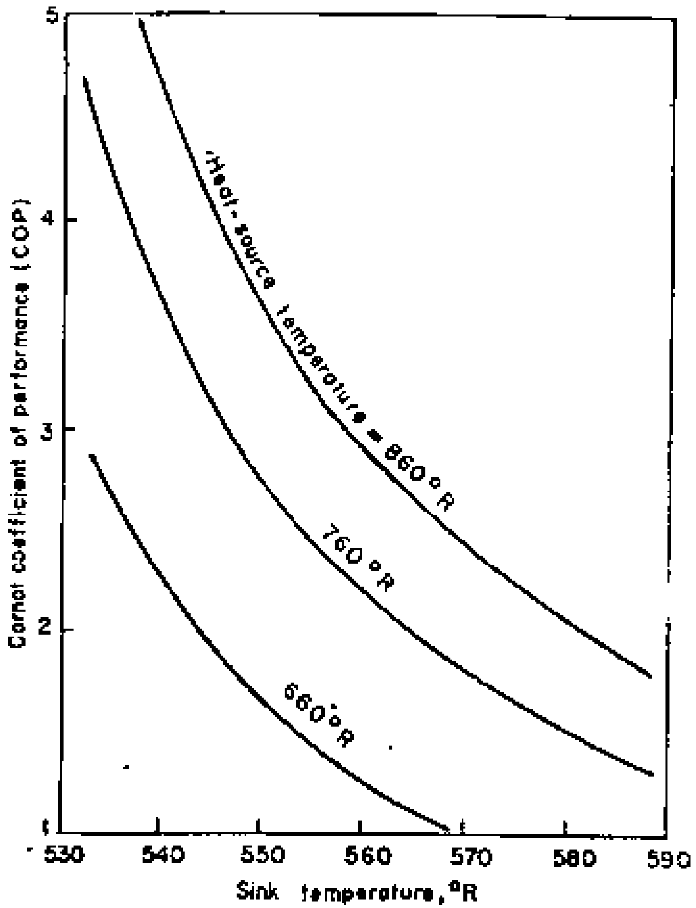


FIG. 5.16 Ideal coefficient of performance for absorption-refrigeration cycles with evaporator (load) temperature T_1 of 500° R.

The coefficient of performance for the combination of this engine cycle and the mechanical-refrigeration machine is given by

$$\text{COP} = \frac{q_e}{q_g} = \frac{T_1(T_h - T_{hs})}{T_h(T_{hs} - T_1)} \tag{5.18}$$

Equation (5.18) applies to the ideal absorption-refrigeration process as shown earlier as well as to the combination heat-engine and mechanical-refrigeration cycle. The coefficient of performance is plotted as a function of sink temperature for various temperatures of the heat source for a Carnot cycle with a refrigeration load at 40°F in Fig. 5.16.

NONMECHANICAL SYSTEMS

Australian Rock System

A nocturnal cooling-storage system first tested in 1955 in a desert in the southwest United States has been more recently tested and developed in Australia. The system consists of a large bed of rocks cooled by drawing cool night air across them and exposing them to night sky radiation. During the day, warm inside air may be cooled by circulating it through the rock bed. Augmented cooling can be achieved by drawing the night air through a porous surface having a high emittance at low temperature and facing the night sky. Such a system operates best in a desert climate, where the night skies are clear and humidity is low. In a desert climate, the diurnal temperature variation may be 45°F. Although this system is not an active solar cooling system, it uses the same pebble-bed storage that an air-cooled solar heating system uses for heat storage.

The use of a pebble bed to provide energy storage for both heating and cooling cycles has been described by Close[2] and Dunkle.[3] Figure 4.13 shows how a solar air heater can be combined with pebble-bed storage to provide a heat source for a building. The cycles in Fig. 5.17 illustrate the operation of the same pebble bed when it is used for cooling. During the night, cool air from the outside is brought through an evaporative cooler into the pebble bed

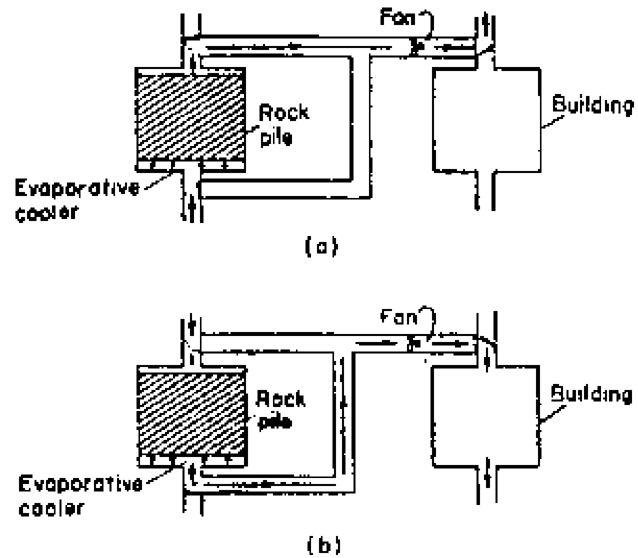


FIG. 5.17 Operation of a pebble bed thermal storage as a source of air conditioning.

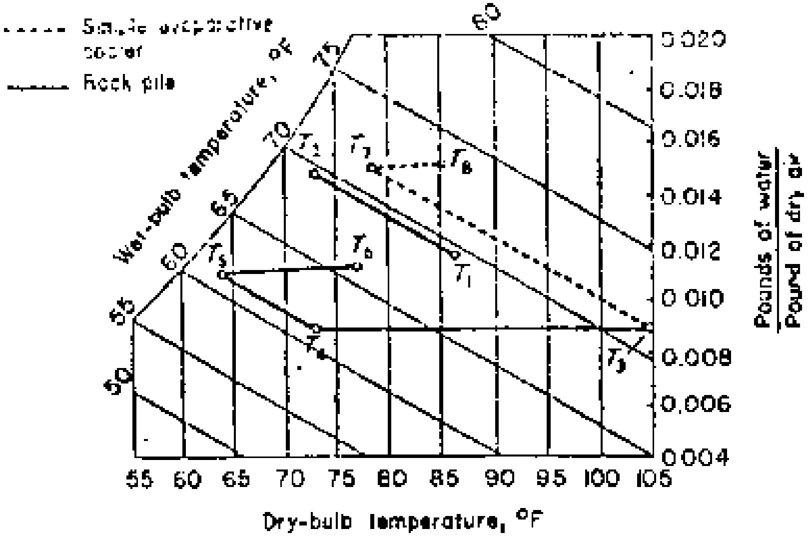


FIG. 5.18 Cooling cycles for pebble bed with and without evaporative cooler.

and is cooled at approximately wet-bulb temperature to a condition approaching saturation. The entire bed is eventually brought to this temperature by passing the cooled air through it for several hours, as shown in Fig. 5.17(*a*). On the next day, when cooling is required in the building, outside air is drawn vertically downward through the bed and cooled to the bed temperature. As the air leaves the bed it may be cooled further by evaporation and is then passed into the building as shown in Fig. 5.17(*b*).

The mode of operation of the cycle just described can be illustrated quantitatively by means of an example. The psychometric chart in Fig. 5.18 indicates the state points of the air passing through the cycle during a 24-hr period with environmental conditions corresponding to a night with a wet-bulb temperature of 70°F and a dry-bulb temperature of 86°F, and a day with a dry bulb temperature of 105°F and wet-bulb temperature of 71°F. In Fig. 5.18, the line $T_1 - T_2$ corresponds to evaporative cooling of the nighttime air to 80 percent of saturation, which will cool the rocks in the bed to 73°F if steady state can be achieved at the lowest temperature level.

When the building requires cooling the next day, air is introduced into the pebble bed under conditions corresponding to point T_3 in Fig. 5.18, cooled in the bed to 73°F, corresponding to point T_4, and then cooled evaporatively at constant wet-bulb temperature to a dry-bulb temperature of 63°F, corresponding again to 80 percent saturation. This air is then passed into the building to

ambient conditions of 77°F and about 57 percent relative humidity. The increase in internal energy of the air, corresponding to the amount of heat transferred from the hot interior of the building to the air, is 3.5 Btu/lb. Thus, for a cooling load of 30,000 Btu/hr or 2.5 tons, the required air circulation rate is about

$$\frac{(30{,}000\ \text{Btu/hr}) \times (14\ \text{cu ft/lb of air})}{(3.5\ \text{Btu/lb of air}) \times (60\ \text{min/hr})} = 2{,}000\ \text{cfm}$$

For comparison, the dotted line in Fig. 5.18 corresponds to a simple evaporative cooler. To maintain a temperature of 85°F in the building, the required air-flow rate is about 30 percent larger than for a rock bed that maintains the building at 77°F.

To determine the size of the pebble bed necessary for a cooling period of 12 hr, a heat balance must be made on the rocks, or

$$V_r \rho_r c_r (T_{a,\text{in}} - T_{a,\text{out}}) = \dot{m}_a c_a\, (T_{a,\text{in}} - T_{a,\text{out}})\theta \qquad (5.19)$$

where
V_r = volume of the rock in the bed, ft³
ρ_r = density of the rock, lb/ft³
c_r = specific heat of the rock, Btu/(lb)(°F)
$T_{a,\text{in}}$ = temperature of air entering bed, °F
$T_{a,\text{out}}$ = temperature of air leaving bed, °F
$\dot{m}_a$ = air-flow rate, lb/hr
c_a = specific heat of air, Btu/(lb)(°F)
θ = cooling period, hr

Equation (5.19) assumes that all the thermal energy stored can be extracted at the maximum temperature potential. For less efficient operation the size of the rock pile must be increased.

The size of the pile is approximately

$$V_r = \frac{(2{,}000 \times 0.24)\,(T_{a,\text{in}} - T_{a,\text{out}})\,(12 \times 60)}{(85 \times 0.21)(T_{a,\text{in}} - T_{a,\text{out}})\,14} = 1{,}400\ \text{ft}^3 \qquad (5.20)$$

However, since the pile has empty spaces, the actual volume will be larger by the inverse of the empty-space fraction, defined as

$$\frac{\text{Volume of rock pile} - \text{volume of voids}}{\text{Volume of rock pile}}$$

To design a rock-pile storage system completely the friction factor for packed beds and the heat-transfer coefficient for air passing through the pile must be known. In Fig. 5.19 the friction factor for packed beds, f_r (defined as 2 times the pressure drop Δ divided by $\rho_f v_f^2$ times the ratio d_r/l, where l is the packed bed length) is plotted as a function of the *Particle Reynolds number*, Re (defined as $v_f \rho_f d_r / \mu_f$). In Fig. 5.19 v_f is the superficial air velocity (air-flow rate per pile cross-sectional area), d_r is the equivalent spherical diameter of the rocks $(6\,V_p/\pi)^{1/3}$, V_p is the rock-particle volume, μ_f is the viscosity of the air in the pile, ρ_f is the density of the air and Δp is the pressure drop across the pile. These parameters must be in a consistent set of units to make the abscissa and the ordinate dimensionless. This correlation, proposed by Dunkle,[3] agrees well with other correlations but is simpler to use. Experimentally measured heat-transfer coefficients from Close[2] are shown in Fig.

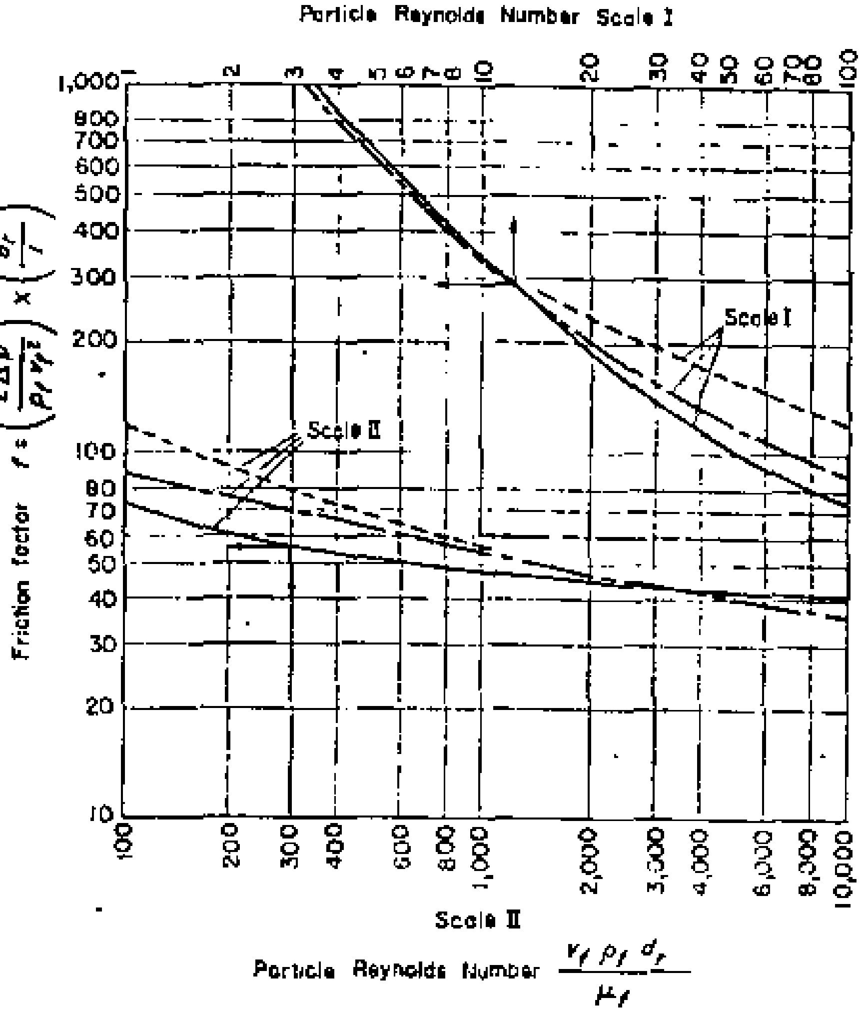


FIG. 5.19 Friction factors for packed beds as functions of particle Reynolds number.

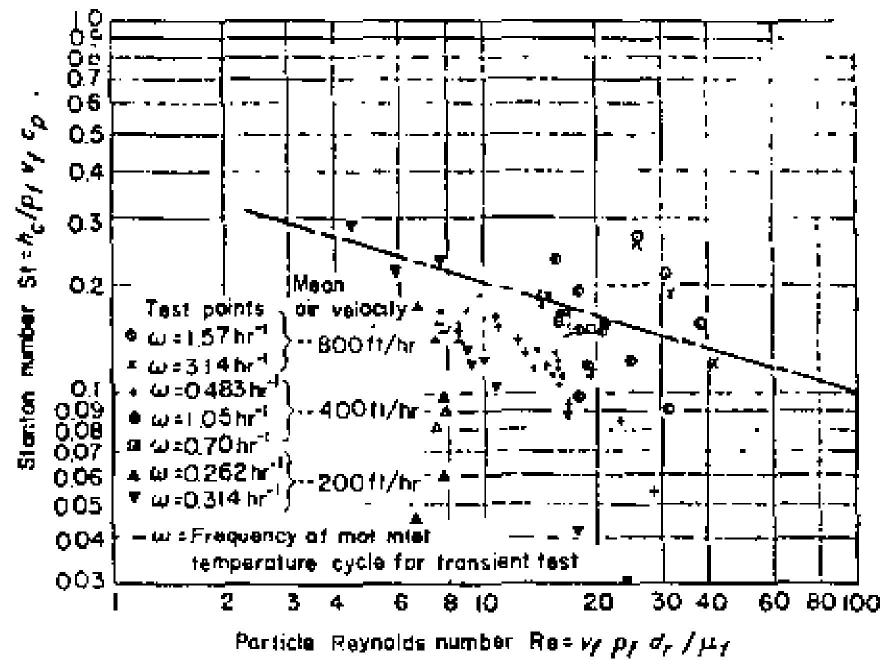


FIG. 5.20 Comparison between measured heat-transfer coefficients for packed beds as a function of particle Reynolds number. (*Adapted from Close.*[2])

5.20 as a function of particle Reynolds number. In Fig. 5.20 the *Stanton number*, St, defined as a heat-transfer coefficient divided by the product of the air density, the velocity, and the specific heat, is plotted again as a function of the particle Reynolds number. Figure 5.21 shows the pressure decrease in inches of water per foot of the depth of the pile and the heat-transfer coefficient as a function of the superficial air velocity in feet per minute for various rock sizes. The following example illustrates the calculations for a rock-pile storage system. For a more detailed analysis the variation in temperature during a 24-hr period must be taken into account.

EXAMPLE

A rock pile is required to store 1 million Btu. Charging and extraction are at constant rates, and each lasts approximately 10 hr. The temperature difference is to be 60° (70°F minimum and 130°F maximum). The maximum allowable pressure decrease is 0.1 in. of water. Approximately 80 percent of the energy stored in the pile can be extracted. Determine the fluid flow rate and ratio of energy storage to energy required to move the air through the bed.

SOLUTION

Assume the rock has a density of 85 lb/ft^3 and a specific heat of 0.21 Btu/(lb)(°F); the total volume of rock required for the storage would then be 934 ft^3. If this storage is to be charged in 10 hr, the mass flow rate of air, $\dot{m}_a$, may be obtained from a heat balance. If it can be assumed that all the heat is extracted at the stored temperature

$$\dot{m}_a = \frac{10^6 \text{ Btu}}{10 \text{ hr} \times [(0.24 \text{ Btu})/(\text{lb})(°\text{F})] \times 60°\text{F}} = 7{,}000 \text{ lb/hr}$$

The volumetric flow rate for air at 70°F is thus about 1,600 ft^3/min. If the maximum allowable pressure decrease is 0.1 in. of water, the ratio of heat stored to energy required to operate the pile is approximately 400:1.

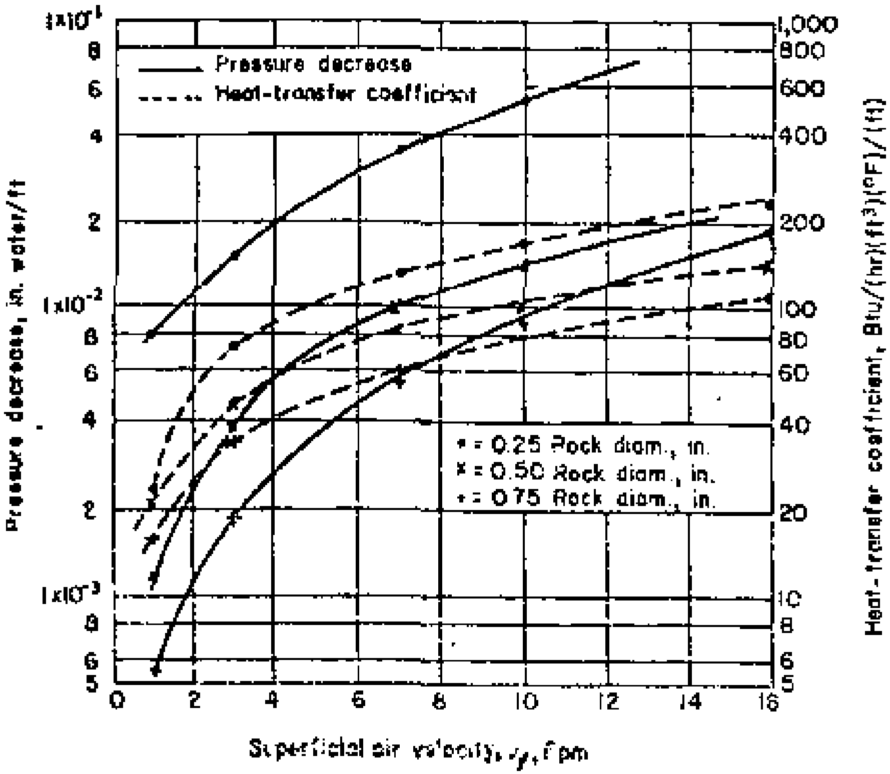


FIG. 5.[illegible] [illegible] coefficients and pressure [illegible] for various air flows and rock sizes [illegible] bed

TABLE 5.2 Dimensions and Air Velocity for Various [illegible] Beds

Bed dimensions and air velocity	Rock diameter, in. 0.25	0.5	0.75	Design basis
Bed height, ft	3.4	5.9	7.4	Maximum allowable
Bed area, ft^2	275.5	159	126	p[illegible] drop
Air velocity, fpm	6	10.5	13.1	[illegible] height)
Bed height, ft	2.75	4.0	5.0	Inter[illegible] height
Bed area, ft^2	340	233.5	186.6	
Air velocity, fpm	4.85	7.07	8.8	
Bed height, ft	2	2.0	2.0	Minimum height
Bed area, ft^2	467	467	467	
Air velocity, fpm	3.53	3.53	3.53	

Table 5.2 summarizes the dimensions and air velocities for various pebble beds as compiled by Close[3] for engineering design. It should be noted that best performance is obtained when the rocks are as small as possible and the bed sized for the maximum allowable pressure decrease. The smaller the rocks, however, the more the pile becomes subject to blockage by dust, and the installation of a dust-removal screen may be necessary.

Sky-Therm™ System*

H. R. Hay has built a home in Atascadero, Calif., which uses his patented, passive, solar heating and cooling arrangement. It consists, in summary, of a combined collector-radiator-storage system mounted on the horizontal roof of a one-story building. The combined energy medium consists of 8-in.-deep pools of water enclosed in plastic bags located between beams of the house and on top of a black, plastic liner used to further waterproof the roof. Solar energy heats the water to 85°F, a purposely maintained low temperature. Insulated shutters are then placed over the panels during winter nights to reduce heat loss.[4,5]

During the summer the shutters cover the panels to prevent heating during the day. However, the collection area used for service water heating remains uncovered during daytime. At night the primary ponds are uncovered to permit radiation of the heat collected from the building during the day. The system is currently under test at the Atascadero test site. A smaller building was maintained at a temperature of 70°F ± 2°F for a year in Phoenix, Ariz., by this method.

*®Registered trademark, Skytherm Processes and Engineering, Los An[illegible] Calif.

The summer function of such a system relies on nocturnal radiation loss. Such losses are usually in the range of 10 to 35 Btu/(hr)(ft²). To provide 1 ton-hr of heat removal, 500 ft² of radiator surface is required. If the entire roof of a 2,000 ft² house were used as a radiator, only 4 tons of heat would be removed, assuming the water ponds do not reach an equilibrium temperature and night heat loss averages 25 Btu(hr)(ft²). For an 8-hr night this cooling effect amounts to 32 ton-hr. In the Southwest, where the system is proposed for application, additional daytime cooling might be necessary to maintain comfort. In the 2,000 ft² house, the water ponds would create a total physical load of 42 tons.

THE ECONOMICS OF SOLAR AIR CONDITIONING

A detailed economic analysis of solar air conditioning today suffers from the lack of knowledge of costs and performance of the LiBr-H_2O system when the system is modified for solar use. Several investigators have studied the system in detail, and a performance picture is beginning to emerge. As described under "Design of a Collector for a Building," earlier in this chapter, Löf and Tybout have modeled a combined solar-heated and solar-cooled residence by computer using current estimates on costs and performance of

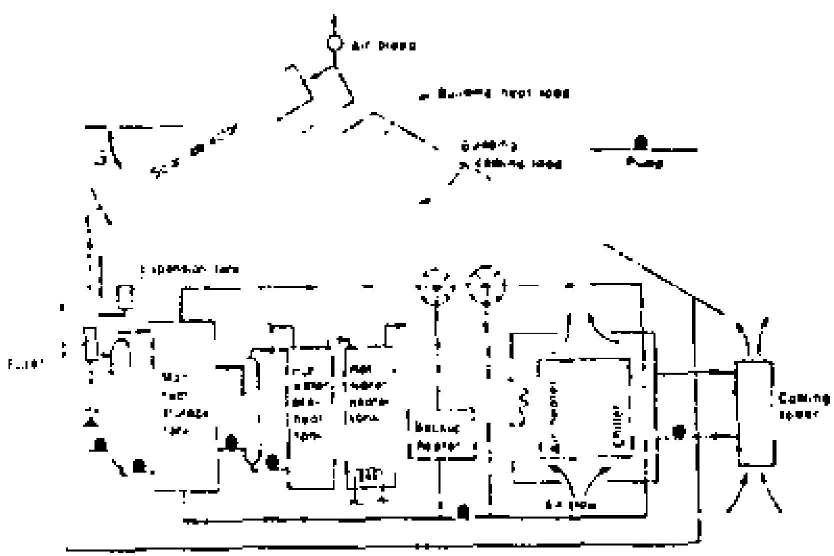


FIG. 5.22 Combined solar-heating and -cooling system schematic diagram (control valves not shown).

TABLE 5.3 Costs Assumed in Löf and Tybout Solar System*

Item	Cost, $	Comments
Storage costs	0.05/lb water	Per lb water stored per ft² collector area (including tank, etc.)
Controls	150	Fixed cost
Pipes, fittings	$100 + 0.10A_{coll}$	Fixed plus variable cost
Motors, pumps	$50 + 0.20A_{coll}$	Fixed plus variable cost
Heat exchangers	$75 + 0.15A_{coll}$	Fixed plus variable cost
Collector	$2.00A_{coll}$	Projection based on economies of scale
LiBr-H_2O air conditioning	1,000	Cost above mechanical A/C

*Equipment useful life is assumed to be 20 yr; discount rate is assumed to be 8% (CRF = 0.102). For more realistic costs see Fig. 5.23.

a small (3 to 5 ton) LiBr-H_2O absorption air conditioner. Their analysis is much like the approach described in Chap. 4, "Computerized System Optimization," for optimizing solar heating systems. Figure 5.22 shows a detailed schematic diagram, including all components of the combined system.

Table 5.3 shows the additional costs in the solar system used by Löf and Tybout. The model optimization runs showed that

1. In climates where both air conditioning and heating are required, a *combined solar-heating–air-conditioning system is more economical* than either a solar-heating or solar-cooling system by itself. Figure 5.23 shows one of the plots presented in the study with more realistic costs substituted for their values.
2. *Optimal storage was found to be about 10 to 15 lb_m/ft^2*, the same value determined for the optimal heating-only system described in Chap. 4.
3. *Between 30 and 70 percent of the combined loads could be met by the solar-optimal system*, modeled in the eight climatic zones studied, at a cost of $1.75 to $3.00 per million delivered Btu. (More realistic cost is $4.00 to $6.00 per million Btu.)
4. Solar energy costs less in nearly all locations than electrical energy used for heating and cooling. The costs were computed in 1970 dollars.

In this study the optimal mix of solar and auxiliary energy was not determined. The optimal mix may be obtained by determining the mix at the point where marginal costs of solar and auxiliary energy are equal, as described in Chap. 4, "Computerized System Optimization."

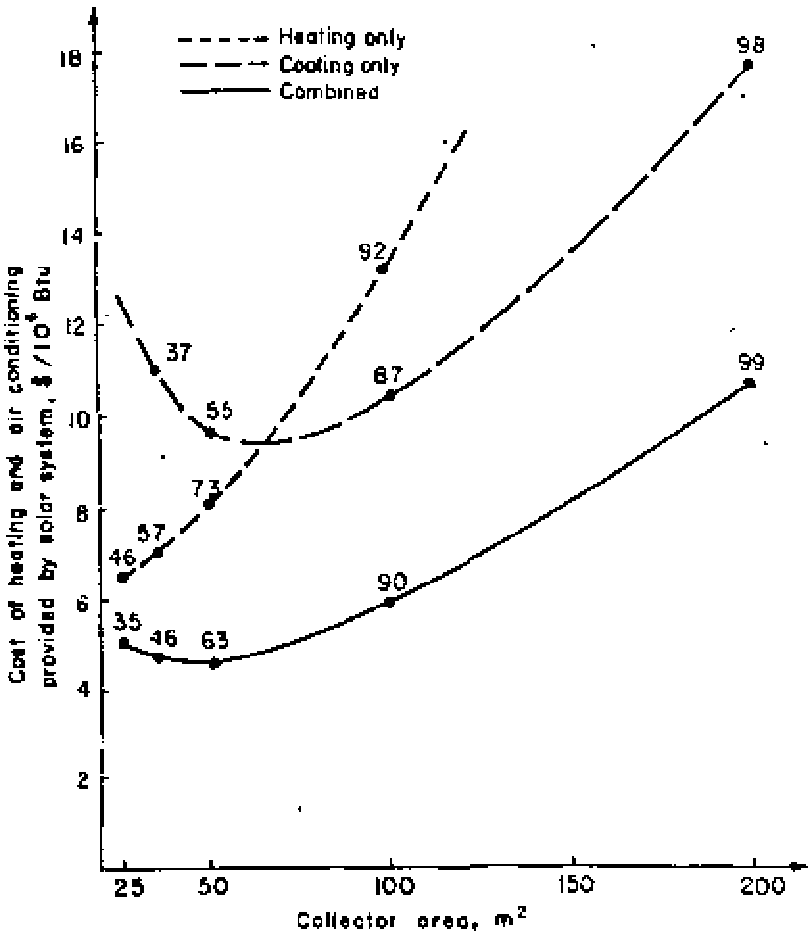


FIG. 5.23 Annual cost of solar heating, solar cooling, and combined solar heating and cooling for a model home in Albuquerque, N. Mex. Numbers on the curves are percentages of load carried by solar under the following conditions: collector tilt β = latitude L = 35.05°N, heating demand = 25,000 Btu/°F per day, system cost amortized for 20 yr at 8%, collector cost with two glass covers = \$12/ft², absorption air conditioner \$1,000 more costly than standard mechanical system. (*Adapted from Löf and Tybout.*[6])

SUMMARY

This chapter deals with various methods by which solar energy can be used to provide building cooling. The first section presents the procedure for calculating the cooling load on a building during the cooling season. A design study of a flat-plate collector-lithium-bromide air conditioner showed that the three most important design parameters for solar collection system are the tilt angle, number of covers and c ctor area.

Several thermodynamic cooling cycles are considered in detail in the remainder of the chapter. Performance criteria for the Rankine cycle-powered vapor-compression cycle are described and the use of vapor-compression heat pumps with solar assist is explained. The absorption cycle is also discussed and the method of analyzing the cycle thermodynamically is shown in detail for a lithium-bromide system. A nonmechanical cooling system that uses pebble bed storage as a means of summer cooling in climates where cool nights are frequent is described. Design correlations for pressure drop and heat transfer coefficient for this sytem are given. The last section of the chapter summarizes the economic considerations which determine the viability of solar cooling systems.

REFERENCES

1. Beckman, W. A., and J. A. Duffie: "Modeling of Solar Heating and Air Conditioning," Nat'l Tech. Information Serv., Springfield, Va., 1973.
2. Close, D. J.: Rock Pile Thermal Storage for Comfort Air Conditioning, *Mech. Chem. Engrg. Trans. Inst. Engr. (Australia)*, vol. MC-1, p. 11, 1965.
3. Dunkle, R. V.: A Method of Solar Air Conditioning, *Mech. Chem. Engrg. Trans. Inst. Engrs. (Australia)*, vol. MC-1, p. 73, 1965.
4. Hay, H. R., and J. I. Yellott: A Naturally Air Conditioned Building, *Mech. Engrg.*, vol. 92, p. 19, 1970.
5. Hay, H. R.: Energy Technology and Solarchitecture, *Mech. Engrg.*, vol. 94, p. 18, 1973.
6. Löf, G. O. G., and R. A. Tybout: Design and Cost of Optimal Systems for Residential Heating and Cooling by Solar Energy, *Solar Energy*, vol. 16, p. 9, 1974.
7. Löf, G. O. G.: "Design and Construction of a Residential Solar Heating and Cooling System," Nat'l Tech. Information Serv., Springfield, Va., 1974.

THE ROLE OF THE VAPOR COMPRESSION CYCLE IN SOLAR ENERGY UTILIZATION*

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ABSTRACT

The vapor compression cycle lends itself to solar energy utilization in two important ways. Its ability to utilize a relatively low temperature heat supply to produce space heating via heat pumps allows the use of solar input to the evaporator to provide potential Coefficients of Performance which are 2 to 3 times higher than present electric driven heat pumps, and the use of relatively inexpensive solar collectors is possible since the collection temperatures can be low grade. Secondly, the compression process of the vapor cycle can be powered by a solar-driven heat engine, typically using a Rankine cycle, for solar cooling purposes. Discriminating coupling of solar with vapor compression allows the well-developed technology and manufacturing capability of the vapor compression industry to be brought into play in the solar field, widening its base and promoting its diversification.

This paper overviews the cycle thermodynamics, potential practical hardware, and R&D projects in both of these areas. Particular attention is given to the Solar Assisted Heat Pump and its characteristics and the heat pump simulator activities at Brookhaven National Laboratory.

I. INTRODUCTION

The thermodynamic cycle known as the vapor compression cycle is characterized by its ability to move heat from a low temperature reservoir to a higher temperature one. To accomplish this, work must be input, as required by the Second Law, and devices which are reversed heat engines generally known as heat pumps are used. Space conditioning in the form of either heating or cooling is produced depending on whether the low temperature reservoir or source (cooling) or the high temperature reservoir, or sink, (heating) is in the space to be conditioned. The work input is less than the useful heat quantity and a multiplying effect, denoted by a Coefficient of Performance, results.

Solar energy can be utilized to advantage in the heat pump/refrigeration cycle in two principal ways. First it can serve as a heat source which is high by heat pump standards, though low in solar terms, for the evaporating process in the heating mode. The resulting work inputs required are low, producing very efficient cycle COP's which are potentially 2 to 3 times higher than current values. This application is salient for electrically driven heat pumps, and although solar energy is directly used only in the heating function, cooling mode performance can be abetted by opportunistic use of the solar system components. The second method is to drive the compression process of the cycle with a heat engine powered by solar thermal energy. This is typically accomplished by a Rankine or modified Rankine power cycle and has its principal usage in the cooling task, but can also be used for heating.

Discriminating combination of solar energy with vapor cycles is one of the more promising avenues to the difficult goals of cost effective and energy conservative solar space conditioning. This coupling allows the well-developed technology, manufacturing, and distribution capabilities of the vapor compression industry to be brought into play in the solar field, thus widening its base and promoting solar diversification. This diversification effect is more pronounced when it is noted that the level of technology involved spreads in either direction from that of basic electric-driven air conditioner/heat pump. That is, toward the lower technology side, the use of the relatively low solar-supplied temperatures required 283-311°K (50-100°F) as heat pump input permit the use of low temperature, simple collectors which can be manufactured significantly more inexpensively, and diffusely than collectors which must heat a building directly. On the high technology side, the more sophisticated "aerospace" type of technology is introduced on a decentralized basis via Rankine systems and their turbomachinery, which while unquestionably costly at present, can potentially fuse with the demands of meeting a mass consumer market to provide viable systems over the long term.

*Work performed under the auspices of the United States Department of Energy.

2. THE VAPOR CYCLE AND SOLAR ENERGY

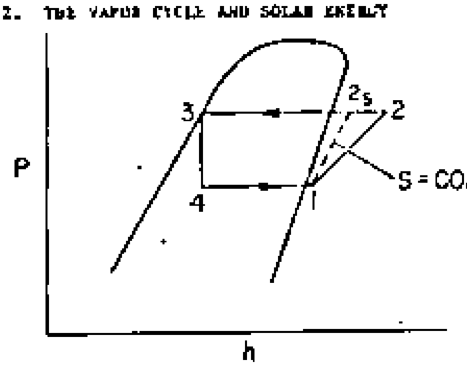


Fig. 1. Basic Vapor Compression Cycle

The basic vapor compression cycle is pictured on the pressure-enthalpy diagram of Fig. 1. In the heating mode, the useful energy derived per unit mass of the working fluid is $h_{2s} - h_4$ for an Ideal Vapor Cycle. The ideal work input by the compressor is $h_{2s} - h_1$, and the COP is:

$$COP = \frac{h_{2s} - h_4}{h_{2s} - h_1} \tag{1}$$

The actual work input is $h_2 - h_1$, a larger value, due to irreversibilities in the compression process (indicated by the compressor isentropic efficiency); and there are a number of other sources of efficiency loss in the actual vapor cycle which further lower the COP from ideal – including pressure drops, heat losses, prime mover efficiency and those due to practical measures necessary to produce a viable device. In either case, the amount of work input required for the compression process depends on the difference between the condensing temperature, T_3, and the evaporating temperature, T_1, since the compressor must produce a pressure ratio equal (approximately) to the ratio of the corresponding saturation pressures. For a given condensing temperature required for heating, an increase in evaporator temperature causes a decrease in compressor work required per pound of working fluid (refrigerant) and a corresponding increase in COP. The limiting maximum COP obtainable between temperatures, T_3 and T_1, is the Carnot cycle COP given by:

$$COP_{max., heating} = \frac{T_3}{T_3 - T_1} = \frac{1}{1 - \frac{T_1}{T_3}} \tag{2}$$

where the temperatures are in absolute units. The Carnot COP is plotted against evaporating temperature for a constant condensing temperature of 322°K (120°F) in Fig. 2. Also plotted is the COP for the Ideal Vapor Cycle, 1-2s-3-4 in Fig. 1, for refrigerants R-12 and R-22 (they are very close in the Ideal Cycle). The latter curve is below that of Carnot primarily because the expansion process is at constant enthalpy, rather than being the isentropic one of the Carnot Cycle. It is clear that both COP curves increase significantly with evaporating temperature, and, moreover, the slope increases with increasing temperature. Herein lies the motivation to introduce solar energy into a heat pump cycle as the heat source, since it can provide temperatures well in excess of those available from ambient air during a heating season and concomitant instantaneous and seasonal COP's which are greatly increased.

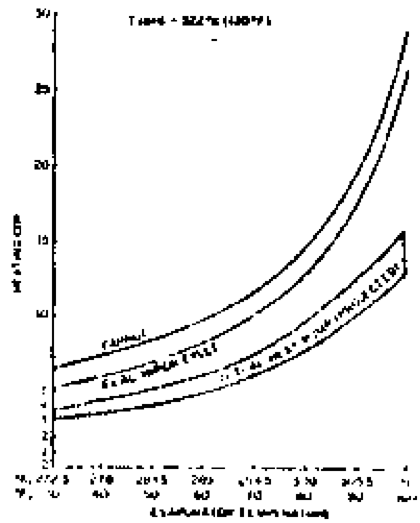


Fig. 2. Heat Pump COP vs Evaporator Temperature

Direct solar heat input makes use of a natural renewable resource as an extension of the traditional search by heat pump applications engineers for a suitable site-specific earth or water source sink; but herein the potential COP gains are much greater and the source is universal. As in any other solar system, the solar heat input is not "free" because a system to collect it must be paid for; but because the input temperature range of importance, 277 to 311°K (40 to 100°F) is low for solar, the use of collectors or collector-like devices which are significantly less costly per square foot than direct heating collectors is allowed.

Given the theoretical incentive, applying this approach requires utilizing a vapor cycle machine that will follow the monotonically increasing COP trends of the Carnot and Ideal Vapor Cycle at the lower level of practical hardware. Two aspects of attaining this potential must be treated—those producing good, energy efficient component performance for any refrigerator/heat pump and those which specifically provide extension of this performance to high evaporator temperatures of solar input, as will be discussed later. In Fig. 2 the potential performance which can be obtained by meeting these aspects satisfactorily is given by the shaded band. It was developed by examining operating data for current efficient heat pumps and compressors in the evaporator temperature range up to 283°K (50°F) and performing calculations to obtain component efficiencies which were extrapolated to project performance into the range above 283°K. Heat exchangers large enough to accommodate the heat loads at all temperatures were assumed, and a nominal electric motor efficiency of .85 was used.

The second principal application of solar energy to a vapor cycle is the use of a solar-driven heat engine to produce the compression work for a vapor compression cooling system, and it is one of the relatively few viable techniques which can produce cooling from solar input. This method would not be used to principally drive the heating mode since it is obviously more effective to utilize thermal input directly, and the heat engine suffers from nature's trait that makes it easier to convert work to heat than heat to work. Once present for the cooling task, however, the heat engine/VC system can also be applied to space heating, i.e., as a heat pump, in order to improve potential for cost effectiveness; and in the heating mode, the evaporator of the VC loop can use some of the collected solar energy to improve COP.

Using solar input to drive a heat engine requires collection at temperatures which are high by solar standards, since Carnot limitations demand as high a cycle temperature as possible for reasonable power loop efficiency. The Carnot limiting efficiency for a heat engine operating between a temperature, T_h, and a lower one, T_c, is:

$$\eta_{Carnot} = \frac{W_{out}}{Q_{in}} = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h} \qquad (3)$$

where T_c is the rejection temperature which must be above ambient in a practical device. Thus, high grade collectors which can produce temperatures far above ambient and still attain good efficiency are required; but the fact that higher collection temperatures produce lower collector efficiencies can cause a trade-off to be made with cycle efficiency. The most important factor in a system of this type, though, is to raise cycle efficiency in order to reduce collector area, since collectors are by far the most costly system element. This basically implies higher cycle temperatures.

Current and near-future collectors can reach 422°K (300°F), at most, with any reasonable efficiency, and at this temperature limit the Rankine cycle type of heat engine, which incorporates a liquid to vapor phase change, has received the major development attention rather than gas cycles which need higher temperatures to be effective. Development of concentrating collectors which give temperatures in the 533°K (500°F) range could permit a broader choice of solar heat engines.

A technique to increase Rankine cycle efficiency substantially is the use of a fossil-fuel fired superheat of a working fluid that has been vaporized by solar input at 250-300°F. This "topping cycle" can be used to meet the design cooling load but requires only a relatively small fuel input over the course of a season, compared to the solar input to the latent heat. If water is used as the working fluid, a superheat temperature of 1000°F can be used, doubling the Rankine efficiency and halving the required collector area.

3. SOLAR ASSISTED HEAT PUMPS

Even at this early stage of solar utilization, there has been considerable interest in combining solar energy with heat pumps. A number of ad hoc installations, broad surveys assessing potential, and computer simulations have occurred. Most installations to date have employed solar in parallel with the heat pump, i.e., the heat pump is an auxiliary, and the intrinsic properties of the vapor cycle are not therein exploited. The relative few which have used solar as direct series input to the heat pump have perforce used current heat pumps, which are not designed to accept and efficiently utilize the elevated evaporator temperatures of solar-supplied input. That is, they either may not run at input temperatures above 283°K (50°F) or can be forced to run only by energy inefficient techniques. Consequently they do not at all realize the large COP increases available. Likewise, the surveys and computer studies have considered heat pumps having current performance characteristics, i.e., max. COP's of 3 to 3.5, and not the potential of machines designed for the solar task, nor have they seriously considered the opportunity to utilize inexpensive collectors or storage advantages (such as ground-coupling) that exist for the series configuration. Reference 1 discusses these situations in detail.

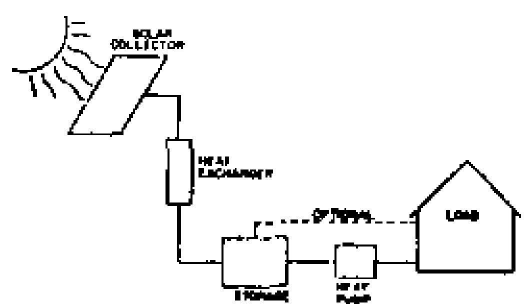


Fig. 3. Schematic of Solar Assisted Heat Pump System.

A basic Solar Assisted Heat Pump (SAHP) configuration is shown in Fig. 3. Solar collectors supply thermal storage, typically a large water tank, which is the heat source for the heat pump. A mode for bypassing the heat pump for direct solar heating can be included for those periods when the solar-supplied temperature is high enough. The collectors may be either liquid or air-cooled and can have a relatively high loss coefficient, since the collector-temperatures will not be greatly above ambient. Air-cooled collectors probably have the greatest potential for low cost, and e.g., could be used with an air/water heat exchanger near them, and indoors, to allow hydronic piping to storage.

Such a SAHP could provide heating and cooling for single family residential, multi-family, and commercial buildings up to loads of approximately 25 tons. It thus can serve the same applications as current air-to-air heat pumps, but with substantially higher COP's, and expanded geographic range. Moreover, since the source temperature can always be kept sufficiently above freezing (and would probably be liquid in most systems), there is no need for a defrost cycle, a necessary feature in current air-source heat pumps which has traditionally been a source of energy inefficiency and reliability problems due to cycling and extra load on the compressor. The liquid source would provide good heat exchange (small ΔT's) in the evaporator, and the water loop could be reversed in the cooling season to allow heat rejection to the storage tank, which can be cooled at night to provide a lower temperature sink than ambient. In certain areas the collectors can assist in this process. Thus, although solar does not assist in the cooling mode, the solar system components can. The indoor heat exchanger could also be of the liquid type for low ΔT, hydronic piping to coils, and the option to re-route water flow instead of refrigerant flow.

The strong potential of the SAHP can be realized only if suitable heat pump hardware is developed. Certain significant changes must be made, not simply small adjustments, but these are well within the technology and capability of current manufacturers - given the market incentive to apply them. These changes may imperatively produce a higher first cost of the machine, but the energy and life-cycle cost savings they can provide can justify this to buyers.

The key to the development problem is making the heat pump operate efficiently and reliably over the input temperature range, 277 to 311°K (40 to 100°F) wherein the attendant suction vapor densities and system mass flows are very high compared to present operating conditions. The positive displacement reciprocating compressors used in the size heat pumps of interest here have a constant displacement volume (bore x stroke x no. of cylinders) and, therefore, at a given (constant) speed, force a mass flow rate approximately proportional to the suction density through the system. The vapor density increases rapidly with suction temperature because of the attendant saturation pressure increase. The effects of this situation on a heat pump (not specifically designed to accommodate them) are many and complicated and can not be dealt with in any detail here. In brief, unduly high pressures and temperatures can develop at the compressor outlet, the condenser can become overloaded and choked up, the expansion valve may not pass the flow and thus starve the evaporator--giving excessive superheat, the balance between liquid and vapor phase may be incorrect, and the refrigerant may just "run around and hide" in various places since there is such a relatively large amount trying to circulate. Of special importance is potential damage to the compressor, particularly the valves, by the high pressure and temperature. And, of course, performance is not efficient.

Changes to accommodate the solar input must be energy efficient, e.g., not of the hot gas by-pass type, in order to realize COP and capacity advantages. An important first step is the use of suitably large and effective heat exchangers to allow the high heat loads to be handled at reasonable temperature splits. This step is vital to effective use of the solar input. Additionally, sufficiently large expansion valves should be used. Externally equalized thermostatic expansion valves appear to offer the best pressure-drop-mass flow characteristics, and the bulb charge selection offers flexibility, including the possibility of newly developed charges if necessary. Multiple valves or an auxiliary by-pass might be employed. Most importantly, however, is the compressor and its ability to modulate the system. Some form of capacity control appears tantamount to success. A salient first choice is variable speed, not a new technique at all. But primarily it has been used to allow operation over a wide range of suction temperatures toward the low side. In a SAHP it can be used to extend the range of efficient suction temperatures toward the high side, with the low speed used for the cooling mode and the low end of the heating mode. A continuously variable speed would be desirable from a theoretical point of view, but in practice a 2/4 pole or 4/8 pole motor producing a discrete step in capacity would probably be satisfactory, with the lower speeds preferred. Alternatively compressor capacity modulation could be provided by cylinder unloading or the use of dual compressors. These methods, too, have previously been employed in AC machinery, and like the two-speed motor produce a step in capacity. The suction temperature at which the step occurs must be optimized as a function of climate, collector size, etc.

In order for SAHP performance to lie within the projected band of Fig. 2, the isentropic efficiency must remain high as suction temperature increases, which is contrary to the usual trend. The use of slow compressor speeds, high bore/stroke ratio cylinders, and efficient valve designs can serve to accomplish this. These three factors also promote high volumetric efficiencies, which tend to increase with suction temperature anyway, but can peak at high vapor densities. Thus, the variable speed method of capacity modulation also has these other important advantages.

It is important to note that as COP increases to high values and compressor work diminishes that the parasitic power requirements have a greater effect on COP and an effort to keep them down is important.

Relative to the incentive of the potential high COP's available at high temperatures as dictated by theory, which has existed for many years, is the question of how far up the COP curve it is truly practical to attempt to climb. This depends, inter alia, on the amount of time solar supplied storage is actually at the highest levels for a given collector type and area, storage volume, and climate. Indeed, the system must be optimized as a whole. There are many trade-offs of cost vs. performance to be addressed when incrementally climbing the COP curve, which include assuring that performance in the medium high range, say 283 to 311°K (50 to 100°F) is not sacrificed by extending the range to the limit.

To implement the development of effective Solar Assisted Heat Pumps, the Solar R&D Branch for Heating and Cooling of the Department of Energy's Solar Division is supporting three two-year development programs which will result in prototype hardware. The contracts, awarded to successful respondents to an RFP, are with Lennox, Northrup, and General Electric (Schenectady, NY) and consist of three phases: (1) conceptual design and commercialization plan (2) detailed design and performance analysis and (3) fabrication and laboratory testing. Lennox is addressing 3-ton residential and 7½ to 10 ton multi-family/light commercial applications using a two-speed compressor with several different system configurations. General Electric is studying a range of sizes, applications, and types of systems and is developing a continuously variable speed compressor drive. Northrup, Inc., which unlike the others does not manufacture its own compressors, is working with several compressor manufacturers on a variety of systems. Dunham-Bush will supply them with R&D versions of a 75-ton rotary screw compressor, adapted to efficiently utilize solar input, and an innovative 3-ton reciprocating compressor which is the analog of a multiple (4)-slide rotary compressor in its ability to accept multiple level inputs and outputs and match compression ratio to operating conditions. This machine is two-speed, utilizes a "stepped" expansion, effective use of sub-cooling, and has projected performance which closely tracks the COP curves in Fig. 2. Northrup will also develop a 7½-10 ton machine using modified compressors from other suppliers. The objective of all three contracts is to produce a marketable heat pump which takes advantage of the high COP's available from solar energy in the 283°K (50°F) and up range, and which will represent the first generation of specifically solar-assisted heat pumps. In conjunction with the hardware programs, Singer is carrying out a comprehensive study for DOE to identify the most cost effective and marketable SAHP systems as a function of geographic area and economic climate.

Brookhaven National Laboratory provides support to DOE as technical monitor of these solar heat pump projects and additionally is carrying out an in-house program to develop SAHP technology. This work includes the construction and operation of a SAHP simulator and laboratory model heat pump to conduct laboratory tests of SAHP performance, including evaluation of the hardware developed by the contractors. A current series of tests is investigating attainable COP's as a function of evaporator and condenser temperature, compressor capacity control technique—particularly variable speed, refrigerant, heat exchanger size, and expansion valve configuration for both steady state and transient operation. In addition to parametric type of testing, the simulator will be able to carry out computer controlled simulations of complete solar system operation for appropriate weather and load scenarios.

4. RANKINE/VAPOR COMPRESSION SYSTEMS

These systems are characterized by the high cost, principally the collectors, of the Rankine power portion but offer promise in cooling COP performance if high cycle temperatures and effective condenser heat rejection can be utilized. Because of the trends in cost/ton and sophistication of hardware, they appear to be only suited for sizes 15 to 20 tons and up in the near term and not for single family residential use. Incorporating a heating mode can improve cost effectiveness. Ref. [2] gives a review of solar Rankine technology and Ref. [3] treats costs.

The VC portion of the system is thermodynamically conventional, but in one generic version utilizes a centrifugal compressor, driven on a common shaft by a high speed turbine, and a low density, high performance refrigerant, such as R-11 or R-113. UTRC is developing an 18 ton turbocompressor heat pump of this type using R-11 in both loops and a power loop max. temperature of 417°K (290°F). Carrier is developing a 25-ton chiller with the same max. temperature and integrated electric motor. GE, AiResearch, and Honeywell have been developing turbocompressor units of various sizes at 367°K (200°F) input under the "404" Program.

Another type of Solar Rankine system uses the fossil-fired superheat of steam vaporized by solar to give power cycle temperatures to 811°K (1000°F). These systems require small, efficient steam turbines which have good off-design performance so that solar-supplied superheat can also be used in the future. Energy Technology, Inc. and Univ. of Pennsylvania are developing 20-ton systems of this type.

All of these projects are DOE supported and BNL is technical monitor for all but the "404" Program.

5. SUMMARY

The Solar Assisted Heat Pump offers significant performance and economic potential and should receive serious development attention to investigate whether it can be realized. This work has begun under a structured plan of DOE supported R&D. Solar Rankine/VC systems can have viable application in the future in specific tasks if development is tailored properly.

6. REFERENCES

[1] J. Andrews, B. Kush and P. Metz, "A Solar Assisted Heat Pump System for Cost-Effective Space Heating and Cooling," Brookhaven National Lab. #BNL50819

[2] H. Curran, "Overview of Solar Rankine Cooling", Proc. of the 3rd Workshop on Solar Energy for the Cooling of Buildings, San, Francisco, Feb. 1978.

[3] R. E. Barber, "Current Costs of Solar Powered Organic Rankine Cycle Engines", Solar Energy, Vol.20

PIPELINE FROM OCEAN TO DESERT TO PROVIDE COOLING FOR SOLAR POWER PLANT COMPLEX*

by

Dr. Robert H. Turner
Jet Propulsion Laboratory

ABSTRACT

A prime factor in large-scale development of solar power plants is lack of water for condenser cooling, since if the facility is located in arid and low population density areas to take advantage of high insolation values and low land costs, then water will likely be unavailable. One possible way to provide water for condenser cooling to Southern California desert power plant sites is to construct a pipeline or aqueduct from the ocean to the desert and pump sea water to the site. Since such a project would necessarily be large-scale, the site would probably be a complex of power plants, and need not be restricted to solar units. JPL has conducted a preliminary study to assess the technical and economic feasibility of such a scheme. Three possible condenser cooling modes are considered, including seawater makeup to 1) wet cooling tower, 2) evaporation cooling ponds, and 3) inverse salt gradient solar ponds where low grade heat would also be collected. Pump power requirements appear to be relatively small. Several techniques are considered for the disposal of concentrated brine, including the introduction of ancillary and complementary industries including salt and distilled water production and chemical production.

A fallout from such a project would be the introduction of evaporated water into the desert biosphere. Preliminary results are described and potential advantages and disadvantages are listed.

1. NEED FOR COOLING WATER

The very features which make a desert an obvious candidate site for solar thermal power plants, namely low land costs and lack of atmospheric moisture, simultaneously militate against availability of water for condenser cooling, since high average annual solar input generally coincides with arid areas. In the Southwestern United States most water rights have already been planned and committed to uses other than large-scale power production. An Edison Electric Institute study (1) predicted that by the year 2000 solar sources will supply an electric generating capacity of about 1% (50,000 Megawatts-electric) of total national consumption, but cited a major barrier would be lack of cooling water availability in arid areas. For this reason it has been suggested that large desert sited solar power plants may have to be air cooled, which would result in tremendous thermodynamic and economic penalties. Even today, cooling water availability is restricting power plant location options. The Southern California Edison Electric Utility transports coal in a pipeline slurry 270 miles from a mine mouth to a conventional power plant sited on the Colorado River, where, water for condenser cooling is available.

2. OCEAN WATER PUMPED TO DESERT COULD PROVIDE COOLING

Since present water supplies in the U.S. Southwest would be inadequate to provide cooling for a large desert sited power plant complex, and dry tower cooling would be a desperate last resort, it is proposed here that ocean water be transported to a desert sited power complex. The seawater would be used as makeup in a condenser cooling loop which would feature wet salt water evaporation. See Figure 1. The heat rejected from the condenser would evaporate salt water either in a wet tower or a large area pond. For a tower, spray drift eliminators would assure that only fresh water, and not salt, would enter the atmosphere. There are a few places in the world where this would be feasible, and the most likely location where this concept would be productive is probably the Southern California deserts. These areas are located within 100 miles of the ocean, claim annual average insolation values among the highest in the world, feature relatively inexpensive land (although right-of-way across might be expensive), and are located close to major metropolitan load areas. Furthermore, California has expertise with large aqueducts.

The quantity of cooling water required for makeup in a wet cooling tower serving as part of the heat rejection apparatus of a power plant is estimated at 60 cubic feet per second (60 cfs) per gigawatt (GW) of which half is evaporated in the wet cooling tower. A preliminary assessment indicates for a 10 GW complex (60 cfs of water makeup) a pipeline would likely be adequate for the ocean-to-desert transport, and for larger flow rates an aqueduct or canal may be necessary.

The blowdown from the power plant wet cooling towers, with a salinity estimated at twice that of ocean water (2 x 35,000 ppm = 70,000 ppm) could be handled in a number of ways. The obvious first

*This paper presents preliminary results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautical and Space Administration.

option is to return the water to the ocean in concentrated form. Other options include: (1) solar salt processing, (2) production of chlorine and sodium hydroxide and perhaps other chemicals, (3) distillation to produce potable water, (4) H_2 production by electrolysis or photosynthesis, and (5) construction of inverse salt gradient solar ponds which would produce low grade process heat. These options are indicated in Figure 2 and are described more fully below.

In order for the aqueduct concept to be viable, the prorated cost of the water transport system must be less than the overall cost of using air to remove waste heat. Our preliminary study indicates a minimum of 12 to 15 GW-e of electrical capacity is the breakeven point, although the actual breakeven point between rejecting heat to the air (dry towers) and using wet cooling towers with ocean supplied make up depends somewhat on the type of plant considered, and the concept is not restricted to solar power plants. For example, a nuclear power complex removed from metropolitan areas might be subject to less social resistance. And the concept of an energy park would accrue other benefits. An energy park could offer more security from terrorists and saboteurs. Additionally, peripheral industries such as water production, sewage treatment, equipment supplies, labor pools, and other O&M services, could be more effective when serving an energy park as opposed to a dispersed power plant system.

Thermodynamically, a dry tower design must be based on a local dry bulb design temperature. The wet tower design is based on a local wet bulb design temperature. In all parts of the United States, the economic advantages favor the wet tower, and in the desert the differential is even greater since the dry bulb temperature is normally higher and wet bulb temperature is lower than in most areas of the U.S. This difference is reflected in fuel and operating cost penalties against the dry tower approach. The other cost differential is in the greater capital costs of the dry tower compared to the wet tower. There is a penalty of approximately 5% for using ocean water in a wet cooling tower. Some of this is attributable to making the piping corrosion resistant, and the rest is due to the higher vapor pressure of salt water. Thus, large dry cooling towers have not yet been built in the United States for power production, although some are in service in Europe (2). A power plant in Texas is using a wet cooling tower with sea water makeup.

In a comparative cost study, the cost of the water transport system must be charged against the wet tower heat rejection system costs, and as noted above, the prorated costs seem to break even around 12 to 15 GW-e. The costs of the aqueduct system can be divided into three categories: (1) right-of-way costs, (2) pipeline or canal costs, and (3) pumping costs. The first is independent of energy park capacity, and the last two are functions of total capacity. Additionally, any reservoirs or holding basin costs would have to be assessed on overall operating parameters such as peaks in generation or pumping loads. Head recovery at the inland terminus is feasible and might recover 30-35% of the energy needed to pump the water over the Southern California mountains (note that San Gorgonio Pass has an elevation of 2600 feet).

The byproduct effluent blowdown, and also the ocean water being transported to the site, will have to be handled in such manner to guarantee no salination or contamination to land areas or to underlying aquifers. The blowdown from the wet towers will have a salinity approximately twice that of ocean water (70,000 ppm as compared to 35,000 ppm). At this concentration no precipitation of dissolved salts or minerals has started and the water can be piped directly back to the ocean for disposal. This is one option. As energy park capacity is increased and peripheral process industries are made operational (assuming that more in-depth study indicates that such peripheral industries are cost effective), then the quality and quantity of water returned to the ocean will vary. It seems unlikely that all blowdown would or could be used in suitable industries so some seaward return is anticipated. The [illegible] ing processes can use the blowdown from the wet towers of the energy park.

2.1 Salt Processing Facility

This NaCl plant would be similar to the salt producing operation of the Leslie facility in the San Francisco Bay Area except for several points: (1) initial concentration would be twice that of the Bay Area intake, (2) evaporation rates would be higher, (3) land costs would be lower, (4) impervious evaporation basins would be required, and (5) gypsum precipitates would have to be disposed of. In either case disposal of bitterns (the liquid end-product of commercial salt producing operations) is a problem. Disposition at the desert complex might mean a secondary industry to use the gypsum and/or bitterns as feedstock. A 1 GW-e power plant will consume enough water for cooling to produce over 1,000,000 tons of NaCl annually from the blowdown. The water evaporated during this process is added to the biosphere. Furthermore, the presence of large evaporation ponds might obviate the need for a cooling tower. If water directly from the aqueduct were passed directly through the condenser, heated, and the warm water discharged directly to the evaporation ponds, then evaporation and heat loss processes would cool the water despite the solar heat gain. After the ponded water cooled, and became somewhat more concentrated due to evaporation, it could be passed again through the condenser. Thus the large area for the salt production evaporation pond would also serve as the power plant heat rejection area, trading [illegible] and area intensive cooling device (the evaporation ponds) against a relatively money intensive device (wet cooling tower unit). See Figure 3. This concept is still being investigated.

3.2 Chlor-Alkali Process Facility
This auxiliary facility would process saline water for Cl_2 and NaOH. Both Cl and NaOH sell for 20¢/pound and the total U.S. production of each is billions of pounds per year. Both products are simultaneously produced commercially by the electrolysis of concentrated brine. A quick calculation indicates that 25% of electricity produced by the seawater cooled power complex would be required to electrolyze all the NaCl. The practical disadvantage is that both Cl and NaOH are feedstocks to other chemical processes, and transportation costs would be high.

3.3 H_2 Production
The production of gaseous hydrogen from the water by electrolysis and/or photolysis is a possibility which our preliminary study has not yet assessed.

3.4 Potable Water Production
The possibility of producing a supply of water in a desert strongly suggests distillation. This is a viable option and could be realized either from a multi-stage flash distillation unit or from a single effect still using passive elements. A multi-stage still would require a source of low grade heat, such as might be obtained from an inverse salt gradient solar pond discussed below. The distillation would be in series with and prior to other processes, such as the above discussed NaCl or Chlor-Alkali units.

3.5 Inverse Density Gradient Salt Solar Ponds
Solar ponds with increasing density with depth, due to a salt gradient which increases with depth, have been discussed in the technical literature as a possible way to collect low grade heat (150°F to 180°F range). Such a pond (perhaps 5 feet deep) might feature the relatively high temperatures (180°F) near the bottom and temperatures in the range of 80°F at the surface. Although many investigators have proposed different uses for the heat, the concept of simultaneously using the cool surface of such a solar pond for heat rejection (consider here a power plant) has not been emphasized. This is a variant to the evaporation pond discussed above which features simultaneous salt production with condenser cooling. Here the top part of the pond is used for condenser cooling and the heat collected at the pond bottom is used either for feedwater preheating in the power cycle, or for some other process, such as water distillation. Water makeup from the aqueduct replaces surface evaporation and also washes the pond surface, preserving the inverse salt gradient as necessary to maintaining the vertical temperature distribution.

3. MISCELLANEOUS CONSIDERATIONS

Calculations indicate that the total pump power necessary to transport seawater 200 miles and up a 4000 foot head without any head recovery, is on the order of 1% of the total power production which the cooling effect of the water will make possible. Therefore, pump power to bring seawater to the desert does not appear excessive.

Since most of the saline intake water coming into the desert is destined to be evaporated in the above scenarios in an environmental sense, the aqueduct can be considered as a one way fresh water river which will enter the atmosphere. The environmental impact should be positive if salt drift and infiltration can be avoided, since the addition of pure moisture to the Colorado River Basin and Mojave Desert region should likely be considered a positive environmental fallout from the project. Preliminary calculations indicate that the amount of moisture added to the atmosphere would not be sufficient to alter the climate of the region.

Since salt water would be contacting metal condensers, provision must be made to protect against corrosion. Galvanized iron or steel can protect against seawater corrosion for temperatures up to 70°C (158°F). Galvanization means zinc coated, and above 70°C the zinc no longer protects the steel. The zinc is electrolytically deposited and can coat the inside of a heat exchanger. For long life a brass or brass-aluminum heat exchanger may be preferable instead of galvanized steel. The best way to protect bare steel against salt water corrosion is with a sacrificial anode made from magnesium (cathodic protection). A slight electric current between the anode and protected element increases the protection. Mg protection strips would require periodic replacement but should provide long life. The Mg anode should not be too expensive, but the manpower to replace the strips could be significant. Dissolved gases, especially CO_2 and O_2, in the salt water give rise to corrosion problems. As the concentration of seawater increases, corrosion against the bare steel pipe and equipment decreases because the increased electrical conductivity of the water enables the Mg protection strip anodes to protect a larger area. But the technology of heat exchangers exposed to marine environments is mature, and potential problems will yield to known solutions.

4. POTENTIAL BENEFITS

Some potential benefits from the proposed ocean-to-desert pipeline are listed below.

(1) Evaporative cooling made possible for desert sited power plants

(2) Evaporated fresh water enters the arid atmosphere

(3) Possible auxiliary by-products may include:

(a) NaCl salt production

(b) Recovery of distilled water

(c) Recovery of chemicals other than NaCl

(d) Collection of low grade heat from saline solar ponds

5. POTENTIAL PROBLEMS AND NEGATIVE IMPACTS

(1) Salt water in open aqueducts may affect desert ecology; may need covered aqueducts.

(2) Corrosion prevention and ongoing maintenance costs may be high

(3) Disposal of concentrated water or bitterns may be a problem

(4) Such a project has never been done before; political acceptance may be an obstacle.

6. REFERENCES

(1) Edison Electric Study as reported in "Solar Energy Intelligence Report, Page 82, April 25, 1977.

(2) Miliaras, E.S., "Power Plants with Air-Cooled Condensing Systems," MIT Press, Cambridge, Massachusetts, 1974.

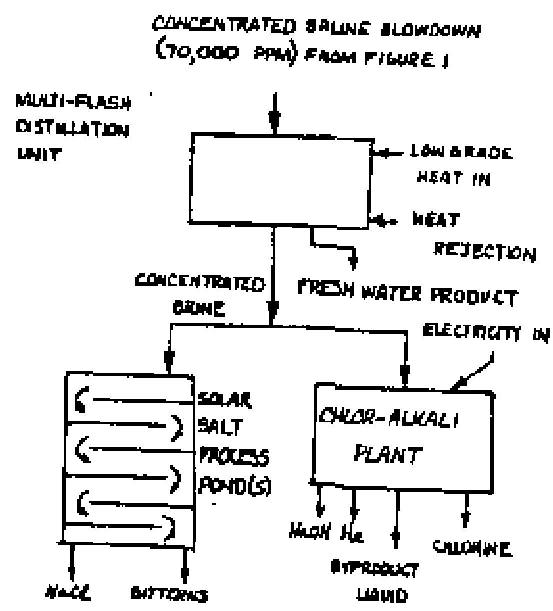


FIGURE 2. Optional Peripheral Industries which might prove cost effective in using concentrated seawater blowdown from the cooling tower in Figure 1.

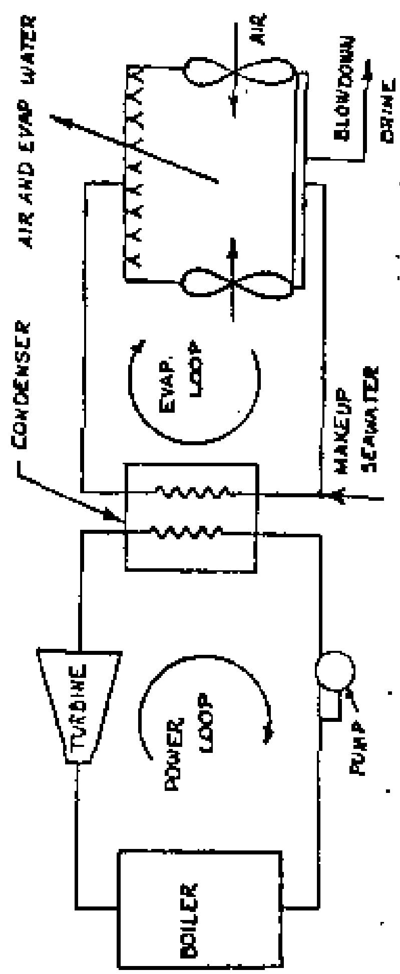
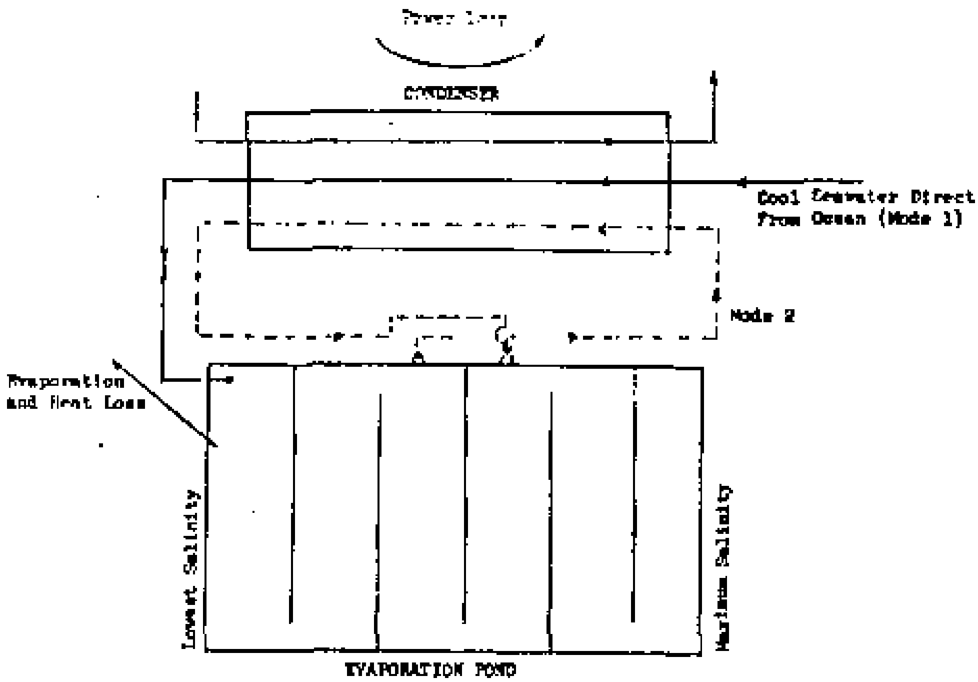


FIGURE 1

UNIQUE TECHNIQUE FOR USING SEAWATER IN DESERT ...



NOTES: (1) Mode 2 cooling flow features cooled concentrated water passing through the condenser. Warm water is returned to the pond.

(2) Heat from the power plant augments solar gain to accelerate evaporation and therefore salt production.

(3) Evaporation pond approach trades off land intensiveness for a relatively capital intensive wet cooling tower.

FIGURE 3 Salt Processing Evaporation Pond Replaces Wet Cooling Tower

DESIGN AND TEST RESULTS OF A 63.4 KW (85 HP)
SOLAR POWERED RANKINE CYCLE

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ABSTRACT

Barber-Nichols Engineering has built a solar powered Rankine cycle to supply shaft power to drive a conventional 351 kw (100 ton) water chiller for Honeywell, Inc. The Rankine cycle (R/C) heat source is solar heated Caloria HT-43 heat transfer oil and the R/C working fluid is Refrigerant 113 while the heat sink is cooling tower water. The specified design point was 63.4 kw (85 hp) shaft output power with 148.9°C (300°F) oil and 29.4°C (85°F) cooling water at 15.8% cycle efficiency. Performance was measured at Barber-Nichols to be 63.8 kw (85.5 hp) shaft power at the design oil and water conditions and the achieved cycle efficiency was 15.9% which was better than specified. Off design performance was measured over the range of 4.5 kw (6 hp) to 78.3 kw (105 hp) and cycle efficiencies up to 17.0% were achieved.

The expander used in this system was a radial inflow turbine of Barber-Nichols design and manufacture. It's measured design point, total to static efficiency was 81%.

1. INTRODUCTION

An advanced solar energy system that will provide more than 60% of the energy for heating, cooling, and 100% of the hot water requirements is being built by Honeywell, Inc. for its new eight-story office building in Minneapolis, MN. The system includes 1881.3 m^2 (20,250 sq. ft.) of advanced solar concentrating collectors. The air conditioning for this system is provided by two 351 kw (100 ton) York centrifugal water chillers. These chillers can be operated using the conventional electric motors or by solar powered organic R/C engines. This paper describes the two identical organic R/C engines built by Barber-Nichols to Honeywell's specifications. The R/C performance was tested at the Barber-Nichols facility and the test results are compared to the predicted performance.

2. RANKINE CYCLE DESCRIPTION

There are numerous variations of the basic R/C, but the one used in this system is shown schematically in Figure 1 and in the photograph of Figure 2, and is described below. In this system liquid

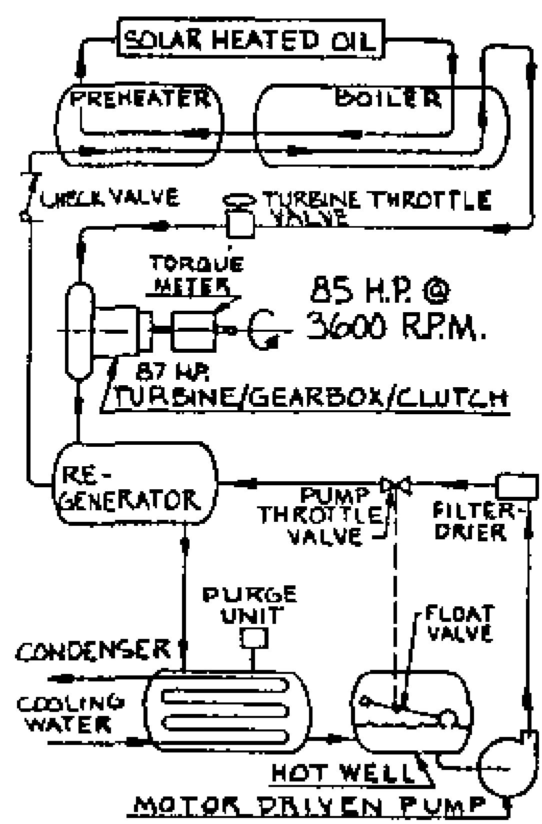


Fig. 1 Solar heated Rankine cycle schematic.

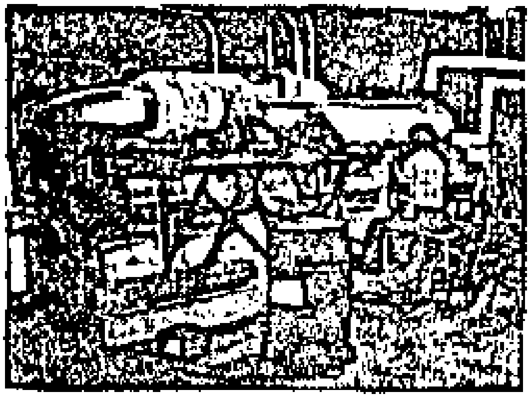


Fig. 2 Photo of the assembled Rankine cycle while connected to the test facility.

Refrigerant 113 (R-113) flows by gravity from the water cooled condenser to a liquid sump called the hot well. The hot well contains a float valve which is used to maintain suction head to the electric motor operated feed pump wherein the pressure of the R-113 is raised to approximately the boiler pressure. The high pressure R-113 flows through a filter drier and then through a pump throttle valve. The pump throttle valve is controlled by the float valve located in the hot well. Upon leaving the pump throttle valve, the liquid R-113 enters the regenerator where it picks up sensible heat from the turbine exhaust gas flow. The warmed liquid then flows through a check valve into the preheater where sensible heat is transferred from Caloria HT-43 heat transfer oil to the R-113. The heated R-113 liquid then flows to the boiler where it is evaporated to produce vapor. The heat source is again the Caloria oil. The R-113 vapor flows through the turbine throttle valve and then to the radial inflow turbine. For reasons of efficiency the turbine operates at 22,400 rpm and the speed is reduced to a nominal 3540 rpm in a two stage gearbox. The R-113 vapor leaving the turbine is highly superheated and some of this superheat is removed by transferring heat to the cooler R-113 in the regenerator. The cooled vapor flows from the regenerator to the condenser where it is condensed thereby completing the cycle.

In addition to the components previously discussed, the system also includes a one-way mechanical clutch to allow the turbine to provide shaft power for the water chiller compressor while preventing the compressor motor from backdriving the gearbox and turbine. The R/C also incorporates a commercially available automatic purge unit to remove water and non-condensible gases that may enter the system. Figure 2 is a photograph of the assembled R/C while connected to the test facility at Barber-Nichols. Shown in the figure is a water brake type dynamometer for measuring R/C system output power. The turbine-gearbox unit is a special unit and was designed and fabricated at Barber-Nichols Engineering.

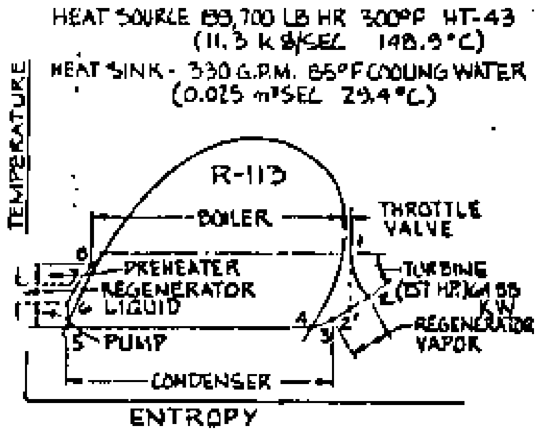
3. SYSTEM DESIGN POINT

The design point R-113 conditions throughout the R/C power loop are shown in Figure 3 which is a state point diagram. The values shown in the figure are for the predicted design point. Measured values are discussed later. The condensed liquid leaves the hot well at 35°C (95°F) and flows to the feed pump where the pressure is increased to 985 K Pa (143 psia). The slight temperature rise of 1.11°C (2°F) across the pump is caused by pump inefficiencies and motor cooling. This system utilizes an electric motor driven feed pump to provide for operating stability and flexibility. The liquid leaves the regenerator at 63.3°C (146°F) and enters the boiler at 120.4°C (245°F). It will be noticed by referring to Figure 3 that the liquid is not raised completely to saturation in the preheater and some preheating is completed in the pool type boiler. Design point turbine exit temperature and pressure are 81.1°C (178°F) and 71 K P. (10.3 psia) respectively. The R-113 flow rate is 2.23 Kg/sec (17,700 lb/hr). It can be seen from the figure that the design cycle efficiency is 15.6% neglecting feed pump work.

4. TEST RESULTS

The R/C system was tested using steam as the heat source, cooling tower water as the heat sink, and the output power was measured using a water brake dynamometer. The system includes a torque transducer and suitable electronics for measuring the torque and speed and calculating output power. Heat balances were made for the condenser, the regenerator, and the overall R/C to verify the validity of the data. Steam was utilized as the heat source rather than the heat transfer oil because of economics and facility limitations. The actual system performance using heat transfer oil will be measured in the field.

The measured design point performance is compared to the predicted performance and the results summarized in Figure 4. The test data summarized in Figure 4 is the average of 15 separate data points all taken at design conditions. As is shown in the figure, the measured design point cycle pressures and temperatures compare very favorably to the predicted conditions. However, the pressure drop across the turbine throttle valve and the regenerator vapor side are greater than anticipated. Subsequent testing with the second



Q_{PH} =	(515,000 BTU/HR)	151 KW
Q_{BOILER} =	(876,000 BTU/HR)	257 KW
$Q_{REG.}$ =	(202,000 BTU/HR)	59.2 KW
$Q_{COND.}$ =	(1,174,000 BTU/HR)	345 KW
$\dot{W}$ =	(17,700 LB/HR)	2.23 KG/SEC
η_{CYC} =	15.6 %	
ELECTRICAL INPUT =	5.0 KW	

POINT	TEMP. (°F) °C	PRESS. (PSIA) kPa	ENTHALPY (BTU/LB) J/g	DENSITY (LB/FT^3) KG/M^3	ENTROPY (BTU/LB °F) J/G-°K
0	(275) 135	(134) 924	(119) 278	(3.96) 6.34	
1	(275) 135	(133) 917	(119) 278		(0.19) 0.79
2'		(10.3) 71	(102.4) 238		(0.19) 0.79
2	(178) 81.1	(10.3) 71	(106.6) 248		
3	(112) 44.4	(9.5) 65.5	(95.2) 222		
4	(95) 35	(9.5) 65.5	(92.3) 215	(0.30) 0.481	(0.17) 0.71
5	(95) 35	(9.5) 65.5	(28.7) 66.8	(95.99) 153.78	(0.05) 0.21
6	(97) 36.1	(143) 986	(29.1) 67.7		
7	(146) 63.3	(132) 910	(40.5) 94.3		
8	(265) 129.4	(136) 938	(69.6) 162		

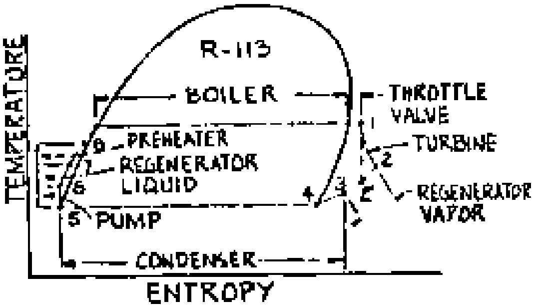
η_T = 0.75
η_P = 0.50
GEARBOX POWER = 85 HP (63.39 KW)

Fig. 3 Rankine cycle state point diagram

unit has shown closer to predicted values. The reasons for these discrepancies are not apparent at this time. The system mass flow rate is approximately 90% of design primarily because of smaller than design nozzle throat areas. The reduced mass flow resulted in less than design heat addition but because of greater than predicted turbine efficiency, the system produced the required 63.4 kw (85 hp) and achieved 15.0% cycle efficiency which is approximately 2% better than the 15.6% predicted.

It should be pointed out that the detailed turbine performance calculations predicted a turbine efficiency of 80% but the cycle calculations were made assuming a 75% turbine efficiency for conservatism. The higher than design turbine efficiency would have resulted in significantly greater cycle efficiencies if the regenerator vapor side pressure drop had been achieved. Referring to the pressure at state 3 in the diagram the measured condensing pressure was approximately 4.14 K Pa (0.6 psia) less than design. If the regenerator pressure drop had been the 3.45 K Pa (0.5 psia) assumed in the design point calculations instead of the measured 11 K Pa (1.6 psia) the R/C would have produced approximately 89 hp which would result in a 16.8% cycle efficiency which is felt to be significant. The reason for the large regenerator pressure drop is not clear at this time.

System off-design performance is summarized in Figures 5 and 6. Figure 5 shows the effect of R/C boiler temperature on cycle power for 3 different cooling water temperatures. As expected the figure shows R/C output power increases with increasing boiler temperature and decreasing cooling water temperature. The data summarized by the figure was taken at the design speed of 3560 rpm. The lubrication system of the water chiller limited the allowable operating speed range of this system as is discussed later. Figure 5 shows that at the design operating conditions of 135°C (275°F) boiler temperature and 1.0208 m^3/s (330 gpm) of 29.4°C (85°F) cooling water the R/C system produced 373 watt (1/2 hp) greater than the design 63.39 kw (85 hp). Increasing the boiler temperature to 140°C (284°F), the R/C output power was approxi-



	PREDICTED	MEASURED
Q ADD	(1,390,000 BTU/HR.) 408 KW	(1,363,000 BTU/HR.) 399 KW
Q REG.	(202,000 BTU/HR.) 59.2 KW	(139,000 BTU/HR.) 41 KW
Q COND.	(1,176000 BTU/HR.) 345 KW	(1,121,000 BTU/HR.) 327 KW
ṁ R113	(17,680 LB/HR.) 2.23 Kg/SEC.	(16,907 LB/HR.) 2.13 Kg/SEC.
η CYC.	15.6%	15.9%
η TURB.	0.75	0.80
GEARBOX POWER	(85.0 H.P.) 63.4 KW	(85.5 H.P.) 63.7 KW

POINT	PREDICTED TEMP. (°F) °C	PREDICTED PRESS. (PSIA) kPa	MEASURED TEMP. (°F) °C	MEASURED PRESS. (PSIA) kPa
0	(275.6) 135.3	(134.3) 925	(275.3) 135.2	(133.5) 921
1	(275.3) 135.2	(133.3) 918	(272.6) 133.7	(131.9) 909
2'		(10.3) 71		
2	(178.5) 81.4	(10.3) 71	(165.3) 74.1	(10.5) 72
3	(111.9) 44.4	(9.5) 66	(118.7) 48.2	(8.9) 61
4	(95) 35	(9.5) 66	(90.9) 32.7	(8.9) 61
5	(95) 35	(9.5) 66	(90.9) 32.7	(8.9) 61
6	(96.9) 36.1	(143.4) 989	(96.5) 35.8	(181.6) 1252
7	146.3 63.5	132.4 913	133.4 56.3	
8	265.0 129.4	136.4 940	NOT SIMULATED IN TEST	

Fig. 4 Comparison of measured and predicted design point performance.

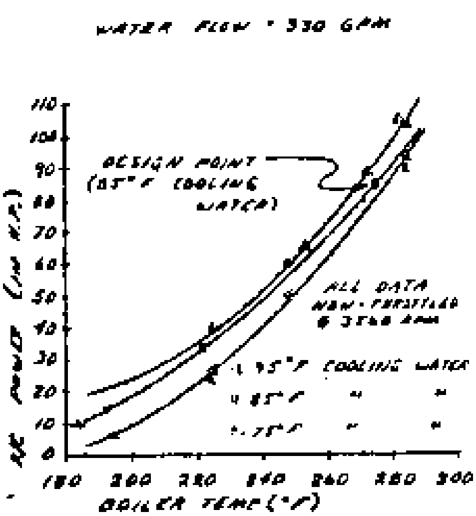


Fig. 5 Effect of boiler temperature and cooling water temperature on Rankine cycle power.

mately 78.30 kw (105 hp) with 23.9°C (75°F) cooling water. Figure 6 shows the measured effect of system heat addition and cooling water temperature on cycle efficiency. As expected, decreasing cooling water temperatures increase cycle efficiency for a fixed heat added. Because system heat added is approximately proportional to mass flow rate which, in turn, is a function of turbine inlet pressure and temperature, the system cycle efficiency increases with system heat addition as shown in the figure. As used in this paper, cycle efficiency is defined as R/C output power divided by system heat addition. At high system heat additions and, hence, high boiler temperatures concurrent with 23.9°C (75°F) cooling water, measured cycle efficiency of 17% was achieved.

R/C gearbox losses were measured by driving the gearbox without the turbine. The losses were measured as a function of speed and oil temperature and it was found that the gearbox loss was approximately .75 kw (1 hp) at design conditions. The gearbox lubricating oil is Zephron 150 refrigeration oil manufactured by DuPont which was

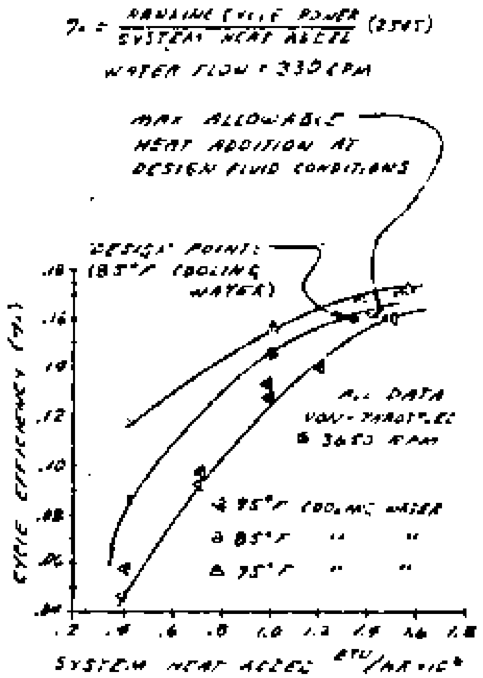


Fig. 6 Effect of heat addition and cooling water temperature on cycle efficiency.

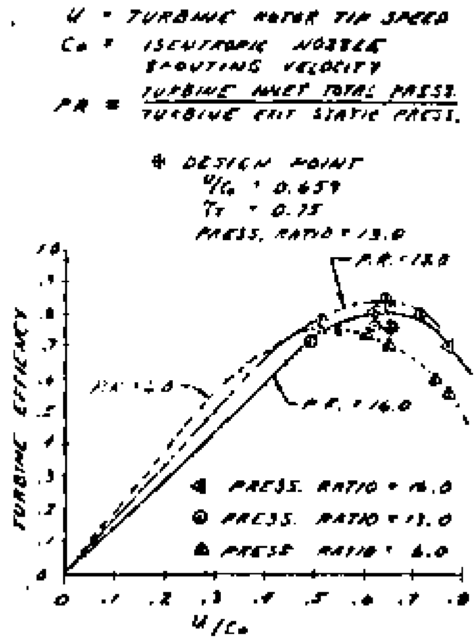


Fig. 7 Turbine performance as effected by U/C_o and pressure ratio.

felt to provide suitable gearbox lubrication and cooling should be compatible with the R/C system in case of seal leakage. The seals between the turbine and gearbox are a double, buffered face seal design. The R/C turbine efficiency was then calculated utilizing measured R-113 fluid conditions across the turbine and measuring the turbine gearbox output power. A constant .75 kw (1 hp) gearbox loss was assumed to calculate turbine output power. Figure 7 summarizes the results of the turbine efficiency measurements as functions of U/C_o and turbine pressure ratio. U/C_o is a dimensionless ratio of turbine rotor tip speed divided by the isentropic nozzle spouting velocity. The isentropic nozzle spouting velocity is the ideal velocity the R-113 vapor would achieve if the entire turbine head were taken across the nozzle. Turbine pressure ratio as shown in the figure is the inlet total pressure divided by the exhaust static pressure. It can be seen from the figure that at the design pressure ratio of 13.0 the turbine efficiency was approximately 81% at a U/C_o of .66. This exceeds the conservatively specified turbine design point efficiency of 75%. Turbine efficiency decreases with operation away from the optimum U/C_o and with off-design pressure ratio. Turbine performance for pressure ratios of 6 and 16 were also obtained during tests and are shown in the figure for reference.

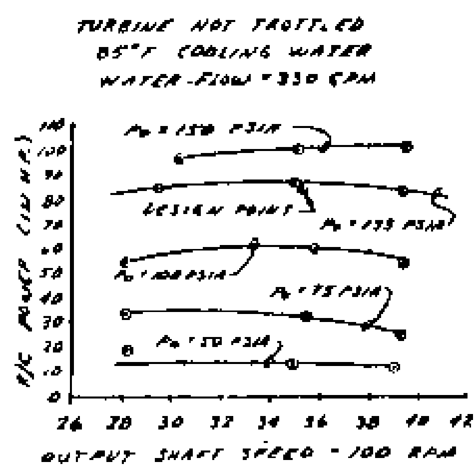


Fig. 8 Effect of turbine inlet pressure (P_o) and output shaft speed on Rankine cycle power.

The effect of turbine speed on R/C power is shown in Figure 8. The operating speed range of the turbine gearbox is limited by the requirements of the York chiller unit. It can be seen from the figure that over the allowable gearbox output shaft operating speed range of approximately 2800 to 3900 rpm, the effect of speed does not have a significant effect on R/C power. The effect of turbine inlet pressure is also shown in Figure 8. R/C power increases with increasing turbine inlet pressure because of increased mass flow and increased head available to the turbine. The choked flow turbine nozzles control the R/C flow rate which is proportional to nozzle inlet pressure. In addition, as the inlet pressure is increased to the design point value of 920K Pa (133 psia) the turbine efficiency also increases because the turbine approaches the design pressure ratio.

5. ACKNOWLEDGEMENT

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PERFORMANCE PREDICTION OF A SOLAR-OPERATED INTERMITTENT AMMONIA-WATER REFRIGERATOR USING A FLAT PLATE COLLECTOR

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ABSTRACT

An intermittent solar refrigerator employing a flat plate collector is comprised of three major components namely, a generator-cum-absorber, a rectifier and a condenser-cum-evaporator. During the process of generation the vapours passing through the rectifier are condensed in the condenser. Ammonia vapours are reabsorbed in the weak solution during the refrigeration process. This paper presents the results of the analysis carried out for the ammonia-water system. The various processes have been simulated on a digital computer using the initial solution concentration and generator temperature as inputs. The heat absorbed during generation and the mass of vapours condensed have been determined for the generation process. Also the minimum evaporator temperature, effective refrigeration and coefficient of performance have been computed. The results of this computation are presented as nomograms and are discussed.

1. INTRODUCTION

Among the different renewable sources of energy solar energy appears to offer a variety of possibilities for its utilisation particularly in tropical countries that receive abundant sunshine. Solar refrigeration that dispenses with the use of electricity altogether would be most welcome in a vast country like India. Since the country's economy is intimately related to the production of agriculture and marine food products, a simple method by which the wastage of perishables can be avoided would go a long way in giving a fillip to the economy. It is in this context that the present investigations of an intermittent solar refrigerator have been undertaken. Its chief merits are that it is inexpensive, has no moving parts and easy to maintain.

2. THEORETICAL CYCLE

Fig.1 shows the theoretical constant temperature refrigeration cycle. Solar radiation striking the generator raises

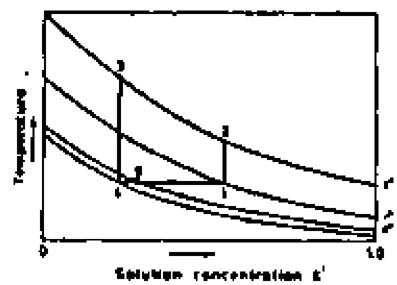

Fig.1. Theoretical cycle for solar refrigerator. 1,2,3,4 and 5 solution states in the generator-cum-absorber, 1*,2*,3* and 5* states of pure ammonia in condenser-cum-evaporator.

the pressure and temperature of the ammonia-water solution as indicated by the path 1-2. At 2 the system pressure is equal to the saturation pressure of ammonia corresponding to the condensing temperature. Generation continues from 2 to 3 at constant pressure as solar heating is continued. The generated vapours pass to a water cooled condenser through a rectifier and ammonia is condensed. State 3, the end of the generation process depends upon the maximum attainable temperature in the flat plate collector. At this instant when the state of liquid ammonia in the condenser is at 2*3* and the state of solution in the generator is at 3, the generator and the condenser are isolated. The generator is cooled to ambient conditions so that the solution state reaches 4. At 4, the solution concentration, temperature and pressure are low and hence the generator is ready to operate as an absorber. The communication between the condenser and absorber is now restored. A fraction of liquid ammonia in the condenser at 2*3* flashes adiabatically into the absorber to change the solution state to 5. As a consequence of flashing the temperature of the remaining quantity of ammonia in the condenser decreases to bring its state to 5*. The condenser is now ready to operate as the evaporator. From 5* to 1* the evaporator absorbs energy from the surroundings to provide the effective refrigeration, and the rising vapours are reabsorbed in the absorber until the solution reaches the initial state 1.

3. THERMODYNAMIC ANALYSIS OF THE CYCLE

In the cycle analysis it is assumed that the condensing temperature is 30°C and that the pressure during the generation process 2-3 (Fig.1) is 11.67×10^5 N m^{-2} which is equal to the saturation pressure of ammonia at 30°C. The different relations that are used in the analysis are given below and the method of obtaining these relations are discussed in references [1],[2] and [3].

Heat added to the ammonia-water solution during the generation process 1-2-3 (Fig.1) is given by:

$$q_g = m_3 h_3' - m_1 h_1' + \int_3^2 dm\, h'' \qquad (1)$$

The mass of generated vapours and the mass of condensed ammonia are respectively obtained from:

$$m_{vg} = m_2\left(1 - \exp \int_{x_2'}^{x_3'} \frac{dx'}{x'' - x'}\right) \qquad (2)$$

$$m_{vc} = m_{vg}\left(\frac{x'' - x'}{1 - x'}\right) \qquad (3)$$

The mass of ammonia flashing is given by:

$$m_{fl} = m_{vc}\left[1 - \exp\left(\frac{h_{5*} - h_{2*}}{h_{fg_{av}}}\right)\right] = \frac{m_4(x_5' - x_4')}{1 - x_5'} \qquad (4)$$

The minimum evaporator temperature is evaluated with the help of the relations

$$x_5' = 0.007804\, t_{5*} + 0.55847 \qquad (5)$$

and

$$\exp\left(\frac{h_{5*} - h_{2*}}{h_{fg_{av}}}\right) = 0.00331 t_{5*} + 0.893 \qquad (6)$$

Effective cooling and the c.o.p are obtained from the relations

$$q_o = (m_{vc} - m_{fl})\left(\frac{h_{fg_{5*}} + h_{fg_{1*}}}{2}\right) \qquad (7)$$

and

$$c.o.p. = q_o/q_g \qquad (8)$$

3.1 Computation

The different initial solution concentrations selected for the analysis are 0.4, 0.45, 0.5, 0.55, 0.6, 0.65 and 0.7. In each case, the initial solution temperature, condenser temperature and absorber temperature is assumed to be 30°C. Initial mass of solution is 1 kg. The equations presented earlier as well as additional required in the analysis have been expressed in forms suitable for computerisation.

The solution concentrations at different temperatures during generation, corresponding to a pressure of 11.67×10^5 N m^{-2} have been obtained from property tables [4]. The values of x' so obtained on polynomial regression are found to vary with generator temperature according to the relation

$$x' = 1.12604 - 0.0111703 t_g + 0.32261 \times 10^{-4} t_g^2 \qquad (9)$$

A similar procedure was employed for obtaining the relation between enthalpy of vapour and generator temperature

$$h'' = 4.187(320.089 - 0.403487 t_g + 0.00906 t_g^2) \qquad (10)$$

Denoting $dx'/(x'' - x')$ by z and by a similar method as briefed earlier it is found that

$$z = -1.614264 + 0.66686 x' + 1.390321 x'^2 \qquad (11)$$

The heat absorbed during the generation process 1-2-3 can be divided into two parts,

$$q_g = (q_g)_{1-2} + (q_g)_{2-3} \quad (12)$$

Liquid enthalpy values as the temperature changes from t_1 to t_2 determined from tables are used in the equation

$$(q_g)_{1-2} = h_2 - h_1 \quad (13)$$

$$(q_g)_{2-3} = \sum_2^3 dq_g \quad (14)$$

At any temperature t_g during the generation process 2-3,

$$dq_g = m_{t_g} c_p dt_g + dm_{vg} h'' \quad (15)$$

The step interval chosen for the evaluation of heat absorbed during the process 2-3 using eq.(14) and (15) is one deg. c_p and h'' are expressed as functions of t_g. With help of Eqs.(2) and (11) the mass of vapours generated for one deg rise in solution temperature at any temperature t_g is obtained from

$$dm_{vg} = m_{t_g} [1.0 - \exp(z_1 - z_2)] \quad (16)$$

where z_1 and z_2, given by Eq.(11) correspond to t_g and $(t_g - dt_g)$ respectively. It is to be noted here that z is a function of t_g only and when $t_g = t_2$, $m_{t_g} = 1.0$ and $dm_{vg} = 0$. At any temp. t_g

$$m_{t_g} = m_2 - \sum_{t_2}^{t_g} dm_{vg} \quad (17)$$

With the help of properties obtained from tables it can be shown that

$$(x''-x')/(1-x') = 1.02283 - 1.6035 \times 10^{-3} \times t_g + 3.5499 \times 10^{-5} \times t_g^2 \quad (18)$$

With the help of Eqs.(16),(17) and (3) dm_{vc} can be expressed as function of t_g. Relevant equations are made use of in evaluating the values of q_g, $m_{vg} = \Sigma dm_{vg}$, $m_{vc} = \Sigma dm_{vc}$, x_3' and m_3 for various generator temperatures upto a maximum of 125°C, at intervals of one deg. The minimum evaporator temperature is obtained from Eqs.(4),(5) and (6). From property tables the relation between h_{fg} and evaporator temperature is obtained by polynomial regression and this is used in conjuction with Eq.(7) to get the value of q_0.

4. RESULTS AND DISCUSSION

Fig.2 shows the variation of q_g with t_g for various initial solution concentrations. For a given initial solution concentration heat added in the generator increases with increase in generator temperature. At any initial solution concentration the heat transfer required to bring about a certain change in the generator temperature is smaller at higher generator temperatures, for at higher temperatures the solution mass and concentration will have reached smaller values which in turn reduces the vapours distilling off. Heat transfer to the generator increases with increase in x_1' for a given maximum generator temperature.

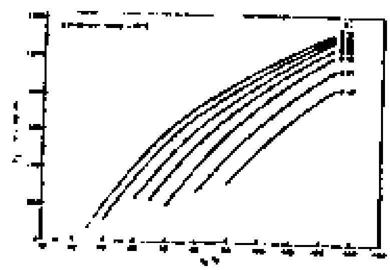

Fig.2. Effect of t_g and x_1' on heat adde

Fig.3 shows the variation in the quantit of ammonia condensed during the generati

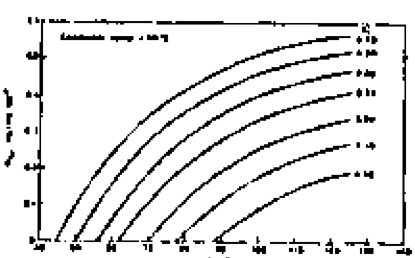

Fig.3. Effect of t_g and x_1' on m_{vc}.

process plotted against t_g for different initial solution concentrations. The mass of condensate increases with temperature for any x'_i. Also the increase in the condensate for a given t_g is smaller at higher temperatures. This effect is more pronounced at higher initial solution concentrations.

Figs. 4 and 5 show the variation of effective refrigeration, minimum evaporator temperature and c.o.p. for various generator temperatures and initial solution concentrations in the form of nomograms.

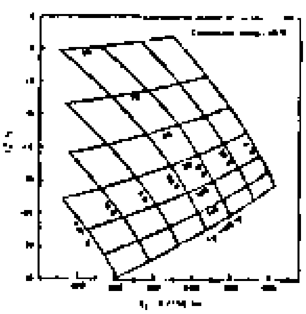

Fig. 4. Effect of t_g and x'_i on q_e and t_{5*}

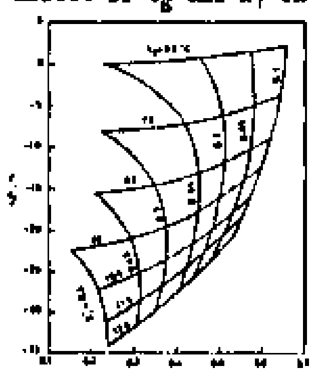

Fig.5. Effect of t_g & x'_i on t_{5*} & c.o.p.

t_{5*} the minimum evaporator temperature decreases with increase in t_g for a given x_i. As the generator temperature is increased, state 3 shifts to lower concentrations as a consequence of which state 4 shifts to lower pressures and hence the pressure difference ($p_{2*} - p_4$) available for flashing increases. The increased pressure difference causes a larger fraction of the condensed ammonia to flash thereby reducing the temperature of remaining ammonia in the condenser. Also for a given t_g, t_{5*} increases with increase in x'_i. As x'_i increases the condensate increases, and since the quantity of ammonia flashing is mainly influenced by the pressure difference, the latent heat of vaporization is now borne by a larger mass of condensate to increase its temperature. Effective refrigeration which follows adiabatic flashing increases both with the increase in x'_i and t_g. At a given initial solution concentration x'_i, c.o.p. increases rapidly at first and then slowly until a maximum is reached beyond which it decreases gradually.

5. CONCLUSIONS

It has been demonstrated that the performance of the refrigerator can be predicted provided the initial solution concentration and the condensing temperature are known. The results of the analysis show that in order to obtain higher c.o.p (higher q_e) higher generator temperatures and higher initial solution concentration are imperative. However attainment of low evaporator temperature dictates the use of low x'_i. Hence a compromise has to be struck as regards the initial solution concentration for obtaining optimal performance bearing in mind the purpose for which the refrigeration is intended.

6. NOMENCLATURE

- c.o.p. - coefficient of performance
- h' - enthalpy of solution, kJ/kg
- h'' - enthalpy of vapour
- h - enthalpy of liquid ammonia
- m - mass, kg
- m_{fl} - mass of ammonia flashed
- m_{vc} - mass of ammonia condensed
- m_{vg} - mass of vapours generated
- p - pressure, Nm^{-2}
- q_e - effective refrigeration, kJ/kg
- q_g - heat added during generation
- t - temperature, °C
- x' - solution concentration, kg/kg sol.
- x'' - vapour concentration

Subscripts

- 1,2,3,4 & 5 - properties corresponding to the states in Fig.1
- 1*,2*,3* & 5* - properties corresponding to the states in Fig.1
- g - properties of sol. in generator.

7. REFERENCES

[1]. A.Venkatesh and M.C.Gupta,"Analysis and Performance of an Ammonia-Water Intermittent Solar Refrigerator", International Solar Energy Congress 77, Paper No.0334,Jan 16-21,1978, New Delhi,India.

[2]. A.Venkatesh and M.C.Gupta,"Analysis of Ammonia-Water Solar Refrigerator Operating with a Flat Plate Collector", International Symposium-Workshop on Solar Energy,June 16-24,1978, Cairo, Egypt.

[3]. A.Venkatesh and M.C.Gupta,"Performance Prediction of a Solar-Operated Intermittent Ammonia-Water Refrigerator Using a Flat Plate Collector",2nd International Solar Forum,July 12-14, Hamburg, West Germany.

[4]. George Scatchard et al, "Thermodynamic Properties- Saturated Ammonia-Water mixtures", Journal of ASRE,p 413, (1947).

SOLAR ABSORPTION COOLING FEASIBILITY

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ABSTRACT

The feasibility of solar absorption cooling systems is dependent upon its technical and economically competitive position with respect to other cooling system alternatives. Technical feasibility can be shown by comparisons of the thermodynamic efficiency of solar absorption cooling with conventional vapor-compression cooling equipment and by reference to numerous experimental evaluations. Economic feasibility is heavily dependent upon the financial parameters assumed (in particular the inflation rate of conventional fuel costs). In particular cases, i.e., particular assumptions of the financial parameters, economic feasibility of solar absorption cooling can be demonstrated.

1. INTRODUCTION

Solar space cooling of buildings may be accomplished by a number of alternative methods. One of the most promising is the use of an absorption refrigeration cycle. A principal advantage of this method is the small amount of mechanical work required. And, while a heat input many times greater than the work input of a mechanical vapor-compression cycle is required, the absorption cycle can be economically attractive if the heat is sufficiently cheap.

An absorption refrigeration system could be labeled a vapor-compression system, where several of the components of the absorption refrigeration cycle (notably the absorber and generator) are required to perform the function of the compressor in a mechanical vapor-compression system. But, while the coefficient of performance (COP) of a vapor-compression system is typically 2 to 4, the COP of absorption cycles is limited; the maximum attainable COP for an absorption system is equal to the COP for a Carnot refrigerating cycle working between the evaporator temperature and the ambient temperature, multiplied by the efficiency of a Carnot engine working between the generator temperature and the ambient temperature. For a given ambient temperature, the COP will increase with an increase in the heating medium temperature input to the generator.

The fluid in the generator consists of a solution of refrigerant and absorbent which have a strong chemical affinity for each other. In most commercial systems the refrigerant/absorbent combinations are water/lithium bromide and ammonia/water.

The ammonia/water absorption system may be [illegible] able whenever ammonia is a suitable refrigerant. However, because the absorbent (water) is [illegible] the refrigerant vapor leaving the generator [illegible] contain too much water, so that additional [illegible] ment to rectify the generator vapor and [illegible] the ammonia concentration is required.

An outstanding feature of the water/lithium bromide absorption system is the non-volatility of the lithium bromide. In the generator only water [illegible] is driven off, eliminating the need for rectifying equipment. Compared to the ammonia/water system, the water/lithium bromide system is simpler and operates with a higher COP. The primary disadvantage of the water/LiBr system is its requirement for relatively high evaporating temperatures.

Other differences between ammonia/water and water/LiBr systems includes water-cooling versus [illegible] cooling requirements, need for a solution pump, use of direct-expansion evaporators. Ammonia [illegible] systems, for example, can be air-cooled [illegible] generator inlet temperatures of 120 to 180°[illegible] available. Water/LiBr units always require [illegible] cooling, as do ammonia/water systems operating [illegible] generator inlet temperatures of less than [illegible]

Ammonia/water systems require mechanical [illegible] pumps to pump the working fluid from the [illegible] pressure to the generator pressure; thus [illegible] additional parasitic electrical power. [illegible] the small pressure differential between the [illegible] and low pressure portions of the water/LiBr [illegible] vapor-lift (or "bubble") pumps may be utilized along with gravity return of solution from the absorber to the generator. Thus the parasitic electrical power requirements of water/LiBr [illegible] can be less, although in larger cooling capacity units, mechanical solution pumps are often [illegible]

Finally, ammonia is considered flammable [illegible] so that it is not utilized with direct-expansion evaporator coils whenever the air to be [illegible] will be in direct contact with the evaporator [illegible] a separate chilled water loop is necessary.

Carnot coefficients of performance for [illegible] cooling equipment could range from 0.5 to [illegible] operated at temperature and heat input [illegible] cable for solar applications [1]. Practical

...ption cycles are, of course, non-ideal cycles ... hardware limitations, irreversible processes, ... fluid properties, etc. Thus a practical COP ... commercially available, single-effect unit is ... range of 0.5 to 0.7 for ammonia/water units ... to 0.8 for water/LiBr units.

...lar Absorption Cooling Experiments

...tilization of solar energy as the heat input to ...nerator of absorption cooling units has been ...ied by numerous researchers. These include ef... Löf [2], Trombe, et al [3], Williams [4], ...midt, et al [5], Chinnappa [6], Chung, et al ...uffie, et al [8], Swartman, et al [9,10] and ... [11]. The basic conclusion of these papers ... demonstrated ability of solar energy flat-...collectors to achieve the required tempera-... necessary to provide the heat input to operate ...sorption refrigeration units.

...ent years the experimental incorporation of an ...ption chiller into a solar heating and cooling ... has also been accomplished. Noteworthy ex...ents have been conducted by Ward, et al [12,13, ...], Namkoong [16], San Martin, et al [17,18] and ... [19]. Numerous other experimental cooling ... have been designed and fabricated, but ex...tive performance data are not yet available. In ...tion to systems testing, continuing efforts have ... directed toward additional experimental testing ... absorption cooling units as well as a variety of ...ter simulations. Recent efforts in the absorp-... refrigeration experiments on independent ...ies include Anderson [20], Simmons, et al [21], ... et al [22,23] and Merrick [24].

...siderable importance must be directed toward the ...erimental performance of the solar cooling sys-... because it is these results which constitute ... severest test of the feasibility of solar ab-...ption cooling. Computer simulations suffer from ...ere lack of ability to predict and model actual ...ting conditions. And, while continued efforts ... in progress, such efforts have meaning only in-...r as they improve the system performance. This ... has been emphasized by Newton [25].

... Solar Absorption Cooling System Performance

...use of their nearer term commercial availability ...er/LiBr absorption units have received the bulk ... cooling system performance testing. Therefore ... below discussion is directed toward those sys-... using the water/LiBr units.

... first noteworthy factors are the temperature ...uirements. The water/LiBr residential-sized ... are designed for generator input temperatures ... 88° to 90°C under conditions of cooling water ...eratures of 30°C, and in order to achieve chilled ...er or evaporator temperatures of 7° to 8°C. ...er generator input temperatures are possible when ... cooling capacity is acceptable (75° to 80°C ... temperature to the generator allows for about ... the cooling capacity) or if lower cooling ...er temperatures are available (70° to 75°C gen-...ator inlet temperatures are possible for cooling ...er at 25°C and a cooling capacity of 80% is ac-...table).

It is important to realize that 88°C temperatures are easily obtained with existing, high quality, liquid-heating solar flat-plate collectors and at reasonable efficiencies. In fact, the summer operating efficiency can be expected to be better than the winter performance.

The latter result can be seen if we assume some typical operating conditions [e.g., see ref. 26]. In January the collector inlet temperature (T_i) might average 55°C with an ambient temperature (T_a) of -5°C. The January solar radiation on a tilted surface (H_T) would be approximately 600 watt/m². This gives a value for $(T_i-T_a)/H_T$ = 0.1 m²-°C/watt. In July we could expect T_i = 90°C, T_a = 30°C, and H_T = 800 watt/m²; so that $(T_i-T_a)/H_T$ = 0.075 m²-°C/watt. Under these circumstances we can therefore expect improved solar collector efficiency for the summer months.

A critical assumption in the foregoing calculation is that thermal storage heat losses do not affect the results. In general, such heat losses cannot be neglected and can substantially alter the results. This point is seen most clearly when we choose a hot water storage tank as the thermal storage medium. Note that a phase change storage subsystem is not feasible for storing the collected solar energy for both the summer and winter seasons because of the totally different seasonal temperature ranges (35° to 70°C winter; 75° to 100°C summer). This leaves hot water as the thermal storage medium.

A critical problem with hot water is the heat losses from the storage tank. Jacobsen [19] has observed an actual heat loss coefficient of 1.65 watts/m²-°C, which was approximately 50% greater than the predicted value of 1.19 watts/m²-°C. For a 55°C temperature difference between storage and ambient the actual heat loss becomes 1200 watts! Such deviations from predicted values are apparently common [18,26,27]. For example, Ward [26] has reported heat losses from a hot water thermal storage unit of 880 watts (equivalent to two hours of operation of the installed chiller). Increased and heavier insulation reduced this to 330 watts.

A common design in solar heating systems is to locate the thermal hot storage unit inside the heated space so that heat losses from the storage help to meet the heating demand. In this case, it is, of course, permissible to neglect the heat losses. But the addition of a cooling system implies that the heat losses not only degrade the ability of the solar system to meet the cooling load, but actually increase the cooling demand itself. Ward [26] has reported that the effect of heat losses during a month of June actu... ...duced the percent of cooling load carried by solar to a negative number.

One method of avoiding this increasing of the cooling load by thermal storage heat losses is to locate the thermal storage outside the conditioned space. Unfortunately, this increases the winter heat losses from storage (because of the greater temperature differential between storage and ambient), reduces the ability of the thermal storage to meet the heating load, and increases the chances of freezing the storage unit.

A more preferable alternative would be to use a triple thermal storage system. Ward [28] has discussed the use of a "cool storage" system to reduce the normal operating temperature of the hot thermal storage unit to the minimum temperature that the absorption chiller can effectively utilize, and to allow operation of the chiller whenever solar energy is available, irregardless of the cooling demand. It is noteworthy that a cool storage will undergo some heat gains from the ambient and that, if the cool storage units are located within the conditioned space, this will constitute a heat removal method and assist the solar system to meet the cooling demand. In this respect it is similar to the concept of heat losses from a hot thermal storage unit contributing to the winter heating load.

In order to take advantage of these aspects, an alternative storage system could be comprised of three water storage tanks. The first tank would be located exterior to the conditioned space and would be twice the volume of the other two identically-sized tanks, both of which would be located within the conditioned space. During the winter heating season the exterior tank would be empty and the two interior tanks used as a (slightly stratified) hot thermal storage unit. During the summer cooling season, the exterior tank would be used for the thermal hot storage subsystem and the interior tanks would be used in the cooling subsystem (as described by Ward [28,29]). Thus heat losses from the interior tank in winter would aid in meeting the heating load and in summer assist in meeting the cooling load. The heat losses of the exterior tank in summer would be less (due to a lower temperature difference, i.e., a higher ambient temperature) and would not add to the cooling load. And, because of the triple storage system, calculation of the higher summer collector efficiency described above can be justified and can be expected to result in an improved system efficiency.

1.3 Ammonia/Water Absorption Systems

A principal motivation for the development of an ammonia/water solar absorption unit has been for the purpose of eliminating the use of a water cooling tower [21]. This is particularly important at the residential level because regular preventative maintenance of the cooling tower is not always feasible and because of questions of local water quality.

Dao [23] has reported recently on the results of a long-term research and development program for ammonia/water absorption chillers. Past accomplishments include the modification of a 5-ton (17.58 kW), gas-fired unit to operate at a capacity of 1.7-tons (6.00 kW) for conditions of generator temperatures of 77°C, condenser-absorber temperatures of 35°C, and evaporator temperatures of 6°C with a COP of 0.65. Work is continuing on units of 3 to 5 tons with a minimum COP of 0.65 and generator temperatures of 95° to 115°C. The estimated costs of these units are $3,000 to $4,000, or about $1,000 per ton.

The potential for ammonia/water chillers to replace water/LiBr chillers in the near future does not appear too great. The development of these smaller units is clearly in a less advanced stage than ... units; there have, for example, been no complete solar system experiments with ammonia/water. In addition to systems configurations, there is also the safety hazard of using ammonia within the interior of the building. Consequently, in the remainder of this paper, the water/LiBr system will be emphasized because of its commercial availability and because of the more extensive experience with water/LiBr units in solar cooling systems.

2. COOLING SUBSYSTEM DESIGN

In designing a solar heating and cooling system it is particularly important to consider the results of the solar cooling experiments briefly reviewed above. These include: (1) The near-term commercial availability of water/LiBr absorption machines ... compared to the research stage for ammonia/water units); (2) Experience in research and development of solar cooling with water/LiBr machines (both components and system) which demonstrate the technical feasibility; (3) The importance of adhering to design conditions (temperatures, flow rates, etc.) in the operation of an absorption cooling unit; (4) High quality, liquid-heating flat-plate solar collectors are adequate for providing solar heat to absorption units; (5) Thermal storage heat losses/gains are of vital importance in system design and must not be allowed to degrade the designed performance of the system; (6) Cool storage may provide for higher seasonal coefficients of performance ... as well as allowing for smaller tonnages of ... for the same cooling load; (7) Temperature stratification in the cool storage subsystem is critically important; (8) System designs should allow for safeguards against crystallization of the LiBr solution and other potential absorption unit failures.

Based on the above criteria, design schematics of the solar heating and cooling system may then be developed. If we consider the cooling capability of the solar heating and cooling system as an addition to a solar heating system, we might describe the additional complexity in terms of additional components or equipment. Thus, from an economic viewpoint, solar cooling adds the following equipment (and associated costs) to the solar heating system: (1) Water/LiBr absorption chiller (of appropriate tonnage); (2) Water cooling tower (of appropriate tonnage); (3) Two thermal storage tanks (cool storage) [OR specially designed temperature stratified tanks for larger commercial applications]; (4) Two pumps (cooling tower pump, chilled water pump); (5) Four automatic valves; (6) Liquid-to-air heat exchanger ("cooling coils"). The existing "heating coils" may be used (see Fig. 1); (7) Additional piping, hand valves, vents, etc.; and (8) Additional control instrumentation and complexity.

Fig. 1 shows the arrangement of the absorption chiller in relation to three thermal storage ... Table I provides the operational modes of the system. As previously mentioned, the advantage of this system is to ensure that the heat losses/gains from hot/cool thermal storage always contribute to the heating/cooling loads. The principal disadvantage is the requirement of shifting from heating to cooling modes in the spring and back to heating in the fall; thus assuming an accurate anticipation ...

weather. This problem, however, can be alleviated by only a slight increase in the complexity of the system and would reduce to a problem of ensuring that Tank #1 does not encounter freezing conditions when it is full.

The importance of Fig. 1 is to provide an indication of the necessary components for the addition of solar cooling to an existing solar heating system. These additional components are critical when we consider the thermodynamic efficiency and economic feasibility of solar cooling. Figure 1 at the end of paper.

THERMODYNAMIC EFFICIENCY

The essence of the feasibility of solar absorption cooling systems is its technical and economically competitive position with respect to other space cooling system alternatives, including in particular conventional vapor-compression cooling units. The critical factors here are the differences in seasonal coefficients of performance between the absorption and compression systems (including the differences in parasitic power requirements), a technical consideration; and the economic factors of the solar system capital costs (which are not subject to inflation over the life of the system) and conventional system fuel costs (which are strongly dependent upon the anticipated conventional energy inflation rates).

In order to obtain a system efficiency for a cooling alternative, it is necessary to consider the efficiencies of all steps in the conversion of an energy source to the useful work performed, i.e., the extraction of heat from a building. For example, the overall conventional cooling system efficiency (η_{VC}) would be defined as the amount of heat removed from the building (i.e., the amount of space cooling) by the conventional vapor-compression unit when operating with electrical energy (C_{VC}), divided by the fuel input required for producing the electrical energy to operate the vapor-compression cooling unit (E_C), i.e., $\eta_{VC} = C_{VC}/E_C$. E_C is just the electrical energy input necessary to operate the vapor-compression system (E_e) divided by the efficiency of generating and delivering energy to the consumer (η_e). Thus the expression for η_{VC} can be written, $\eta_{VC} = \eta_e C_{VC}/E_e$. However, C_{VC}/E_e is just the COP of the vapor-compression unit, $(COP)_{VC}$. Thus:

$$\eta_{VC} = (COP)_{VC}(\eta_e) \tag{1}$$

For a solar water/LiBr absorption system using an auxiliary fired by conventional fossil fuels (natural gas, coal, fuel oil, propane, etc.), the various efficiencies which we must consider include the efficiency of the auxiliary furnace in converting the fuel input to useful heat energy for delivery to the generator of the absorption unit (η_A), the rated COP of the solar power unit, and the parasitic power requirements of the solar and auxiliary systems. For a solar absorption cooling unit utilizing solar for a fractional percentage of the cooling load, we obtain the overall system efficiency of the solar absorption cooling system of:

$$\eta_S = [f\,C_S/(G_S+E_S)] + [(1-f)\,C_A/(G_A+E_A)](\eta_A) \tag{2}$$

where (f) is the fraction of the cooling load carried by solar energy being delivered to the generator of the absorption unit; (C_S) is the amount of heat removed from the building (i.e., the amount of space cooling) by the absorption cooling unit when operating with solar energy; (C_A) is the amount of heat removed from the building (i.e., the amount of space cooling) by the absorption cooling unit when operating with auxiliary (conventional) energy; (G_S) is the amount of solar energy delivered to the generator of the absorption cooling unit; (G_A) is the amount of auxiliary energy delivered to the generator of the absorption cooling unit; (E_S) is the fuel input required for producing the electrical energy used by the solar subsystem; and (E_A) is the fuel input required for producing the electrical energy used by the auxiliary subsystem.

We can simplify eqn. (2) by defining ε_S and ε_A as the percentage of electrical energy input necessary to deliver the solar and auxiliary energy (respectively) to the cooling unit so that:

$$E_S = \varepsilon_S G_S/\eta_e \qquad E_A = \varepsilon_A G_A/\eta_e \tag{3}$$

Utilizing eqn. (3) and the fact that C_S/G_S and C_A/G_A represent the COPs for the solar-driven $(COP)_S$ and auxiliary-driven $(COP)_A$ absorption units, respectively, we can modify eqn. (2) to obtain:

$$\eta_S = [f(COP)_S/(1 + \varepsilon_S/\eta_e)] + [(1 - f)(COP)_A/(1 + \varepsilon_A/\eta_e)](\eta_A) \tag{4}$$

Eqns. (1) and (4) now allow us to directly compare the coefficients of performance for solar absorption and conventional (electrically-driven) vapor-compression machines. For example, we may utilize some previous experimental data [14,28] to assume the values of some of the parameters in eqn. (4), i.e.,

$$(COP)_S = (COP)_A = 0.65 \quad \varepsilon_S = 0.08 \quad \varepsilon_A = 0.01$$

In addition we can assume an auxiliary furnace efficiency of $\eta_A = 0.75$ and an overall average efficiency for different electrical-generating power plants of $\eta_e = 26\%$. (Electric generating efficiency (30%), transmission efficiency (91%), and distribution efficiency (95%); ref. [30]) Under these assumptions eqn. (4) becomes:

$$\eta_S = 0.469 + 0.028\,f \tag{5}$$

An intermediate observation is that the fraction of the cooling load carried by solar has a minimal effect on η_S, i.e., f has a minor effect on the thermodynamic efficiency of the solar/auxiliary system for the condition where the above assumptions are applicable.

For an f = 0.5 to 0.8, η_S = 0.48 to 0.49.

For the conventional vapor-compression system we may use a seasonal COP of $(COP)_{VC}$ = 2 to 3. In this case, eqn. (1) yields η_{VC} = 0.52 to 0.78.

Thus the conventional vapor-compression system yields a thermodynamic improvement over the solar absorption system of:

$$\eta_{vc}/\eta_S = 1.08 \text{ to } 1.63 \quad (\text{avg} = 1.35) \tag{6}$$

On the other hand, the absorption system has some practical advantages. It has, for example, fewer mechanical moving parts and is thus less subject to wear and should require less maintenance. The absorption system may operate at reduced evaporating pressures with little decrease in refrigerating capacity and liquid carry-over from the evaporator does not cause difficulties as in the mechanical systems. The only practical disadvantages of absorption systems are the greater complexity and lower COP of the ammonia/water systems and the potential for crystallization of the absorbent and the maintenance of a strong vacuum (against production of hydrogen and mechanical leaks) with a lithium bromide absorption system.

4. IMPROVEMENTS IN SOLAR ABSORPTION EFFICIENCIES

As previously mentioned, the COP of a single-effect absorption unit using a conventional working fluid is limited and always less than 1.0. Some substantial improvements are possible, however, for higher generator inlet temperatures. For example, hot water at a temperature of 175° to 200°C could be employed in a double effect absorption cycle to improve the COP. For water cooled, double-effect, water/LiBr units, COPs could obtain values as high as 0.99, and the COP of the double-effect unit is no longer limited to 1.0. Unfortunately, the double-effect operation with air-cooled, ammonia/water units is not practical. See ref [1] for further discussion of the double-effect absorption cycles.

Combination absorption-resorption cycles (CAR cycle) also have the potential for higher COPs (0.8 to 1.0) but again involve high temperatures (≈150°C) in providing heat to the generator [1]. And, in this case, as well as for double-effect units, cooling capacities are normally in the range of 400 to 1100 tons. Thus for smaller tonnages, the apparent limitation of COP of absorption units is about 0.8.

It is noteworthy that the efficiency of solar absorption cooling, defined in eqn. (4), would increase to a value of 60% for a COP of the absorption unit of 0.8 (instead of 0.65). This represents a 22% increase in performance and lowers the relative thermodynamics efficiencies of conventional vapor-compression systems to solar absorption systems to a range of: η_{vc}/η_s = 0.87 to 1.30. Effectively, therefore, the solar absorption system is equivalent to the vapor-compression systems in terms of total system efficiency.

5. ECONOMIC CONSIDERATIONS

A critical factor in the question of the utilization of solar absorption cooling systems is the economic feasibility. Generally an assumption is made to consider only the costs of the absorption chiller and the specific cooling subsystem costs as the capital cost of the solar cooling, and consider the cost of solar collectors, thermal storage, etc. as part of the solar heating system. This assumption favors solar cooling since the savings in the cost for cooling must offset only the cost of the chiller and related hardware, and not other portions of the solar system. (A listing of the required solar components is given above)

Economically much of the thermodynamic advantage of a conventional system (see, e.g., eqn. 6) is lost in the costs of profit and overhead of the electrical utilities (in effect, the consumer pays for the capital cost of the power plant, plus administrative costs and profit). Therefore even in the event of natural gas prices increasing to the point of equal competition with other fuels, the cost of electricity over the cost of natural gas will still be substantially higher to account for power plant efficiency and utilities' overhead and profit.

In point of fact, 60% of the cost of electricity is "demand related" [30], which means that the rapidly escalating costs of capital construction of new or replacement power plants constitutes 60% of the total cost of electricity. The remaining 40% of the electrical cost is "base load-related", i.e., the cost of fuel and administrative overhead and profit constitutes only 40% of the electrical costs.

For example, Public Service of Colorado pays about $0.75/mBtu for its energy (coal, gas, oil). When the efficiency of conversion, transmission and distribution are included, the fuel cost of the electric bill is about $3/mBtu. Electricity is sold at the price of $11/mBtu. Thus fuel costs constitute about 27% of the total price.

It may be that, when rapidly escalating inflationary costs of the conventional fuels are compared to the stable amortization of a solar system's capital cost, we can realize an economically competitive advantage of solar absorption cooling. This advantage would become even more pronounced when the environmental costs of electrical production are included.

In evaluating the economic feasibility of a solar cooling system, two considerations are necessary. One is the determination of the fractional portion of the load which the solar cooling system can be expected to carry given the building cooling requirements, the location (site), and the size of the solar heating system. The second step is to evaluate the potential savings in life-cycle cost of the system using present worth costing.

Bartlett [31] has performed an analysis of site-dependent factors which affect the economic feasibility of solar absorption cooling. These factors include the need for: (1) a high heating load relative to the cooling load; (2) a high collector efficiency during the cooling season relative to the heating load (a factor easily accomplished); (3) a high insolation during the summer relative to the insolation in the winter; (4) a high absorption COP; (5) a high percent solar heating; (6) a high cost for conventional energy; and (7) a low cost for auxiliary energy.

The results of Bartlett's analysis [31] indicate that, based on the assumptions made, residential applications of solar absorption cooling (i.e., small tonnage units, e.g., 3 to 5 tons) are not currently economically attractive (1976 costs), and that commercial applications were found to be more cost effective. In general, Bartlett found that the larger the chiller the more economically feasible it would be. This latter factor is not partic-

... surprising, since the cost per ton of cooling ... for absorption machines is reduced con... ...ably as we move to larger tonnage units. It ... also noteworthy that conventional absorption ... units are much more feasible at larger ...ages, as evidence by the large number of com... ...ial absorption units now installed (25 tons and ...er) and as compared to the relatively small ...ber of residential sized units currently instal... ...ed.

...is noteworthy, however, that the Japanese firm, ... Corp., has found that by mass production ...niques, they can manufacture four 10-ton cool... ... units cheaper than a single 40-ton unit [32]. ... smaller Yazaki units of 3 to 5 tons, however, ... more expensive per ton and are generally com... ...titive with prices of the American firm, Arkla ...stries [33].

... should be pointed out that Bartlett's analysis ...] was based on the cost of utilities obtained in ... fourth quarter of 1976. This means that solar ... is attempting to compete with natural gas, ... regulated cost is unrealistically low. Bart... ... did use a fuel cost escalation rate of 14%, ... a proposed energy bill in Congress involves a ... year increase in the price of natural gas of ... to 100% or more.

...ter some study it becomes evident that natural ... prices are an unrealistic price basis for con... ...tional energy sources and, because of the com... ... lack of ability to predict future pricing of ..., another source of energy should be considered ... comparing solar and conventional costs. Because ... its wide availability and since it incorporates ... within its rate structure the costs of coal, gas, ...droelectric and fuel oil, the cost of electricity ... best be used for analysis. However, the econo... ...c feasibility of solar absorption cooling is basi... ...ally related to the comparative costs of conven... ...tional electrically-driven vapor-compression units ... solar absorption units with a non-electric ...xiliary. Because natural gas can be expected to ... used for the solar absorption system's auxiliary ... source, it is necessary to relate the current ... of electricity to some hypothetical, unregu... ...ated price of natural gas.

...is can be done by assuming that deregulation of ...tural gas prices would allow the price of natural ... to rise to the point where it is competitive on ... dollar per Btu basis with coal and fuel oil. Be... ...use the cost of fuel represents only about 25% of ... cost of electricity [30], we can then use a ...ice of natural gas (and its associated cost in... ...flation rate) of 25% of the respective values for ...ectricity. The end result is to use current ...sts of electricity for our non-solar system cost ... energy, and to use one-fourth this price for the ...st of the auxiliary fuel for the solar system.

... ECONOMIC ANALYSIS

... general, the question of economic feasibility of ...lar energy systems is the balancing of the capi... ...al cost of a solar system against the savings in ...nventional fuel costs. The critical factor is whether or not the solar energy system will cost less over a specific life-cycle than the conventional system. In the economics of a solar heating system, procedures have been developed to determine feasibility. Kreith [34] has provided a method for analyzing the economics of heating and cooling for buildings and included an overview of the current state of solar system design and optimization. Barley [35] and others [36] have performed similar analyses.

A critical aspect of the economic feasibility of the solar system is the determination of the fraction of the load that the appropriately sized solar system can be expected to carry, f. Klein, et al [37] has provided a method for determining f for a solar cooling system. Using Barley's [35] economic analysis method, it is a straightforward calculation to determine the potential savings attainable by the use of solar absorption cooling.

We will assume that the installed cost of a solar cooling system includes the equipment and installation costs of: (1) the chiller and cooling tower, C_c; (2) the cool storage units, C_s; (3) the associated equipment (pumps, exchangers, piping, etc.) necessary for interfacing the cooling subsystem with the solar heating system, C_E; (4) the portion of the installed cost of the solar heating system which is chargeable to the cooling system, F; (5) the capital cost of the auxiliary cooling system, C_A; and (6) the cost of installing the solar system, C_I. Thus:

$$AC_a = C_c + C_s + C_E + F + C_A + C_I \qquad (7)$$

Where AC_a is the cost of the installed solar cooling subsystem (as used by Barley [35,38]).

Eqn. (7) may be simplified somewhat by assuming that the solar cooling system is an addition to an economically justifiable solar heating system. That is, we utilize Barley's [35] analysis to demonstrate the economic feasibility of a solar heating system (using AC_a as the installed cost of the solar heating system) and then ask if the addition of a solar cooling system can also be economically justified.

In one respect this favors the economics of solar cooling since the cooling system cost does not include charges for the installation of the solar collectors, thermal (hot) storage, etc. (i.e., F = 0) and thus the capital cost of the solar cooling system is less. On the other hand, for applications where the cooling load is significantly greater than the heating load, the solar system is no longer economically optimized. In this latter case it may be preferable to add collector area (thus F > 0) in order to benefit the solar cooling system.

An analagous consideration is the use of the auxiliary heating unit to supply conventional heat to run the chiller. In this case, C_A = 0. We again obtain the advantage of dual use of equipment, but this assumes that the conversion of fuel to auxiliary heat (at some efficiency) to run an absorption chiller (at some COP) will provide cooling at a more economical rate than the use of a conventional mechanical-compression machine as the solar system auxiliary.

Finally, we note that the additional cool storage tanks will require some building space and therefore some possible additional costs. But this is just the space requirements for the solar heating system, since for our triple tank design (Fig. 1), the interior tanks are used in winter heating and are therefore chargeable to the solar heating costs.

7. ECONOMIC FEASIBILITY

The large number of variables in the economic analysis make specific conclusions tentative and dependent upon the reliability of the assumptions used. Certain variables (particularly the inflation rates) allow for a variety of possible conclusions. Ward [39] has done an analysis of the effects on economic feasibility calculations of variations in the assumed economic parameters. Of course, many of the variables involved in the computations are relatively straightforward. For example, interest rates on a loan for the solar system capital costs can be estimated with some confidence and will, of course, remain constant over the period of the economic analysis. Similarly, the percent of downpayment is also easily determined. Property taxes and insurance are also capable of realistic determination (although their adherence to general inflation rate is questionable).

Income tax rates, deductions, investment credits, depreciation, etc. are strictly viable only for individual case studies, but can be estimated for typical situations. Even the general inflation rates over 20 years can be estimated with reasonable accuracy (about 6% over the last 20 years). Discount rates are also variable and depend to some extent on individual case studies.

The fuel inflation rate is, however, far and away the more unreliable and important variable. One utility [30], for example, estimates an annual inflation rate on the cost of electricity of 11% per year for the next four years. The utility will not hazard a guess at inflation rates over a longer period of time.

Despite these difficulties, it is nevertheless useful to consider some typical results of calculations which evaluate the economics of solar absorption cooling for varying rates of inflation, cooling capacities of the cooling units, and under conditions of different tax incentives. These are shown in Table 2. (Table 3 includes the technical and economic assumptions for the results shown in Table 2.) The values in Table 2 have been rounded off to the nearest hundred dollars even though the accuracy is probably less than two significant figures [39].

An obvious and expected conclusion is that the larger 25-ton unit for commercial applications is economically more competitive than the residential 3-ton unit. But perhaps more significant are the inflation rates necessary for an economic residential application. Based on the assumptions of Table 3, a fuel inflation rate of 13% is needed to break even on the solar installation. This can be compared to the predicted electrical cost inflation rate of one utility of 11% [30].

Income tax incentives (presently under considera-tion) allow for lowering of the necessary inflation rate to 10 or 11%, which is in line with current prediction of electric inflation rates. A combina-tion of the tax rebate and low cost loan places the economic breakeven point at an electricity inflation rate of about 8%.

8. CONCLUSIONS

The thermodynamic efficiency of solar absorption cooling is very nearly equivalent to that of an electrically-driven, vapor-compression system with a high seasonal COP (on the order of COP = 3.0). In addition, water/lithium bromide absorption units have a history of demonstrated technical feasibility, particularly when integrated with a complete solar heating and cooling system.

Economically, solar absorption cooling is marginal but improves considerably with income tax incen-tives. For an electricity cost inflation rate of 11% (one electric power company's estimate [30]), the incorporation of a 25% tax rebate and the availability of a 4% interest loan on the solar equipment, an initial investment in a solar absorp-tion cooling system of $4,500 would result in a savings of about $1,000 in electricity costs (in-cluding the capital cost of the electric cooling equipment) over the period of 20 years. It is noteworthy, however, that the owner of the build-ing receives a return of $1,125 the first year and thereafter operates at virtually a breakeven point.

It must be emphasized that these conclusions are on a "best guess" basis. While the technical con-clusions which demonstrate the relative thermo-dynamic efficiencies of conventional vapor-com-pression units and solar absorption cooling are not heavily dependent upon the quality of the assumptions made, the economic feasibility is critically dependent upon the assumed economic values. And such economic parameters allow only tentative and contingent conclusions.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

1. Auh, P.C., "A Survey of Absorption Cooling Technology in Solar Applications", Brookhaven National Laboratory Report No. BNL 50704, 1977.

2. Löf, G.O.G., "Cooling with Solar Energy", World Symposium on Applied Solar Energy, Phoenix, Arizona, 1955.

3. Trome, R. and Foex, M., "Intermittent Ammonia-Water System with Solar Regeneration", Solar Energy Society and Engineering, Vol. 1, 1957.

4. Williams, D.A., "Cooling Systems Based on Refrigeration", Refrigerating Engineering, Vol. 66, p. 33, 1958.

Eisenstadt, M., Flanigan, F.M., and Farber, E.A., "Tests Prove Feasibility of Solar Air Conditioning". Heating, Piping, and Air Conditioning, Vol. 32, p. 120, 1960.

Chinnappa, J.C.V., "Experimental Study of the Intermittent Vapour Absorption Refrigeration Cycle Employing the Refrigerant-Absorbent Systems of Ammonia Water and Ammonia Lithium Nitrate". Solar Energy, Vol. 5, p. 1, 1961.

Chung, R. and Duffie, J.A., "A Study of a Solar Air Conditioner". Mech. Engr. Vol. 85, p.31, 1963.

Duffie, J.A. and Sheridan, N.R., "Lithium Bromide-Water Refrigerators for Solar Operation" Mech. and Chem. Engr. Trans. Inst. Engrs. Australia, MC-1, p. 79, 1965.

Swartman, R.K. and Alward, R., "Evaluation of an Experimental Intermittent Absorption Refrigerator Incorporating the Generator with the Flat-Plate Collector". Proc. Solar Energy Soc. Annual Meeting, Palo Alto, CA, 1968.

Swartman, R.K. and Swaminathan, C., "Solar Powered Refrigeration". Mech. Engr, p. 22, 1971.

Farber, E.A., "Design and Performance of a Compact Solar Refrigeration System". Proc. Solar Energy Soc. Annual Meeting, Melbourne, 1970.

Ward, D.S. and Löf, G., "Design and Construction of a Residential Solar Heating and Cooling System". Solar Energy, Vol. 17, p. 13, 1975.

Ward, D.S., Weiss, T.A., and Löf, G., "Preliminary Performance of CSU Solar House I Heating and Cooling System". Proc. ISES Congress, Los Angeles, CA, 1975.

Ward, D.S., "Performance of the CSU Solar House I Cooling System". Proc. 2nd Workshop on Use of Solar Energy for Cooling Buildings, Los Angeles, CA, 1975.

Ward, D.S., Smith, C.C., and Ward, J.C., "Operational Modes of Solar Heating and Cooling Systems". Solar Energy, Vol. 19, 1977.

Namkoong, D., "Performance of a LiBr Water Chiller in a Laboratory-Scale, Experimental Solar System Test Loop" Proc. ISES Conf., Winnipeg, Vol. 3, 1976.

San Martin, R.L., Diamond, S., Packard, C., Shaw, H., and Stevens, W., "A Solar Heated and Cooled Office Building". Proc. ISES Conf., Winnipeg, Vol. 3, 1976.

San Martin, R.L., LaPlante, D., Packard, C. and Shaw, H., "Twenty Months of Operating Experience with a Solar Heated and Cooled Office Building" Proc. 1977 Annual Meet. of Amer. Sec. ISES, Orlando, FL, 1977.

Jacobsen, A.S., "Solar Heating and Cooling of Mobile Homes, Test Results", Proc. 1977 Annual Meeting of Amer. Sec. ISES, Orlando, FL, 1977.

Anderson, P., "Progress Report on Solar Cooling at Arkla". Proc. 2nd Workshop on Use of Solar Energy for Cooling Buildings, Los Angeles, CA, 1975.

Siemons, M. and Wahlig, M., "Ammonia water Absorption Air Conditioner". Proc. 2nd Workshop on Use of Solar Energy for Cooling Buildings, Los Angeles, CA, 1975.

22. Dao, K., Simmons, R., Wolgast, R., and Wahlig, M. "Performance of an Air-Cooled Ammonia-Water Absorption Air Conditioner at Low Generator Temperatures". Proc. ISES Conf., Winnipeg, 1976.

23. Dao, K., Siemons, M., Wolgast, R. and Wahlig, M. "Development of Solar-Driven Ammonia-Water Absorption Air Conditioners and Heat Pumps". ERDA Contractors' Meeting, Reston, VA, 1977.

24. Merrick, R., "Engineering Design, Construction and Testing of a Salt Water Absorption Unit Optimized for Use with a Solar Collector Heat Source". ERDA Contractors' Meeting, Reston, VA, 1977.

25. Newton, A.B. "Working Sessions on Absorption Systems". Proc. 2nd Workshop on Use of Solar Energy for Cooling Buildings, Los Angeles, CA 1975.

26. Ward, D.S. and Löf, G., "Design, Construction, and Testing of a Residential Solar Heating and Cooling System". Report to CCMS Solar Energy Pilot Study, July 1976.

27. San Martin, R.L., Private Communication, 1977.

28. Ward, D.S., Uesaki, T. and Löf, G., "Cooling Subsystem Design in CSU Solar House III". Proc. ISES Conf., Winnipeg, Vol. 3, 1976.

29. Ward, D.S. and Ward, J.C., "Design Considerations for Residential Solar Heating and Cooling Systems Utilizing Evacuated Tube Solar Collectors". Proc. Amer. Sec. ISES Conf., Orlando, FL, 1977.

30. Public Service Company of Colorado, Private Communication, 1978.

31. Bartlett, J.C., "Site-Dependent Factors Affecting the Economic Feasibility of Solar Powered Absorption Cooling". Proc. Amer. Sec. ISES Conf., Orlando, FL, 1977.

32. Ishibashi, T., Yazaki Corporation, Private Communication, 1978.

33. Anderson, P., Arkla Industries, Private Communication, 1977.

34. Kreith, F. and Kreider, J.F., "Preliminary Design and Economic Analysis of Solar-Energy Systems for Heating and Cooling of Buildings". Energy, Vol. 1, pp. 63-76, 1976.

35. Barley, C.D., "Relative Areas Analysis of Solar Heating Systems Performance". M.S. Thesis, Colorado State University, 1977.

36. Karaki, S., Ward, D.S., Winn, C.B., and Löf, G.O.G., "Solar Space and Water Heating for Residential Buildings". Training manual for Design and Installation of Systems, Dept. of Housing and Urban Development, Washington, 1977.

37. Klein, S.A. and Beckman, W.A., "A General Design Method for Closed-Loop Solar Energy Systems". Proc. Amer. Sec. ISES Conf., Orlando, FL, 1977.

38. Barley, C.D., Winn, C.B., and Huck, S.E., "Simplified Techniques for Sizing Residential Solar Heating Systems". Proc. ISES U.S. Sec. Conf., Orlando, FL, 1977.

39. Ward, D.S., "Realistic Sizing of Residential Solar Heating and Cooling Systems". Submitted to Solar Energy Journal, April 1978, (Available from Solar Energy Appl. Lab, Colorado State University, Fort Collins, CO 80523).

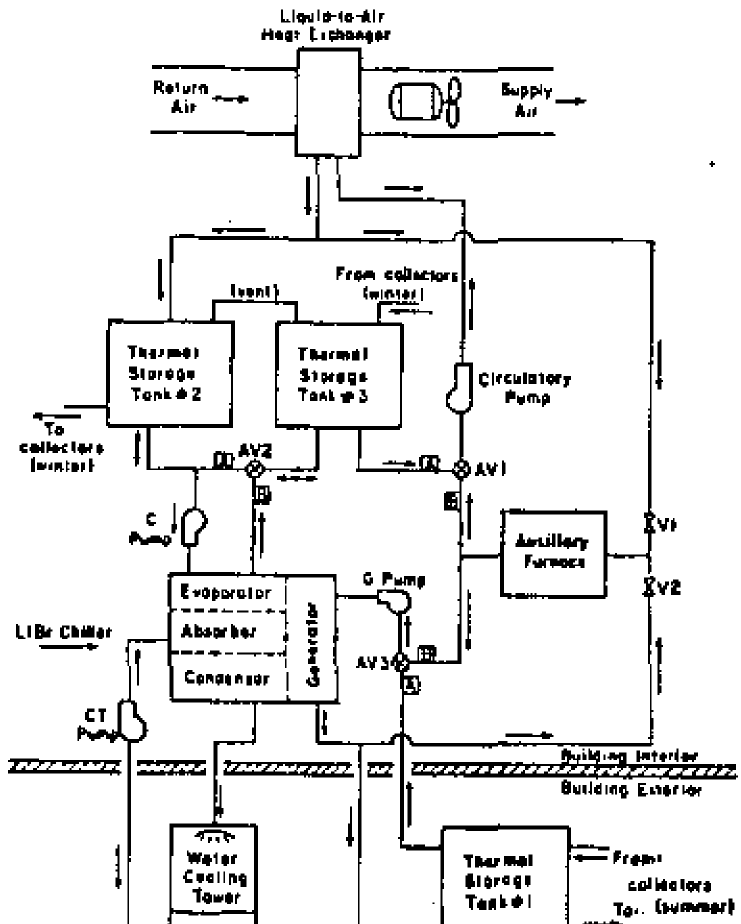

Figure 1. Solar Heating and Cooling System (Triple Storage Tanks)

Operational Modes	Auto Actuated Valves			Pumps				Fan
	AV1	AV2	AV3	Circ	G	C	CT	
WINTER OPERATION (Tank #1 drained, Valve V1 open, Valve V2 closed, Tanks 2 & 3 full)								
1. Collector delivering heat to storage (Tank 3, return via Tank 2)	--	A	A	--	Off	Off	Off	--
2. Storage delivering heat to heating coils	A	A		On	Of[illegible]	[illegible]f	Off	On
3. Auxiliary delivering heat to heating coils	B	--		On	O[illegible]	[illegible]ff	Off	On
SUMMER OPERATION (Tank #1 full, Tank 2 & 3-variable level - half-full, Valve V1 closed, Valve V2 open)*								
1. Collector delivering heat to storage (Tank 1 is hot storage)	A	B	--	--	--	--	--	--
2. Storage delivering heat to chiller	A	B	A	--	On	On	On	--
3. Auxiliary delivering heat to chiller	A	B	B	--	On	On	On	--
4. Chilled storage delivering cool to cooling coils	A	--	--	On	--	--	--	On
5. Recycle chilled water storage (pump warm contents of Tank 3 back to Tank 2)	A	--	--	On	Off	Off	Off	Off

*Tank 1 is for hot storage (~90°C), Tank 2 is for warm storage (~15°C) and Tank 3 is for cool storage (~9°C)

Table 1. Operational Modes for the Solar Heating and Cooling System Shown in Fig. 1

Cost of Electricity Inflation Rate, r_{elec} (%/year)	25-Ton Application Savings ($) (no tax incentives)	3-Ton Application Savings ($)		
		No Tax Incentives	25% Tax Rebate on Solar Capital Equip.	4% Loan Availability on Solar Capital Cost
0	1,000	(2,700)	(1,600)	(2,200)
3	2,800	(2,400)	(1,300)	(1,900)
6	5,000	(1,900)	(900)	(1,500)
8	7,100	(1,500)	(400)	(1,000)
10	9,700	(1,000)	100	(500)
12	12,800	(300)	800	200
14	16,700	600	1,700	1,100
16	21,700	2,700	3,800	3,200
20	35,700	5,100	6,200	5,600

Table 2. Results of Economic Analysis†

( ) indicates a negative value of savings, i.e., a loss

† Based on the economic and technical assumptions listed in Table 3 and the assumption that

$r_{general} = 1/2\, r_{elec}$

$r_{gas} = 1/4\, r_{elec}$

(r is the energy inflation rate)

Variable		3-ton	25-ton
AC_s	Capital cost of solar cooling subsystem	$4,500	$22,000
C_N	Capital cost of non-solar cooling subsystem	$1,500	$16,000
x	Percentage of first year operating costs	0.08	0.05
$C_{mc}-C_m$	Differential maintenance costs	-$50/year	0
L	Seasonal cooling load	63.3×10^6 kJ/year	528×10^6 kJ/year
C_{elec}	First year cost of electricity	5¢/kw-hr	5¢/kw-hr
f	Fraction of cooling load provided by solar	0.75	0.75
r_o	Inflation rate of operating costs	r_{elec}	r_{elec}
r_m	Inflation rate of maintenance costs	g	g
g	General inflation rate	6%/year	6%/year
T	Tax factor for deductible expenses	1	1-t
t	Effective income tax rate of owner	25%	25%
α	Downpayment fraction of first cost	20%	20%
β	Investment tax credit	0	10%
σ	Fractional salvage value at end of equipment life	0	20%
d	Annual discount rate	8%	12%
n	Period of economic analysis	20 years	20 years
i	Annual interest rate of loan	8%/year	8%/year
h	First year insurance rate on capital cost	0.5%	0.5%
m	Term of loan	20 years	20 years
r_f	Inflation rate for auxiliary fuel	$\frac{1}{2} r_{elec}$	$\frac{1}{4} r_{elec}$
r_f'	Inflation rate for non-solar fuel	r_{elec}	r_{elec}
p	First year property tax rate on solar system	0	0
k	Length of time for depreciation of solar equipment (use straight line depreciation)	NA	20 years

Table 3. Economic Assumptions

HYBRID ABSORPTION REFRIGERATION FOR SOLAR APPLICATIONS

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ABSTRACT

Most absorption refrigeration units must have a vapor compression unit in parallel for backup under marginal or night conditions. Furthermore, present absorption units extract no useful cooling work from heat source that is below the generator shut-off temperature even though it is theoretically possible to do so. The subject hybrid system offers a reliable, economical and lower operating cost alternative to conventional units. A compressor is placed between the evaporator and absorber and valved to allow operation in one of three modes: absorption, hybrid (combination of absorption and vapor compression) and vapor compression. In the hybrid mode, the generator shut-off temperature is drastically lowered, thereby allowing the extraction of useful cooling from a low temperature heat source. The use of a small amount of electrical energy by the compressor allows this extension of the useful operating range.

CLIMATIC CONSIDERATIONS

The design requirements of an integrated solar powered heating and cooling system vary widely from one climatic region to another. The worst of all cases is for the areas where available sunlight, the cooling and dehumidification load requirements are out of phase.

In the area that is generally west of the Mississippi Valley, the requirements for a solar powered cooling system are very much different than the requirements for a system in the region covering the Mississippi Valley and regions to the east.

The western half of the United States has many climatic characteristics that are common to any dry region of the world. Days are characteristically clear with high levels of solar radiation. Nights are generally clear and cool in the summer. The humidity is nearly always low. But most important, the solar radiation and the required cooling are in phase. For this western case, a solar powered cooling system requires no backup unit other than thermal storage and a standard absorption cooling unit with flat plate collectors is adequate.

For the eastern half of the United States, the climatic conditions are completely different. Days can be hot and overcast for lengthy periods with nights that are also hot and humid. The summer humidity is frequently high and the average solar radiation frequently can vary as much as 60 percent from one day to another. The problems of varying solar radiation, high dehumidification load, and a cooling requirement that does not vary in phase cause special problems for the designer of a solar powered cooling system. In fact, these conditions dictate that a backup system other than thermal storage be used.

2. DESCRIPTION OF THE CYCLE

At present, there is only one system that can deliver reliable cooling when used in conjunction with a reasonably sized array of flat plate collectors. That is the classical absorption refrigeration system with a standard vapor compression system in parallel for backup. This system is shown in block diagram in Figure 1at the end of the paper.

In this system, the available solar energy is delivered to the generator of the absorption cooling unit. If insufficient cooling is produced by the absorption unit, the vapor compression system provides the difference between the cooling demand and the cooling delivered by the absorption unit. The major fault of this system other than its high cost, is that it cannot extract useful cooling from any heat source below 71.1°C (160°F), even though it is theoretically possible to do so. At night or on overcast days when the storage tank temperature drops below 71.1°C (160°F), the solar driven absorption unit shuts off and all cooling must be supplied by the backup unit.

The proposed hybrid absorption cooling system is shown in block diagram in Figure 2. This system can operate in one of three modes: Absorption, combination of absorption and vapor compression, i.e., hybrid, and pure vapor compression. Figure 2 is at the end of the paper.

2.1 Modes of Operation

Solar Power Absorption Mode - The hybrid system will operate in a solar power absorption mode when sufficient radiant energy is available. Valves 1 and 4 are open, valves 2 and 3 are closed, the compressor is off, and the liquid solution pump is on and the system is operating in the pure absorption mode. Operation in this mode is identical to conventional solar absorption cooling devices. The generator operating temperature should be 190°F (87.8°C) or higher.

Absorption/Vapor Compression Mode - In the hybrid operational mode, valves 1 and 3 are closed, valves 2 and 4 are open, and both the compressor and liquid pump are operational.

In the hybrid mode, the evaporator temperature and pressure available to the absorber is much higher than the actual temperature and pressure in the evaporator. The resultant refrigerant concentration in the solution discharged from the absorber is much higher. This increased refrigerant concentration of the solution in the input to the generator drastically lowers the generator shut-off temperature. In this mode, the constant evaporator temperature and constant volume compressor will result in a compression ratio that changes with absorber conditions.

Vapor Compression Mode - In the vapor compression mode, vales 1, 2, and 4 are closed, valve 3 is open, the liquid pump is off and the compressor is on. In this mode, operation is identical to existing vapor compression systems.

Another configuration is possible if the compressor is added between the generator and condenser. However, in this configuration, disposal of the heat from compression and waste heat from the compressor motor must be accomplished in the condenser. The heat transfer coefficients of a superheated dry gas are very low. Since heat transfer in the absorber is limited by resistance to absorption in the liquid film and not by the heat transfer properties of the dry gas, disposal of waste heat from the compressor is much easier in the absorber than in the condenser. If the compressor is between the generator and condenser, the temperature, pressure and volume of the suction gas will vary over a wide range. This would present problems in properly cooling and lubricating the compressor that are not present in the configuration which places the compressor between the evaporator and absorber.

2.2 Fluid Pair Selection

The selection of the fluid pair to be used is influenced by the classical selection criteria for absorption refrigeration and compatability with the selected compressor. An absorption refrigeration apparatus can be built with any two fluids that have different boiling points. For a single effect absorption machine, that is, a machine with one absorber, condenser, evaporator and generator, the generator shut-off temperature is the same regardless of what fluid pair is chosen. Therefore, the following fluid pair selection criteria are used:

1. The pair must be chemically stable.
2. The pair must be able to contact all the exposed components of the compressor without electrical breakdown or corrosion.
3. The pair must be non-corrosive to common construction materials such as copper, steel or aluminum.
4. The pair must allow low construction cost; that is, no excessively large heat transfer surfaces and no extreme pressures should be involved.
5. The pair must allow a reasonable Thermal Coefficient of Performance in the absorption mode.
6. The pair must allow low pump work in the absorption mode.
7. The pair must allow a reasonable electrical Coefficient of Performance in the vapor compression mode.
8. The pair should be non-toxic.
9. The pair should be non-flammable.
10. The pair should be two reasonably common materials.

The performance of any fluid pair in an absorption refrigeration apparatus must ultimately be rated by three criteria. First, the ultimate Coefficient of Performance allowed by a fluid pair is shown in Equation (1):

$$C.O.P. = H_v/(H_v + Hd) \quad (1)$$

Where H_v = heat of vaporization of a unit of refrigerant
Hd = heat of dilution of that same unit of refrigerant absorbed

Second, the minimum pump work required for a given unit of refrigeration delivered:

$$W = V(\Delta P) \quad (2)$$

Where: V = volume of refrigerant rich absorber solution that must be pumped to the generator to deliver a unit of refrigeration
ΔP = press in generator - press in absorber

Third, the Recovery Heat Exchanger duty for each unit of refrigeration delivered:

$$R.H.E. = VP\ Cp\Delta T = M\ Cp\Delta T \quad (3)$$

Where: P = density of generator solution
Cp = heat capacity of generator solution
M = mass of generator solution
ΔT = temperature of generator - temperature of absorber

The classical approach to fluid pair selection has been to choose a refrigerant with a very high heat of vaporization and to choose a fluid pair that has a high heat of dilution. The effect of choosing a refrigerant with a heat of vaporization an order of magnitude above the heat of dilution is easily seen from Equation (1). The effect of a high heat of dilution is not so apparent. A high heat of dilution indicates a large negative deviation from Raoult's Law. A large negative deviation from Raoult's Law means that the solution has a much lower vapor pressure than would be predicted by Raoult's Law or that it takes a more concentrated

...on than predicted to yield the same vapor ...ure. This requires that the amount of absorber ...tion that must be circulated to produce a given ...t of refrigeration is lower than for a solution ...h deviation from Raoult's Law. This results ...ering both the required pump work in Equation, ...d the recovery heat exchanger duty in Equation ...multaneously.

...e present time there are several fluid pairs ...at popular among solar energy researchers. ...f these pairs are shown in Table I.

Refrigerant	NH_3	H_2O	NH_3	CHF_2Cl	CH_3NH_2
Absorbent	H_2O	LiBr	NaSCN	DETEG	NaSCN

TABLE I
Refrigerant - Absorbent Pairs

...f the pairs shown in Table I show large nega- ...e deviations from Raoult's Law. The first four ...s listed have been demonstrated to be ...mically ...le over a wide range of conditions. Any of ...e pairs could be used in a hybrid absorption ...rigeration device if a compressor compatible ...h that pair were available. The first three ...s listed in Table I would require the use of a ...l free compressor. The fourth pair, Freon 22 ...rbed into Dimethylether of Tetraethyleneglycol, ...d be used with a compressor requiring minimal ...l, such as the heli-rotor compressor.

...re the invention of the modern halocarbon re- ...erants, ammonia was used in vapor compression ...rigeration. The compressors used had oil flooded ...kcases. Since oil and ammonia are immiscible, ...e systems required the use of oil traps at ...us places in the system to trap oil that es- ...ed from the compressor and return it to the ...kcase. Any ammonia that entered the crankcase ...s vaporized and returned to the ammonia circula- ...n path. It is technically possible, but not ...tically feasible, to use such a compressor system ...h an ammonia/water absorption unit. Some oil ...d inevitably contaminate the absorber fluid and ...d have to be removed. Any system that trapped ...e oil to return it to the compressor crankcase ...d allow small amounts of absorber fluid to get ...o the crankcase. This absorber fluid would then ...difficult to remove from the crankcase because ...e water component could not be vaporized out of ...e crankcase at normal compressor temperatures and ...em pressures.

...milar problem would arise if Freon 22 were used ...h Dimethylether of Tetraethyleneglycol (DETEG) ...a compressor assisted absorption system. DETEG ...s a boiling point of 273°C (523°F) and is soluble ...compressor oil. It would therefore be impossible ...separate the compressor oil from absorber fluid ...d return each to their proper places in the ab- ...ption unit.

...s possible to use compressor oil as an absorber ...d since a variety of refrigerants are soluble ...l. However, the surface needed in the recovery heat exchanger and the power needed for the solution circulation pump would both be prohibitively large.

Oil free compressors and heli-rotor compressors are considerably more expensive than the common hermetically sealed piston compressor and refrigerant - absorbent combinations compatible with this compressor must be investigated. These fluid pairs must fulfill the first seven of the ten criteria listed plus the pair must allow removal of absorbent solution from the crankcase and the removal of compressor oil from the absorbent solution. One pair that is suited to these requirements is Freon 12 absorbed into Freon 113.

As was stated earlier, an absorption refrigeration device can be built with any two fluids with different boiling points. Furthermore, there is some advantage in choosing a fluid pair that little or no deviation from Raoult's Law and, therefore, little or no heat of dilution. Equation (1) shows how a fluid pair having little or no heat of dilution can allow a higher C.O.P, which in turn would allow a smaller collector to be used. The adverse effects resulting from the increased flow rate of absorber solution can be partially overcome by choosing an absorbent with a lower heat capacity and choosing a refrigerant with less pressure difference between the generator and observer. From Equation (2) it can be seen that a lower pressure difference has the same effect on pump work as a lower volume circulation rate. From Equation (3) it can be seen that a lower heat capacity has the same effect on recovery heat exchanger duty as a lower mass circulation rate.

However, Equation (1) does not completely describe thermal performance. When all factors are combined, Equation (4) results.

$$C.O.P = Hre - Hrc/(Hrg-Hra) + MCp\Delta T + Hd \qquad (4)$$

Where:
- Hre = heat content of one unit of refrigerant leaving the evaporator
- Hrc = heat content of one unit of refrigerant leaving the condenser
- Hrg = heat content of one unit of refrigerant leaving the generator assembly
- Hra = heat content of one unit of refrigerant leaving the absorber
- M = mass of absorber solution entering the absorber to absorb one unit of refrigerant
- Cp = heat capacity of absorber solution
- ΔT = temperature of solution entering the absorber - temperature of absorber
- Hd = heat of dilution of one unit of refrigerant when absorbed

One can easily see from Equation (4) that choosing a fluid pair with no heat of dilution can lead to increased thermal C.O.P. if the heat losses in the recovery heat exchanger are held to a minimum.

When Freon 12 absorbed into Freon 113 system is compared to ammonia absorbed into water under ideal conditions, the comparison in Table II results.

Given: 9072 Kcal/hr (3 tons) refrigeration
93.3°C (200°F) generator
32.2°C (90°F) absorber and condenser
4.4°C (40°F) evaporator
5.5°C (10°F) approach in the recovery heat exchanger

	NH_3/H_2O	F-12/F-113
RHE Duty	6300 Kcal/hr	16000 Kcal/hr
Pump Work	27.77 Watts	104.9 Watts

TABLE II
Comparison of Recovery Heat Exchanger Duty and Pump Work for NH_3/H_2O and F-12/F-113

Now compare Figure 1 and Figure 2. Note that both have one compressor and that the hybrid unit in Figure 2 has two less heat exchangers than the standard absorption refrigeration unit in parallel with a vapor compression unit shown in Figure 1. The area of the two additional heat exchangers is two times larger than the added area in the recovery heat exchnager of the hybrid.

Although the pump work done in the hybrid absorption system is 3.77 times larger than the pump work done by an ammonia absorption unit, the hybrid unit is able to utilize input temperatures that cannot be used by an absorption unit.

2.3 Performance Comparison of the Hybrid

The thermal and electrical performance for the hybrid system is shown in Table III and IV. The electrical power is calculated on the basis of ideal motors and no parasitic power. The relative power consumption shown in Table IV will increase for both cases when motor inefficiency and parasitic power are considered. However, the power consumption of the hybrid system will always be equal to or less than the power consumed by a conventional absorption and parallel vapor compression cooling unit.

Given:
1. Freon 12 absorbed into Freon 113
2. 3 tons constant output- 9072 Kcal/hr
3. Absorber and Condenser - 32.2°C (90°F)
4. Evaporator - 4.4° (40°F)
5. Approach in Recovery Heat Exchanger 5.5°C (10°F)
6. Super heat of Refrigerant leaving generator assembly - 11.1°C (20°F)
7. 80% approach to saturation in absorber

Generator Temp.	C.O.P. Thermal	Ideal C[illegible] Electric[illegible]
93.3°C (200°F)	0.715	[illegible]
82.2°C (180°F)	0.685	[illegible]
71.1°C (160°F)	0.672	25.3
60°C (140°F)	0.650	17.6
48.8°C (120°F)	0.628	11.3
Pure Vapor Compression		8.[illegible]

TABLE III
Thermal and Electrical Performance of the Hybr[illegible]

Given: Same Conditions as in Table III

Generator Temperature	Ideal Power Consumed (Watt[illegible]) Hybrid	Conventional Absor[illegible] and Vapor Compressi[illegible]
93.3°C (200°F)	167	167
82.2°C (180°F)	276	616
71.1°C (160°F)	417	1237
60°C (140°F)	599	1237
48.8°C (120°F)	901	1237
37.7°C (100°F)	1237	1237

TABLE IV
Power Consumption of a Hybrid Versus a Conventional Absorption Unit with Vapor Compression Backup

The fraction of rated cooling that is produ[illegible] solar power under various operating conditi[illegible] the hybrid and conventional systems is show[illegible] Table V.

Generator Temperature	Hybrid	Conventional Abso[illegible] With Vapor Compre[illegible] Backup
93.3°C (200°F)	1.000	1.000
82.2°C (180°F)	0.911	0.6369
71.1°C (160°F)	0.7967	0
60°C (140°F)	0.6481	0
48.8°C (120°F)	0.3861	0

TABLE V
Solar Contribution to Total Cooling

..CLUSIONS

..ly, there is only one reasonable method to .. reliable solar powered cooling with flat ..ollectors. That method is to put an absorp- ..efrigeration unit in parallel with a vapor ..ssion unit as is shown in Figure 1. It is ..clear that the hybrid absorption cooling unit ..re 2 is a reasonable and more economical ..ative.

..LIOGRAPHY

..ton, R. T., Kurst, G., Peck, R. E., Reed, .. F., Research Bulletin No. 14, The Absorption ..ing Process. Chicago: Institute of Gas ..nology, 1957.

..lerth, John F., Albright, Lyle F., Solubility .. Mixtures of Refrigerants 12 and 22 in Organic ..lvents of Low Volatility. Portland, Oregon: ..RAE Paper, July 5-7, 1965.

.., D. J., Development of a Solar Powered Resi- ..ntial Air Conditioner. Cape Canaveral: NASA ..tract NAS8-30756, Chrysler Corporation Space ..ivision, March, 1976.

..ss, Robert A., Selecting Refrigerant-Absorbent ..uid Systems for Solar Energy Utilization. ..llas, Texas: ASHRAE Paper, Institute of Gas ..chnology, February 1-5, 1976.

.., Robert, H., Chilton, Cecil H., Perry's ..emical Engineers' Handbook. New York: McGraw ..ill, Fifth Edition.

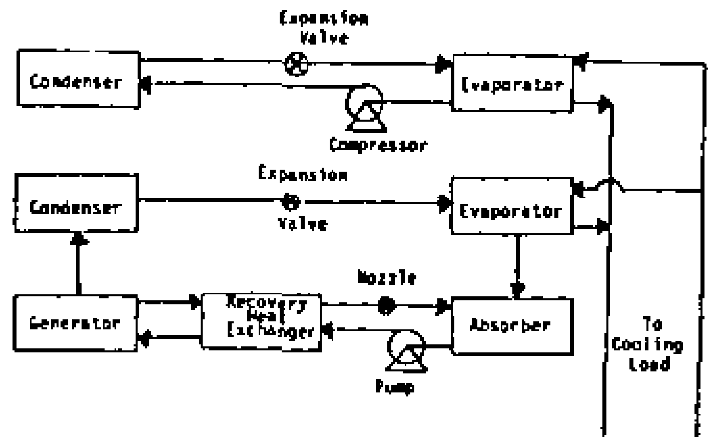


Figure 1. Conventional Solar Absorption Air Conditioner

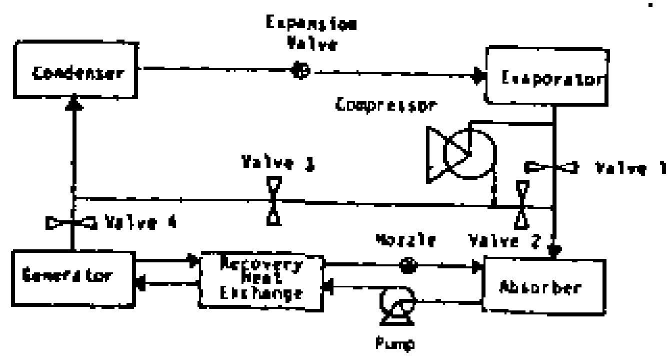


Figure 2. Hybrid Absorption Cooling System

PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

OIL POLITICS IN THE 1980'J PATTERNS OF
INTERNATIONAL OYSTEIN NORENA

MC. GRAW-HILL NY. NY. 1978

AGOSTO, 1979

he international oil companies continued to express their fears over unprecedented rice rises, as t[illegible]ad done before the crisis erupted. But their very ability to distribur upplies more [illegible]ss adequately during the early months of the crisis, from October, 1973, to the end of the year, blunted the effects of their expressions of concern. American public opinion tended to see the oil crisis primarily as a maneuver of the companies hemselves, not so much as a threat by the Arabs. A preoccupied President continued to oncern himself with Watergate. An involved Secretary of State worked around the lock on peacemaking efforts. Anti-environmentalists saw the crisis as a blessing in heir war against the Sierra Club and its allies; environmentalists and conservationists aw high prices as a boon in discouraging oil consumption; independent oil companies aw the crisis as an opportunity to counterattack the majors; tax reformers saw it as a hance to end certain provisions that benefited the major oil companies abroad.

The inability to shift course rapidly was not confined to the United States alone. In many countries, the crisis was seen by various groups as an opportunity to promote any cause that the situation seemed to serve, whether that cause was in fact related to the crisis or not. Tsurumi points out that, in Japan, MITI (the Ministry for International Trade and Industry) used the crisis as a peg for bolstering its waning power to control the Japanese economy. In France, the crisis provided a platform for independent political action in the Arab world, action that had only a partial relation to the oil issue itself. In Britain and Norway, governments cast an eye to their future in the North Sea, cautiously asking themselves what precedents they might be setting that would embarrass them when they themselves became major oil exporters.

So it was business as usual on the political front, at least in the short run. If any effective reaction to the crisis was to be expected from the rich oil-importing countries, a good deal more time would be needed. Indeed, it would be late 1974 or even early 1975 before the full gravity of the crisis would begin to be reflected in governmental policies.

Part 2: THE CRISIS

JOEL DARMSTADTER AND HANS H. LANDSBERG

The Economic Background

Introduction

THIS PAPER ADDRESSES THE QUESTION: What major developments in the energy fiel and particularly in oil, predisposed the world economy to the shocks to which it h been subjected since the end of 1973? By "shocks," we have in mind, first of all, t drastic rise in world oil prices and, second, the intimation (based partly on what ha pened during the October, 1973, war and partly on subsequent OPEC actions ar pronouncements) that supply would be manipulated to maintain the new level prices and for other ends.

The answer has both economic and non-economic components. In essentially ec nomic terms, it comes down to asking what factors on the energy-demand and energ supply sides provided a receptive setting for the actions of the producer cartel. In i non-economic—and largely political—aspect, it comes down to asking what policies the Arab-Israeli conflict (and perhaps with respect to other issues as well) made for th cohesiveness that was necessary not only for the implementation of the embargo bu looking beyond that short-term disruption, also for the degree of bargaining effe tiveness that, on purely economic grounds, could not have been predicted on the bas of previous efforts at cartelization.

This paper, however, deals exclusively with the economic component—that is, surveys those world-wide developments that seemed to render the major oil-consumin countries susceptible to the supply and price pressures that began late in 1973. We c not point to such developments as sufficient by themselves to account for the crisis, f we make no pretense either of exhaustiveness or of knowing how the behavior of th producers might have shifted had a different set of economic circumstances prevaile Our exercise does not even permit a quantitative "feel" for how much of the supp and price crisis has its roots in the developments we will recount. All we suggest is th the phenomena we will review contributed significantly in setting the stage for th events of 1973 and 1974, and that, to the extent that these phenomena are recurren they represent enduring issues. Their consideration and discussion are therefore nece sary for an appraisal of the shape of things to come. Above all, we find it important stress that an "energy crisis" was developing, that both decision-makers and the publ were aware that it was long before the October, 1973, war, and that many of th factors singled out below were combining toward a new constellation of forces in wo ıergy. The embargo and the ensuing price revolution brought to an early and violent oil what probably was inevitable in the longer run, but what might have been more anageable at lower temperatures and with greatly attenuated disturbances.

Several fairly distinct trends on the world energy scene helped create the climate in hich the producer-country actions of 1973-74 could bear fruit. These trends revolve, their physical manifestation, around the growth in overall energy consumption, the sing share of petroleum within the total, and, in turn, the steadily rising share—al-ady high in the early nineteen-sixties—of Eastern Hemisphere (particularly Persian ulf and North African) oil in accommodating that rise in oil consumption. In general, number of these trends accelerated more rapidly than had been anticipated. Con-irrently with the growing dependence on energy from this concentrated geographic gion, major changes benefiting the producer countries were occurring in oil-pricing ıd in the financial relationships between the companies and their host governments. he resulting increases and, especially, the prospective accumulation of revenues made possible at least for the principal exporters to contemplate slowdowns or even cut-icks in production without adversely affecting—and perhaps even benefiting—their onomies. Finally, a comfortable reserve-production situation *globally* tended to ob-ure the political, economic, and distributional aspects of converting these reserves into pplies where and when needed, while at the same time removing urgency from the velopment of alternative sources of energy.

Table 1

WORLD ENERGY CONSUMPTION AND POPULATION, SELECTED YEARS, 1925-72

	Total energy consumption[a]			*Energy consumption*[a] *per capita*
	10^{12} Btu	10^6 barrels/day oil equivalent	*Population* (million)	(10^6 Btu)
ı25	44,249	21.6	1,890	23.4
ı50	76,823	37.5	2,504	30.7
ı60	124,046	60.5	2,990	41.5
ı70	214,496	104.7	3,609	59.4
ı72	237,166	115.7	3,747	63.3
	Average annual percentage rate of change			
ı25-50		2.2	1.1	1.1
ı50-60		4.9	1.8	3.1
ı60-72		5.5	1.9	3.5

[a]One barrel of crude oil has a heat content of about 5.6 million Btu. Therefore, 1 million barrels a day uals approximately 2,044 trillion (= 10^{12}) Btu per year. Oil consumption is sometimes also expressed in tric tons per year and energy consumption in metric tons oil-equivalent per year. Since 1 ton of crude [illegible] to about 7.3 barrels, 1 million barrels a day equals approximately 50 million tons a year. From foregoing approximate calorific equivalents, we can then derive an additional one: 1 million tons of oil uals approximately [illegible] trillion Btu.

[illegible] Darmstadter and Schurr, "The World Energy Outlook to the Mid-1980's: [illegible] Alternative Supply Path [illegible] the United States," *Philosophical Transactions*, 276 ([illegible] London, 1974).

Trends in Aggregate Energy Consumption[1]

By 1972, world-wide energy consumption had reached an estimated level of 237 quadrillion Btus—representing, in more familiar terms, the equivalent of 116 million barrels a day of petroleum (see Table 1). The rate of energy-consumption growth appears to have been accelerating throughout much of the twentieth century: from 2.2 per cent between 1925 and 1950 to a postwar rate of nearly 5 per cent annually, rising during the most recent decade to about 5½ per cent. While the more recent change in rate may not seem dramatic, one must realize that, at the aggregate consumption levels prevailing in 1970, each tenth of a percentage point of consumption was equivalent to over one million barrels a day, compared to slightly over half a million a decade earlier—that is, acceleration by even a fraction of a percentage point represented a substantial amount.

At 2 per cent per annum population growth, the aggregate energy growth rate of 5½ per cent during 1960-72 meant a yearly growth in per capita energy consumption of approximately 3½ per cent. The worldwide average spanned a range of per capita energy-growth rates, varying from around 3 per cent in the United States to over 10 per cent in Japan, with a number of regions clustered in the 4 to 5 per cent growth-rate bracket. But regional differences in the *level* of per capita energy use, while narrowing, have remained dramatically wide. In 1970, per capita energy consumption in the United States and in Canada—which was only slightly lower—was more than two and one-half times the level of the next ranking regions—Western Europe, the Soviet Union, and Oceania. An even more extreme disparity is reflected in the fact that North American per capita consumption was between thirty and forty times the levels prevailing in Africa and the developing portions of Asia.[2]

To be sure, trends and levels in per capita energy consumption are not proxies for per capita income or gross national product; nor are the latter measures, in turn, truly reflective of living standards, however defined. Nonetheless, while recognizing clearly the potential for considerable energy savings of a sort that would not inhibit economic aspirations, the existence of such disparities, coupled with a close—if not fixed—correspondence between levels of per capita energy consumption and general economic development, has an important implication for the future: the drive toward a substantial improvement in living standards in the years ahead will exert added claims and growing burdens on world energy supplies.

In the early seventies, an almost unprecedented concurrence of boom conditions prevailed in North America, the European Community, and Japan. Growth rates of real GNP were at peak levels in the two years preceding the oil crisis. For the developed countries as a whole, real GNP rose as follows between 1970 and 1973:[3]

1969-70	3.2
1970-71	3.6
1971-72	5.5
1972-73	6.3

Especially [illegible] was th[illegible] of growth rate [illegible] diately preceding the crisis. For example, [illegible] the change from [illegible]

+10.3 per cent in Japan, but −0.4 per cent in the United States, between 1972 and 1973, and especially during the first three quarters of 1973, rapid expansion in the industrial coun[illegible] coincided. For the year 1973 as a whole, these were the individu GNP growth rates of the major areas:

United States	5.9%
Western Europe	5.4%
Japan	10.4%

Many industries worked at increasingly high rates of capacity utilization; some energy-intensive primary industries in the United States operated at rates approaching 100 per cent in 1972 and into 1973. The near-capacity utilization of industrial facilities can be illustrated by data for the United States compiled by the board of governors of the Federal Reserve System. The index of capacity utilization in materials industries (ranging from steel and copper to paper and fibers) reached 96 per cent in the third calendar quarter of 1973 and averaged 95 per cent for the year as a whole. "For much of 1973," says the *Federal Reserve Bulletin* of January, 1974, "basic materials-producing industries were operating at rates higher than at any other time in the postwar period." Similar conditions seem to have prevailed abroad. Such high utilization rates necessarily involve the operation of less efficient equipment and a strain on the supply capacity of both materials industries and energy suppliers. In Japan, for example, fuel consumption by manufacturing industries in October, 1973, was nearly 30 per cent above the monthly level for calendar 1972; while, for the same month, the rate of capacity utilization in manufacturing stood at a remarkable 102 percent.*

Shifts Among Energy Sources to Meet Demand

Table 2 provides a picture of postwar shifts in the role of the different energy sources to supply the rapidly rising demand documented above. A sharp relative decline of coal and marked relative increases in both oil and gas characterize the period. The latter two sources accounted for 38 per cent of world-wide energy consumption in 1950, but had risen to 64 per cent in 1972; concurrently, coal experienced a relative decline, from 56 to 29 per cent. The primary electricity share—hydroelectricity along with a thus-far modest but rising nuclear component—remained essentially unchanged.

With variations, these shifts occurred throughout the world, as can be seen in Table 3. In no area did the share of coal fail to decline. In most areas, the share of oil and natural gas was higher in the early nineteen-seventies than in 1950 and, more often than not, substantially or radically so. Only in two regions—Eastern Europe and China—did coal continue to contribute more than half of total energy consumption in recent years. In Western Europe, there was a sharp decline in coal's relative share from over three-fourths to a little over one-fourth in the short span of less than two decades, and its absolute use declined as well. Concurrently, the share of oil and gas went from

Table 2

World Energy Consumption: Distribution by Sour[illegible] 0-72

	1950	1960	1965	1968	1970	1971	1972
Aggregate consumption (10^{15} Btu)	76.8	124.0	160.7	189.7	214.5	223.5	237.2
			Per cent shares				
Coal	55.7	44.2	39.0	33.8	31.2	29.9	28.7
Oil	28.9	35.8	39.4	42.9	44.5	45.2	46.0
Natural gas	8.9	13.5	15.5	16.8	17.8	18.3	18.4
Primary electricity*	6.5	6.4	6.2	6.5	6.5	6.6	6.9
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Average annual percentage rates of increase

	1950–60	1960–72
Coal	2.5%	1.8%
Oil	7.1	7.8
Natural gas	9.4	8.3
Primary electricity	4.8	6.2
TOTAL	4.9	5.5

*Comprised of geothermal, nuclear, hydro. For 1972, the 6.9% figure in the table broke down approximately as follows: geothermal, 0.03; nuclear, 0.7; hydro, 6.2

Source: Same as for Table 1.

15 to 62 per cent. Japan's energy patterns underwent similarly dramatic shifts. The Soviet picture is highlighted by a big postwar rise in the share of natural gas.

Changes in the American pattern were different, but eventually aggravated those noted above. The early emergence of oil and, subsequently, of gas had resulted in important shares for these fuels in the country's total energy consumption far ahead of most other regions. The proportion of oil in United States energy consumption rose rather modestly between 1950 and 1970, with the sharply declining relative position of coal being principally compensated for by increases in the use of natural gas. However significantly for the 1973 events (and discussed more fully below), in the past several years United States oil consumption has advanced at a disproportionately fast rate, as gas output leveled off, power-station coal utilization encountered tight environmental constraints, and oil demand in the transport sector accelerated. The significant factor in the American situation is thus not the sharp shift to oil and gas in the past two decades but rather the recent acceleration in oil demand and the meeting of this increased demand not from indigenous but from foreign sources.

Table 3

DISTRIBUTION OF ENERGY SOURCES FOR MAJOR REGIONS, 1950 AND 1970
(percentage except for Btu columns and row)

	1950						1970					
	coal	oil	natural gas	primary electricity	total %	total 10^{15} Btu	coal	oil	natural gas	primary electricity	total %	total 10^{15} Btu
North America	38.0	38.7	16.7	6.4	100.0	16.86	18.3	45.7	32.1	6.0	100.0	74.48
Canada	40.6	28.6	2.8	27.9	100.0	2.71	9.6	41.3	26.9	22.2	100.0	7.04
United States	37.8	19.5	18.0	4.7	100.0	14.15	19.1	43.9	32.7	4.3	100.0	67.44
Western Europe	77.4	14.1	0.3	8.0	100.0	17.48	27.4	55.6	6.1	10.8	100.0	47.87
Oceania	65.3	27.3	—	7.4	100.0	0.89	39.8	48.6	2.2	9.3	100.0	2.45
Latin America	9.8	72.9	8.3	9.0	100.0	2.40	4.9	67.8	18.4	8.8	100.0	9.15
Asia (excl. Comm.)	53.3	28.3	1.4	16.9	100.0	3.80	21.3	64.1	6.2	6.4	100.0	20.82
Japan	61.9	5.0	0.2	32.9	100.0	1.74	22.4	68.8	1.3	7.5	100.0	11.26
Other Asia	46.0	48.3	2.4	3.3	100.0	2.06	24.3	58.7	11.8	5.2	100.0	9.56
Africa	61.4	36.9	—	1.7	100.0	1.30	43.5	48.7	1.5	6.2	100.0	3.68
U.S.S.R. and Comm. Eastern Europe	81.4	14.6	2.3	1.7	100.0	12.84	49.6	28.7	18.5	3.1	100.0	44.76
U.S.S.R.	75.6	19.7	2.5	2.3	100.0	8.43	40.4	33.3	22.5	3.8	100.0	31.99
Eastern Europe	92.5	4.8	2.0	0.7	100.0	4.41	72.7	17.4	8.4	1.5	100.0	12.76
Communist Asia	92.8	0.9	—	6.3	100.0	1.25	89.4	8.2	NA[a]	2.4	100.0	11.30
WORLD: per cent	55.7	28.9	8.9	6.5	100.0	76.82	31.2	44.5	17.8	6.5	100.0	214.50
WORLD: 10^{15} Btu	42.80	22.20	6.82	5.00			66.90	95.48	38.21	13.91		

[a] The U.N. shows no figures on China's natural-gas production and consumption. A recent analysis puts China's natural-gas production at 0.4×10^{15} Btu in 1965 and 1.2×10^{15} Btu in 1971 (C.S. Chen and K.N. Au, "The Petroleum Industry of China," *Die Erde*, 1-4 (Berlin, 1972), p. 319. Such a quantity would clearly raise the estimate of China's energy consumption — shown above — quite markedly. Another estimate (*Oil and Gas Journal*, August 20, 1973) credits China with only about 20% of this amount of gas output.

Source: Same as for Table 1.

The Growth of Oil Imports

The increasing dependence on oil as the "balancing" element in meeting United States energy demand is reflected in substantially expanded American oil imports dur-

Table 4

ENERGY CONSUMPTION, OIL CONSUMPTION, AND OIL IMPORTS: UNITED STATES, WESTERN EUROPE, AND JAPAN, 1962 AND 1972

	1962			1972		
	United States	Western Europe	Japan	United States[c]	Western Europe	Japan
	10^6 barrels per day					
Energy consumption (oil equivalent)	23.27	15.96	2.25	35.05	23.84	6.58
Oil consumption	10.23	5.24	0.96	15.98	14.20	4.80
Oil imports[a]	2.12	5.19	0.98	4.74	14.06	4.78
From Middle East/ North Africa[b]	0.34	3.80	0.72	0.70	11.30	3.78
From elsewhere	1.78	1.39	0.26	4.04	2.76	1.00
	Percentage of energy consumption					
Oil consumption	44.0	37.5	42.7	45.6	59.6	73.0
Oil imports[a]	9.1	37.2	43.6	13.5	59.0	72.6
From Middle East/ North Africa[b]	1.5	27.2	32.0	2.0	47.4	57.4
From elsewhere	7.6	10.0	11.6	11.5	11.6	15.2
	Percentage of oil consumption					
Oil imports[a]	20.7	99.0	102.1	29.7	99.0	99.6
From Middle East/ North Africa[b]	3.3	72.5	75.0	4.4	79.5	78.6
From elsewhere	17.4	26.5	27.1	25.3	19.4	20.9
	Percentage of oil imports					
From Middle East/ North Africa[b]	16.0	73.2	73.5	14.9	80.4	78.9
From elsewhere	84.0	26.8	26.5	85.1	19.6	21.1

[a] Imports are "gross" rather than "net"; that is, exports are not deducted. Thus, they exclude product exports from West European refineries. For Japan, excess of imports over consumption arises because of small quantities of product exports, refinery losses, and (presumably) independent construction of the two series. By showing gross rather than net imports, we overstate slightly the degree of foreign dependence. The overstatement matters, if at all, only in the case of Western Europe.

[b] Includes negligible quantities from West Africa in 1962.

[c] For changes in the U.S. import situation after 1972, see accompanying text re...

Sources: Data for 1962 based on Joel Darmstadter et al., *Energy in the Wo*... 1971), and British Petroleum Co. ... *of the World Oil Industry* ... 1972 based on British Petroleum Co., *Stat*... *of the World Oil* ...

ing the past ten years (Table 4). Rising from 2 million barrels a day in 1962 to near[l]y 5 million b[arrels] a day in 1973—or at a growth rate of 8½ per cent per year—import share [of] United States oil consumption has gone from 20 to 30 per cent, and just before the October, 1973, war was running at close to 35 per cent. Nonetheless, as a share in aggregate national energy consumption, American oil imports stand far below comparable levels elsewhere. In Western Europe, oil imports went from 37 per cent of total energy consumption in 1962 to nearly 60 per cent in 1972; in Japan, from 44 to 73 per cent; while, for the United States, the increase was from 9 to 13 per cent. Even so, the high absolute level of United States energy consumption and the pervasive role of oil in transportation make even this relatively small increase a substantial one in the face of supply difficulties.

For Western Europe and Japan, the dominance of the Middle East and North Africa as suppliers of oil, coupled with the importance of oil in West European and Japanese energy consumption, has meant that these two producing areas have come to occupy a crucial role in the *total energy* position of the consuming areas: 47 per cent for Western Europe and 57 per cent for Japan in 1972.

Traditionally, American oil imports have come in the main from Caribbean and Canadian sources, the Persian Gulf-North African region having maintained an approximately constant share of around 15 per cent of American oil imports (and 3 to 4 per cent of American oil consumption) during the period from 1962 to 1972. However—and this is not brought out in the 1962 and 1972 comparison on Table 4—it has now become clear that, because Canadian and Venezuelan expansion possibilities are at best severely limited, further additions to United States imports must bank heavily on Eastern Hemisphere supplies, particularly from Saudi Arabia, but from other Arab and non-Arab suppliers (Iran, Nigeria), as well. Indeed, during the period June-October, 1973, American crude-oil and oil-product imports coming directly from the *Arab countries only* already amounted to an estimated 1.3 million barrels a day, representing 8 per cent of oil consumption and 19 per cent of oil imports for the United States; if one adds imports indirectly traceable to Arab countries,[3] the respective figures for this mid-1973 period become 10 per cent and 25 per cent.[4] With the inclusion of Iran, the entire Middle East-North African region would figure more prominently still—a minimum of 12 per cent of consumption and 30 per cent of imports.

Contemplation of the continued world-wide shift to imports from the Middle East-North African oil fields during the past decade and the more recent American changes just noted may shed a different light on what has been judged by at least some as a panicky and submissive response to producer-country moves during 1973–74. It may instead reflect this prominent characteristic of acute dependency in world oil flows.

The Past Misreading of Future Trends

None of the three principal lines of development sketched above—the rapid growth of world energy consumption as a whole, the continued shift toward oil everywhere, and the rapidly rising volume of American oil imports—was adequately anticipated in the succession of energy projections that have appeared since around 1960. The review of forecasts summarized in Table 5 is designed merely to convey an impression of the

Table 5

Review of Selected Past Energy Consumption Pr[oje]ctions

Region	Actual Data[a]: Period	Actual Data[a]: Average annual growth rate (%)	Projections: Source	Projections: Year published	Projections: Period	Projections: Average annual growth rate (%)
		Total energy consumption				
World	1960-70	5.6	(A)	1966	1960-70	4.6
					1970-80	4.8
			(B)	1966	1960-80	5.0
Western Europe	1960-70	6.3	(C)	1960	1955-75	2.8
			(A)	1966	1960-70	4.4
					1970-80	4.0
			(B)	1966	1964-70	4.2
					1970-80	4.1
United States	1960-70	4.2	(D)	1963	1960-70	2.9
					1970-80	2.8
			(A)	1966	1960-70	3.6
					1970-80	3.3
Japan	1960-70	11.9	(A)	1966	1960-70	9.1
					1970-80	7.0
			(B)	1966	1964-70	10.0
					1970-80	6.9
		oil consumption				
Western Europe	1962-72	10.5	(B)	1966	1964-80	4.1[b]
United States	1962-72	4.6	(A)	1966	1960-70	3.5
					1970-80	2.7
			(E)	1971	1965-75	3.4
					1975-80	2.9
			(F)	1968	1965-80	3.1
Japan	1962-72	17.5	(B)	1966	1964-70	14.3
					1970-80	8.3
		oil imports				
United States	1962-72	8.4	(F)	1968	1965-80	3.2
			(E)	1971	1965-75	3.5
					1975-80	2.6
			(A)	1966	1960-70	4.4
					1970-80	4.2[c]

Note: Differences in definitional practices among the various projection studies impairs exact comparison, even of growth rates.

[a]From Table 8, Darmstadter and Schurr, "The World Energy Outlook to the Mid-1980's," cited in Table 1.

[a]Highest of range shown in source (B).
[b]Midpoint of range shown in source (A).
urces: (A) European Coal and Steel Community, *Review of the Long-Term Energy Outlook of the European Community*; (B) O.E.C.D., *Energy Policy*; (C) O.E.E.C., *Towards a New Energy Pattern in Europe*; (D) Hans H. Landsberg, Leonard L. Fischman, and Joseph L. Fisher, *Resources in America's Future* (Baltimore); (E) Sam H. Schurr, Paul T. Homan, and associates, *Middle Eastern Oil and the Western World: Prospects and Problems* (New York); (F) U.S. Department of the Interior, *United States Petroleum Through 1980*.

ıds of efforts undertaken. It makes no claim to being comprehensive; a detailed anal-s comparing the different projection studies as well as a comparison between the pro-tions and actual performance cannot be adequately undertaken here.

This said, the degree of underestimation disclosed by the table is still worth ponder-. As we might expect, there is less error in total energy projections than in the pro-tions for oil only. But even for the total, the projections have been markedly con-vative. For example, even though Western Europe's economic growth rate in the ties had been forecast quite accurately, its energy growth noticeably outstripped ex-tations. For Japan, the continuation of the postwar economic boom, carrying energy owth with it, surprised people by its unbroken momentum. In the United States as ll (its experience is dissected in some detail elsewhere[7]), the progressively declining ationship, observed for at least four decades, between energy growth and GNP owth did not, contrary to expectations, endure into the latter part of the sixties. nong the things not foreseen were the halt to fuel-efficiency improvements in the nerican electric-power sector and the acceleration in demand for motor-vehicle ls, based not only on rapid growth of the vehicle population, but also on less efficient l use, which in turn was the result of heavier cars, added "extras" such as air condi-ning, higher speeds, and urban congestion.[8]

Fairly gross misjudgments, also evident in Table 5, were made with respect to the e of oil in Western Europe's energy balance and of American oil consumption and ports. In the case of Western Europe's oil consumption, one source of error seems to ve been that projections—for example, the 1966 OECD study, *Energy Policy*—al-ted for a far greater, though not expanding, role for coal between 1964 and 1970 n actually emerged. The OECD envisaged West European solid-fuel production at ween 410 and 440 million coal-equivalent tons in 1970. In fact, 378 million tons re produced—a "slippage" equal to (on the basis of the midpoint projection) 700 usand barrels a day of oil, or 6 per cent of oil imports for that year. With respect to l, the 1966 OECD study was only the latest in a succession of projections that failed anticipate the rapidly shrinking role of the West European coal industry. Since im-ted-oil prices were decisively competitive with European coal throughout most of [illegible]-fifties and -sixties, this failure was not so much one of economic miscalcu-[illegible] as of misreading the governments' policy intentions regarding the scale of sup-[illegible] for the coal [illegible]ry. But even apart from the extent to which oil (in power gen-[illegible] ailed the incremental demand that coal had been anticipated to [illegible] oil in non-substitutable uses also progressed at a buoyant clip. In the six-nation Common Market area, for example, the demand for automotive fuels advanced at 10 per cent annually throughout the sixties.

The misjudging of the future role of oil imports in relation to domestic supplies applies only to the United States; neither Europe nor Japan was expected to be a significant producer for the period under consideration. As for the United States, the conventional assumptions had been two. The first was that government import controls could hold the import share to a constant percentage. Instead, these provisions were frequently revised, and the import-control program became so eroded that it collapsed entirely shortly before the events of 1973. It should, however, be noted that even those who were calling for an end to the import-control program did not anticipate a staggering rise in imported oil. Consider the relaxed views expressed by the staff of the United States Cabinet Task Force on Oil Import Control as "late" as the beginning of 1970: "Because demand is growing faster than domestic supply, imports would have to expand by 1980 at the present [i.e., 1970] $3.30 price, and by then could amount to about 27 percent of our demand at that price."[9] In fact, as we have already noted, oil imports had already reached a rate of 35 per cent on the eve of the October, 1973, war.

The second assumption was that large unexplored and unexploited areas, onshore and especially offshore, were waiting for the drill and would supply the incremental quantities to meet rising demand. In fact, however, exploratory and developmental activities in the United States declined, as the industry channeled its funds into overseas ventures that were less beset by constraints and generated higher yields in both oil and profits.

Words of alarm from oil interests regarding the lagging domestic effort failed to strike a responsive chord among persons long turned cynical to what they viewed—rightly or not—as special pleading and poor-mouthing by an apparently prosperous industry. Unfortunately, the same plea (greater financial incentives) could equally well be read as an expression of need for capital to sink into further exploration and development, or as solely a desire for enhanced rates of return. Oil companies have not often been given the benefit of the doubt on this proposition.

Insight through hindsight is appealing. Perhaps the forecasters had shut themselves off too much from the real world—and particularly the political world—when they made their assumptions. For, in addition to erring in economic premises, most planning efforts did not appear to have taken sufficiently seriously threats by the Arab governments to use oil as a political weapon as well as to hold back output for what—to the governments, at least—may have seemed a proper means toward income maximization. Popular recognition that a crisis was approaching and acceptance of the necessity for belt tightening and for policies to expand domestic energy resources to counteract it could not easily have been won in this climate.

Oil Prices and Producer-Country Policies

At the same time that snowballing [illegible] nd concentration [illegible] ports and on the Middle East [illegible] ure to price [illegible] during the latter part of the sixties continued to grow very rapidly. Real prices of oil in the early seventies had declined, and they remained below their level in the fifties and middle sixties, thus exerting no pressure toward conservation; nor did falling prices create a climate in which public conservation policies could be instituted or, if instituted, be effective. Concurrently, a leveling off in domestic output of oil and gas and partial restrictions on the use of coal led to the need for rapidly rising imports, made feasible by the abandonment of remaining import controls.

To judge the significance of this emerging foreign component of the American energy supply, we need to note that in the early nineteen-seventies oil accounted for around 40 per cent—and, combined with natural gas, for about four-fifths—of United States energy consumption. At the same time as domestic production of both oil and gas had flattened out in the wake of declining levels of exploration and, consequently, declining reserve levels (see Table 7), consumption of oil—the balancing energy source in times of demand pressures—accelerated. Several factors were responsible. For one, oil was rapidly supplanting coal as a power-plant fuel. Having reached a low of 6 per cent as its share in utility fuels in the mid-sixties, oil's share had unexpectedly risen to nearly 16 per cent by 1972, largely on the basis of the high cost or nonavailability of low-sulfur steam coal. To illustrate, in New England, electric utilities had burned 9 million tons of coal as recently as 1966. By 1972, they had reduced their coal consumption to 1.3 million tons, and this happened during a period of steadily rising power generation. Oil made up for both the decline in coal and the rise in power generation. In the Middle Atlantic states, the absolute volume of coal burned remained constant, but oil, and to a much smaller extent, nuclear power, supplied the growth increment. Nationwide, coal had provided the same share of electric generating fuel in 1972 as it had, say, in the mid-sixties, 1.1 million barrels of oil per day would have been "saved," representing some 7 per cent of United States oil consumption or 23 per cent of oil imports in that year. In the main, environmental restrictions operated against the use of coal and foreclosed that possibility; but one must also note that the coal industry had generally been "written off" as declining, that it had severe manpower problems, difficulties in raising capital, and generally showed many signs of being a depressed industry. Environmental problems, both in mining and combustion, greatly aggravated the picture.

The late sixties also witnessed a largely unanticipated burgeoning demand for motor gasoline. This demand rose by 2.8 per cent yearly between 1960 and 1965. After the mid-sixties, it accelerated to more than twice that rate. Continuation of the lower, 1960-65 growth rate would have "freed" another 630,000 barrels of oil per day in 1972—another 4 per cent of American oil consumption, or 13 percent of oil imports. Though much cited as one of the reasons for this development, reduction of automotive efficiency due to pollution control is probably a minor cause when compared with steadily increasing car weight, large engine size, rapid spread of air conditioning, and other extras that lessened fuel efficiency. Failure of annual mileage per vehicle to decline, as had been anticipated by some as a result of more two- and three-car families, is still another. In any case, the high gasoline requirement of large horsepower cars certainly goes far to explain the high *level* (even if it is only one of the reasons for the high *recent growth rate*) of American oil consumption, and, importantly, there appears to have been little anticipation of the compound effect of these elements on gasoline demand.

One could cite still other factors contributing to the tight American oil situation. A halt to the expansion of natural-gas output, not unconnected with the controversies over continued regulation of the natural-gas price, may have added 1½ million barrels per day to 1973 oil demand. The nonavailability of oil from the Alaskan North Slope and from the Santa Barbara Channel, as well as the delay in offshore operations in general, may have "subtracted" about 2 million barrels per day from potential current production. Finally, nuclear power plants were being constructed at a rate considerably below the level foreseen just a few years earlier, owing to design and construction problems, opposition on grounds of safety and environmental hazards, and cumbersome, time-consuming licensing procedures. Various combinations of these possible, but problem-ridden, supply sources would in all likelihood have greatly diminished the level of import dependence the United States was experiencing when the Middle East war began.

Attempts to cope with these problems substantially preceded the war, but, both before and since, short-run success by way of market adjustments has been limited. In the case of natural gas for space and process heat, for example, it is not easy to switch quickly to substitute energy forms. Redesigning automobiles for greater fuel efficiency runs into resistance from manufacturers and from a not insignificant segment of consumers, given the tradeoffs in size and comfort. In a more general sense, demand restraint is not assured unless energy price increases are of such magnitude that demand is suppressed at the cost of increased unemployment and industrial dislocation.

On the supply side, the regulatory lag inherent in federal controls over natural-gas prices insured sluggish action and sluggish production responses. Productive capacity (as in the case of refineries) is not rapidly expandable; accelerated leasing and new reserve development pay off only after a lag of, say, three or four years, and a quick turnaround after years of declining activity (by 1972, the annual number of oil and gas wells completed had declined to less than half the number completed in the mid-fifties) is beset by supply and other difficulties.

In the meantime, for the last few years, annual gross-reserve additions in both oil and gas have been falling short of production, resulting, as shown in Table 7, in net declines in United States reserves. This is in contrast to the period prior to 1968, when additions to reserves had at least kept slightly ahead of annual output. In the case of oil, a key element in this trend was the propensity of the American oil industry during the sixties to divert increasing shares of its capital investment from the United States to foreign producing areas. Thus, foreign sources of American energy supply began several years ago to loom as a major factor on the national scene. Other oil-importing regions of the world, notably Western Europe and Japan, have, of course, long lived with far higher degrees of import dependence; but for the United States, previously confident that its own excess productive capacity could be deployed in times of crisis (see below), the increased reliance on imports signified an unexpected turn of events. It coincided with—if, indeed, it did not pave the way for—suddenly heightened bargaining *rican oil:* No substantial replacements have come into view. North Sea oil will some hat relieve reliance on imported oil for the United Kingdom and obviously for Nor ay, but it does not appear to be heading for a larger role. Periodic reports of new oil ids elsewhere in the world, even if verified by subsequent drilling, merely indicate re f in a distant future. In the meantime, dependence might increase (as it has done in e United States) rather than decline.

5) *Insurance against supply interruptions:* Due in part—perhaps even largely— the recession, commercial crude-oil stocks have increased substantially in most im- rting countries, with storage space scarce early in 1975. Deliberate attempts to stock- le are more halting. In Western Europe, the OECD, as long ago as 1962, urged its uropean member countries to adopt sixty-day stockpiles. This program seemed ade- uate for a time. But in 1971, the OECD recommended early adoption of ninety-day cks for major petroleum products. This target has slipped. Indeed, the newly created ternational Energy Agency in mid-1975 was still deliberating a time schedule for eting the ninety-day objective. Japan's record in security stockpiling does not appear have been notably more successful than Europe's.

6) *Mutual assistance:* Efforts have been most successful in the financial field (see I ove). Work on a tentative mutual-aid pact among OECD countries to share scarce pplies in specified emergencies was begun in mid-1974 and continued into 1975 hieving domestic acceptance and implementation for the contemplated system esents problems; but the effort has gone faster and farther than skeptics would have lieved possible.

A summary judgment would be that the importing countries are now in a some- hat better position to cope, should a situation arise similar to that of the 1973-74 inter, but, at the same time, so are the exporters. They have as a group, in the mean- ne, accumulated very large financial resources that could see them through a long pe- d of confrontation. What looms ahead, therefore, are probably the most important answered questions: Will the cohesiveness of OPEC be sufficient to stand up during prolonged period of excess oil capacity and will that excess capacity be slowly elimi- ated with a resumption of upward demand in the importing countries, and a reduc- on or cessation of investment in productive capacity? If what we have described in this per as explanatory economic variables emerge as a product of hindsight, the import- g countries might learn enough from the experience to benefit from foresight. A look the post-1973 trends suggests that at best the shift is proceeding slowly.

FERENCES

[1]A portion of what follows in this section and the three subsequent sections has been adapted, in re- ed form, from J. Darmstadter and S. H. Schurr, "The World Energy Outlook to the Mid-1980s: The fect of an Alternative Supply Path in the United States," *Philosophical Transactions*, 276 (Series A) ondon, Royal Society, 1974).

[2]In all energy v... s, only energy moving through commercial channels and statistically recorded is ed for. Undoubtedly, much energy consumption in Africa and Asia escapes the record and thus ... sumption in those areas appear lower than it is.

... rowth rates shown here and in the following paragraph are taken from U.S. Agency for

ternational Development, *Gross National Product—Growth Rates and Trend Data*, Release RC-W- 138, May 1, 1974.

[4]Japan, Bureau of Statistics, Office of the Prime Minister, *Statistical Yearbook 1973/1974*.

[5]"Indirect" shipments refer to Arab crude oil processed in third-country refineries (e.g., in Italy or the Netherlands Antilles) prior to shipment as petroleum products to the United States.

[6]These estimates are contained in a paper by the Petroleum Industry Research Foundation, "U.S. Oil Imports and Import Dependency," New York, December 19, 1974. Similar estimates were presented by E. M. Benosky in testimony before the Subcommittee on the Near East of the House Foreign Affairs Committee, November 29, 1973.

[7]See Joel Darmstadter, "Energy Consumption: Trends and Patterns," in Sam H. Schurr, ed., *Energy, Economic Growth, and the Environment* (Baltimore, 1972), especially pp. 168-71. While, since 1970, the U.S. energy-GNP ratio seems once again to have reverted to its long-term downward trend, it does seem, from the rather erratic energy-GNP elasticities tabulated for a number of countries, that this familiar (and perhaps over-used) relationship may have limited utility as a basis for forecasting energy consumption, particularly at a time when volatile price trends, with or without the reinforcement of purposeful conservation policies, may quite markedly alter historical relationships.

[8]Hans H. Landsberg, "Learning From the Past: RFF's 1960-1970 Energy Projections," in Milton F. Searl, ed., *Energy Modeling: Art, Science, Practice*, RFF Working Paper EN-1 (Baltimore, 1973), pp. 414-36.

[9]U.S. Cabinet Task Force on Oil Import Control, *The Oil Import Question* (Washington, D.C., February, 1970), p. 125.

[10]We might note in passing that, in what was probably a misguided legacy of the "Limits to Growth" debate, skyrocketing oil prices and shortages were deemed by a few as symptomatic of approaching resource exhaustion.

[11]European Economic Community, Eurostat, *Energy Statistics Yearbook, 1969-1972* (Brussels, 1973).

[12]Adapted from "Energy in Crisis," *Resources*, No. 45 (Washington, D.C., 1974), pp. 5-6.

[13]Derived from data appearing in the American Petroleum Institute publications, *Petroleum Facts and Figures* (Washington, D.C., 1971), and *Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada and United States Productive Capacity as of December 31, 1973*, 28 (June, 1974).

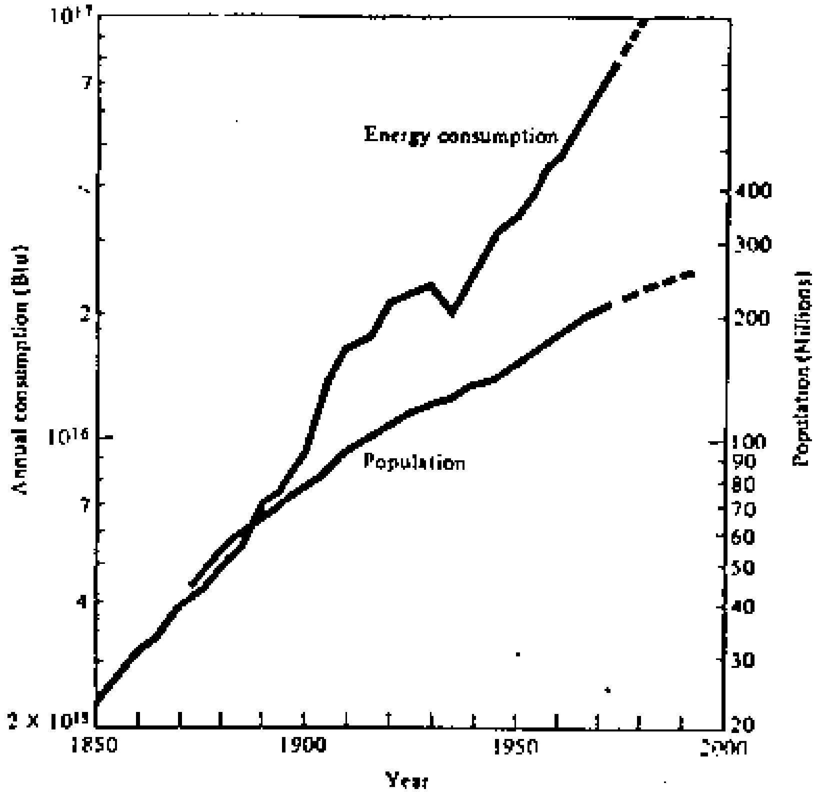


Fig. 1.1 Energy consumption and population growth in the United States from 1850 to 1972.

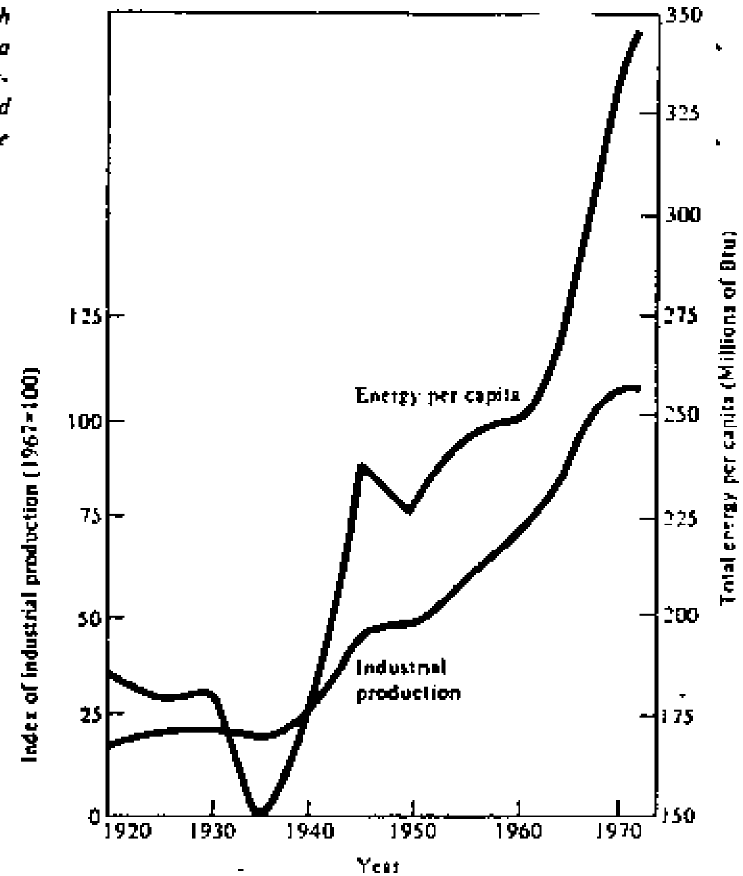
In addition, there is the problem of overcoming the threat of excessive damage to the environment due to extensive use of fossil fuels in transportation and industry. The process of compensating for these environmental effects will consume more energy and will require new approaches. Recycling of materials, rapid transit, sewage treatment, and air-pollution control equipment often consume additional energy and thus increase our total use of energy.

1.3 ENERGY CONSUMPTION

An imbalance of energy consumption exists within the world. Less than 50 percent of the world's population consumes close to 90 percent of its commercial energy; this is a major reason for the great chasm between the industrialized and the underdeveloped nations. The United States itself consumes approximately one-third of the world's energy, although it has only about six percent of the world's population.

The economy of the United States is highly energy-intensive, and per capita use continues to grow. During the period 1945 to 1965, energy consumption

Fig. 1.2 The growth of energy use per capita and industrial production during the period 1920 to 1972 in the United States.



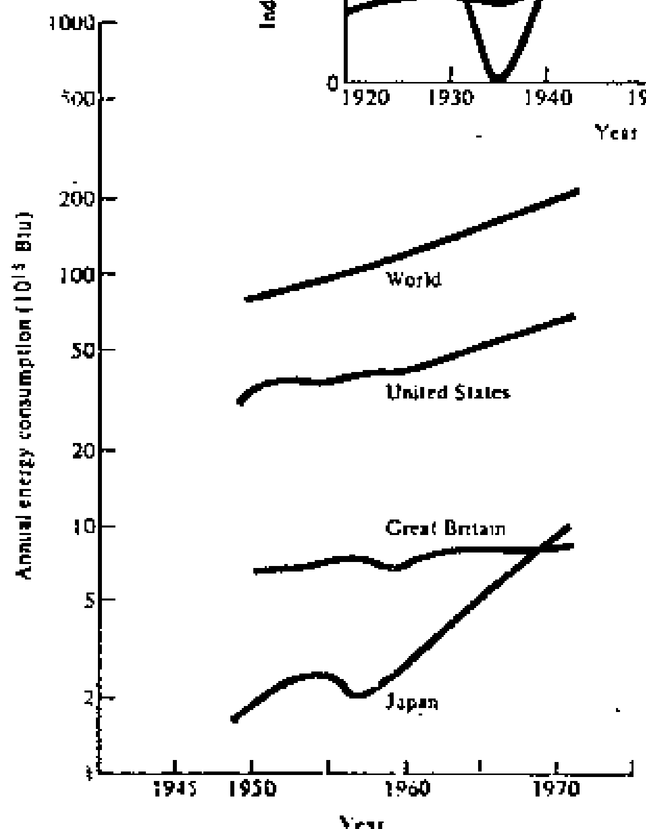


Fig. 1.3 Annual energy consumption for the world, U.S.A., Japan, and Great Britain for the period 1949 to 1971.

increased at an annual rate of 3 percent. During the period 1965 to 1971 the rate accelerated to 4.8 percent, then slowed again to 3 percent following the increases in gasoline and heating oil prices in late 1973 and subsequent years.

World energy consumption has also grown rapidly during the period 1950 to the present. Figure 1.3 shows the growth of world energy consumption during the period 1949 to 1971, during which a rate of growth of 5 percent per year was experienced. The figure also shows that Japan has expanded its use of energy in recent years at an annual rate of approximately 11 percent.

Affluence, as measured by the Gross National Product of a nation, is closely related to the energy consumption of that nation. Figure 1.4 shows the energy consumption per capita versus the gross national product per capita of several nations. There is a clear trend toward higher consumption of energy as a nation industrializes and increases its gross national product. Note how increasing use of energy per capita tends to produce an increase in gross national product per capita, but that the effect is less pronounced once a nation passes into a state of

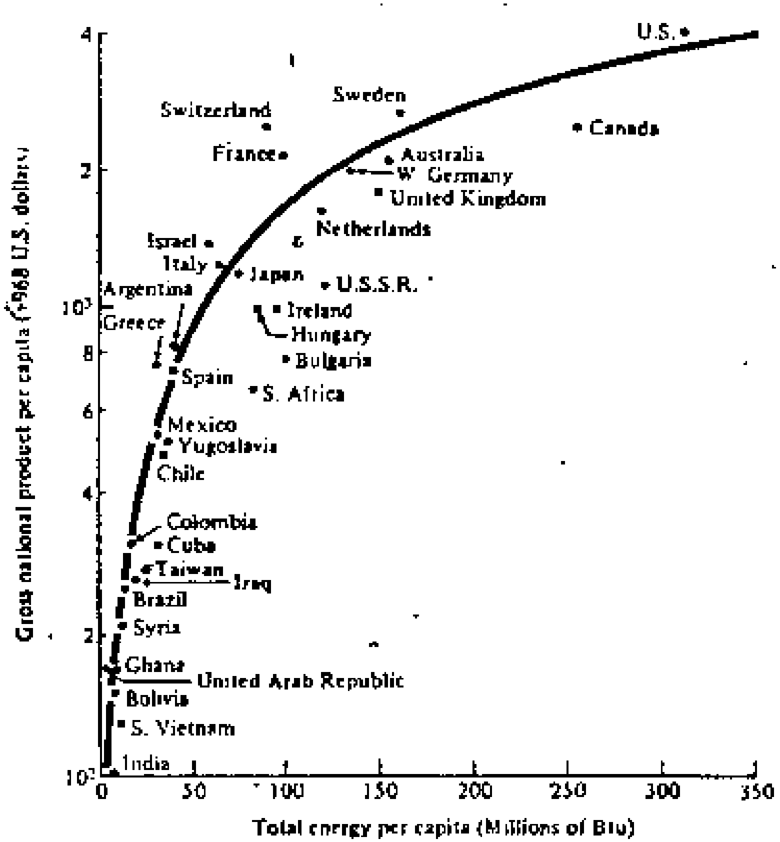


Fig. 1.4 Energy per capita versus the gross national product per capita in 1968 for several nations.

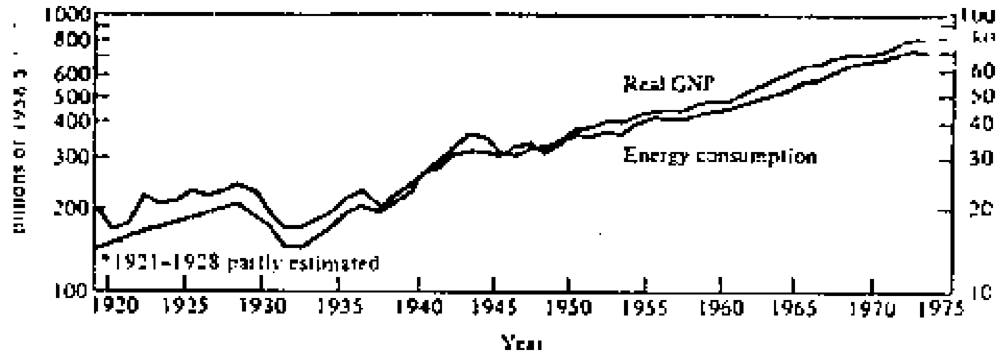


Fig. 1.5 U.S. energy consumption and real GNP as measured in 1958 dollars for the period 1920–1974.

relative affluence (approximately beyond $1000 per capita GNP). (See Fig. 1.4.) The very close relationship of energy consumption and real gross national product, in constant 1958 dollars, is shown in Fig. 1.5. [3] Whether GNP pushes up energy consumption or energy use causes increased GNP is an interesting and important question. We may compare U.S. energy use with consumption in other countries. Our workers commute longer distances than in foreign countries (usually by auto); do our centralized, efficient industrial processes make up for the added expenditure of energy for transportation? In Fig. 1.6, the energy consumed per unit of economic output is shown. [3] Clearly, by this measure, U.S. industry is an efficient user of energy.

The increased standard of living in the U.S.A. over the period 1920 to 1970 can be visualized in Fig. 1.7, where energy consumption per capita is shown versus real GNP per capita. Energy consumption continues to grow throughout the

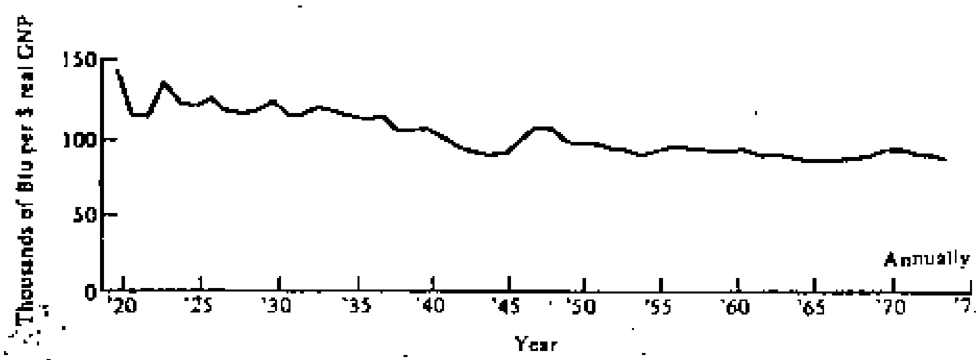


Fig. 1.6 Energy consumed per unit of economic output (real GNP in 19 dollars) in the U.S.A.

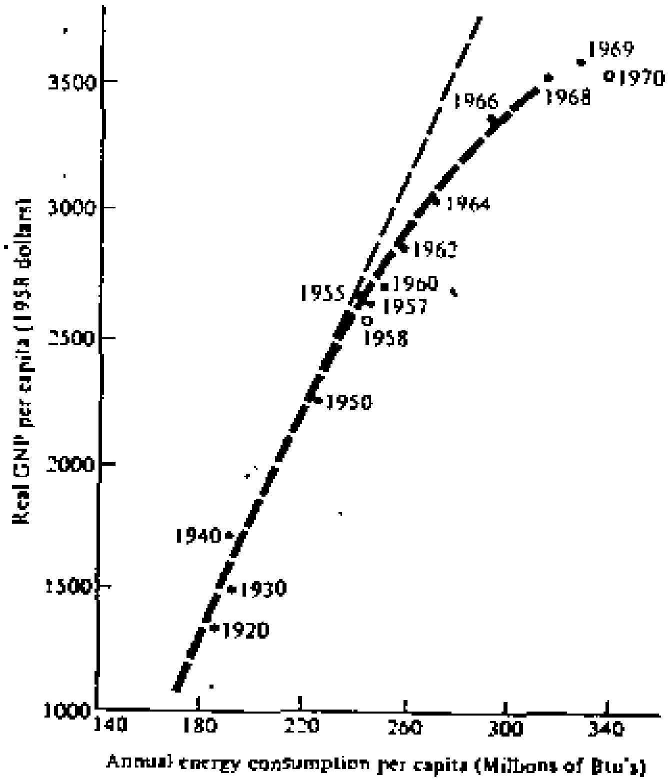


Fig. 1.7 Energy consumption versus real GNP per capita for the period 1920 to 1970, in the U.S.A.

world, as shown in Table 1.2 (for the period 1968–1971). Following the Arab oil embargo and oil price increase of late 1973, the growth in energy use has slowed somewhat, but has not plateaued. As energy costs have risen, energy has taken a greater share of a nation's budgeted allocations.

Table 1.2
ENERGY CONSUMPTION PER CAPITA IN SELECTED COUNTRIES IN 1968 AND 1971

Country	*1968*	*1971*	*Increase (%)*
USA	312*	337	8.1
France	98	117	19.7
W. Germany	134.5	156.5	16.4
Great Britain	148.7	165	11.0
USSR	121.4	136	12.0
Japan	75.5	98	29.7
World	52	58	11.1

* All per capita figures in millions of Btu's.

1.4 ENERGY ECONOMICS

The profound effect of the recent increase in the price of energy has been felt throughout the world's economy. A simple illustration is the cost of energy to U.S. colleges and universities. In the five years from 1969 to 1974, U.S. colleges and universities experienced a 246-percent average cost increase. [4] For example, the energy cost for the University of California, Davis, went from $812,000 to $1,553,000 over the five-year period even after a 10-percent reduction in energy consumption due to energy conservation. Michigan State University experienced a 160-percent increase (from $2,432,000 to $6,332,000) in the five-year period. These are significant portions of the budget of a university. For example, the percentage of the total budget allocated to energy at Michigan State increased from 1.44 percent to 2.81 percent over the five-year period from 1969 to 1974.

Energy is used for four major sectors of the U.S. economy: (1) residential and commercial; (2) transportation; (3) industrial; and (4) electrical power generation. The portion of the total U.S. energy use attributed to each sector is shown in Fig. 1.8. Transportation and electrical generation have grown proportionately as significant users of the nation's energy (as shown graphically in Fig. 1.8 and listed as percentage use in Table 1.3). Electrical power generation is projected to increase its share of the market over the next twenty years as the nation utilizes more nuclear energy.

The flow of energy inputs to the four market sectors and then to useful and rejected (or waste) energy is shown in Fig. 1.9 for 1970. The supply of fuels is shown on the left, and each fuel is shown as a flow of percentage use by each sector. In 1970, the total input of energy was 71.6×10^{15} Btu's. Examining the output side we note that the useful energy, 31.8Q, is only 50.5 percent of the total output

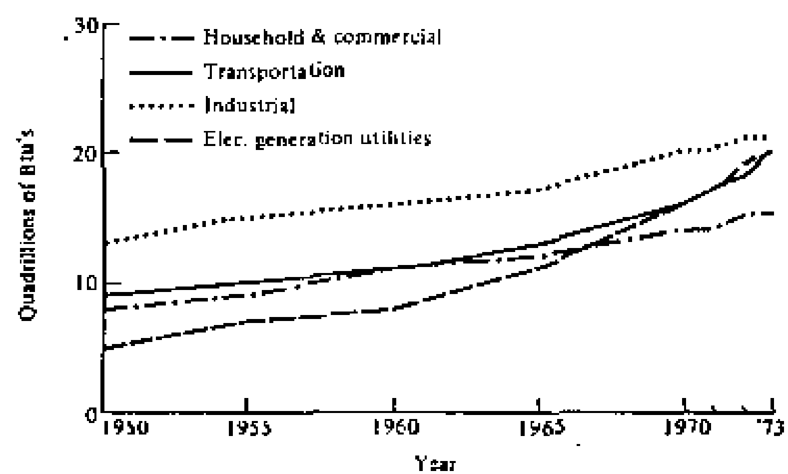


Fig. 1.8 The use of energy in the four sectors of the U.S. market.

Table 1.3
CONSUMPTION OF FUEL RESOURCES BY MAJOR CONSUMER GROUP IN THE U.S.A.

Consumer sector	Percent distribution 1965	1970	1973
Household and commercial	22.2	20.8	20.3
Industrial	32.3	30.2	28.4
Transportation	23.8	24.5	24.8
Electrical generation	20.7	24.2	26.2
Other	1.0	0.3	0.3
Totals	100.0	100.0	100.0

63Q. In other words, approximately half of the energy is lost as rejected or waste energy. In Chapter 3 we will examine further this high proportion of waste energy, in terms of thermodynamic principles.

Energy has been a key to the increased industrialization of Europe and the United States. The availability of inexpensive and abundant energy is important to mechanized agriculture, industrial manufacture, modern transportation, and modern physical comfort. The world has entered an era of profound alteration in traditional patterns and trends in the field of energy. Price relationships, sources of supply, and in its broadest sense, national security, all have become fraught with uncertainty and conflict. The current division of the uses of energy is shown in Fig. 1.10.

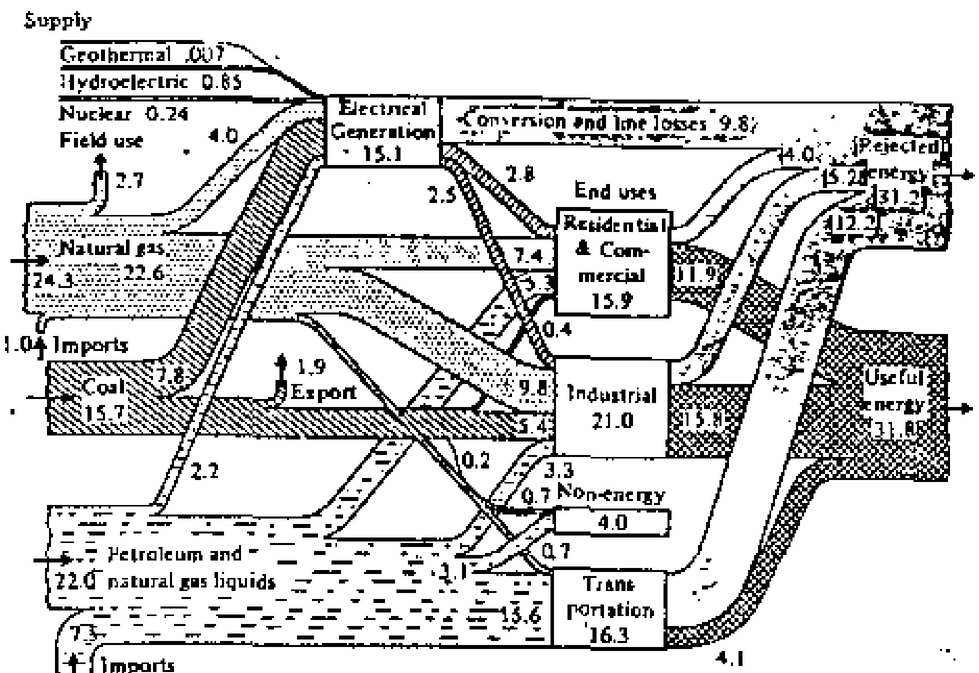


Fig. 1.9 The flow of energy in the U.S. in 1970. All values are given in 10^{15} Btu = 1Q (Q = quadrillion). Total input is 71.6Q.

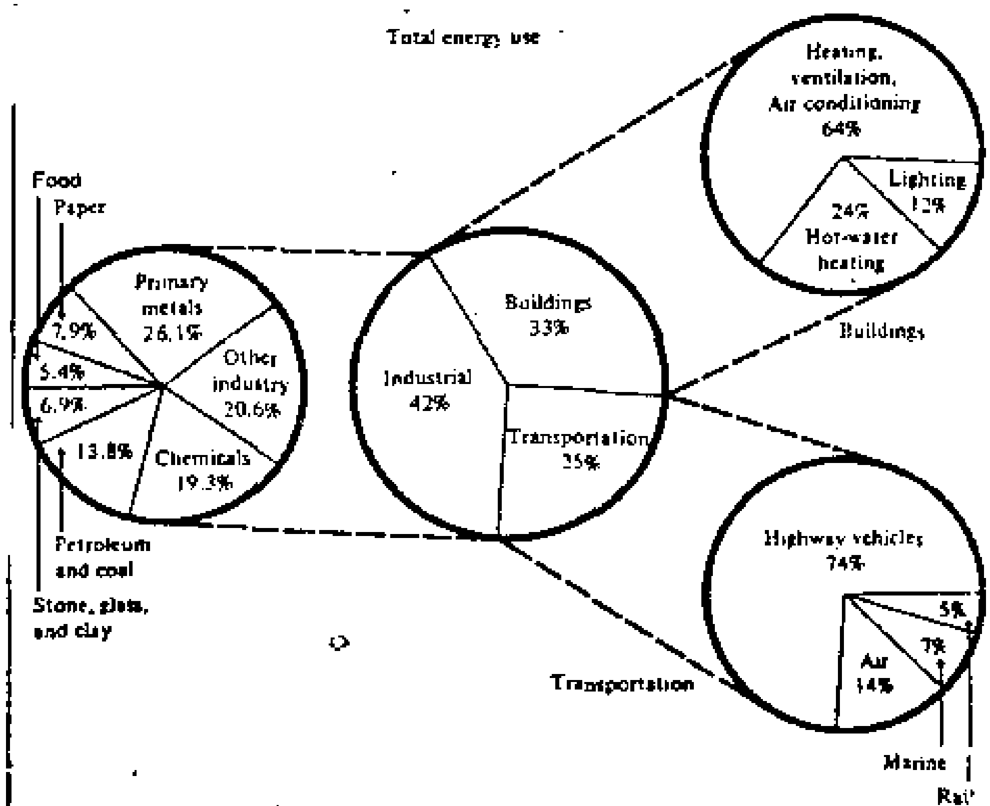


Fig. 1.10 The uses for energy in the U.S.

1.5 ENERGY PROBLEMS

Energy problems did not originate in 1973 with the Arab oil embargo; they were evident much earlier: gas utilities refusing to connect service for new residential customers, enforced electrical voltage reductions, and the electrical blackout in northeastern U.S. in 1965. Recently, the closing of gasoline stations, the rises in gasoline prices, and the shortage of natural gas have brought the energy issue to most Americans. Spurts in the sales of compact autos over those of larger autos may be one of the harbingers of change.

Some Americans are searching for a villain who can be blamed for energy shortages and higher prices. Some blame the oil companies, others the federal government, while others blame the Arab governments or the environmentalists. The three most convenient targets are: the energy industry, the federal government, and the environmentalists. As seen by their adversaries, the first conspires, the second bungles, and the third obstructs. The first is a knave, the second a fool, and the third a dreamer.

The winter of 1976–1977 brought another energy crisis pressing the nation. The harshest winter in decades gripped more than half of the U.S. Factories, businesses, and schools were forced to close because energy was not available to run the machines or heat the buildings. The combination of frigid temperatures and the shortage of natural gas, which provides energy for half of the nation's homes and 40 percent of its industries, was devastating. Schools and factories in Ohio, Pennsylvania, New York, and New Jersey were forced to close for lack of natural gas. Frozen rivers and icy roads blocked deliveries of oil and coal. Trains delivering coal were stalled due to snow and ice. The winter of 1977 exemplified to many the dependence of the nation on the ready availability of energy sources.

Industry is accused of withholding supplies—and information on the magnitude of its resources, which are alleged to be much greater than reported. Thus it is alleged the energy industry creates shortages, resulting in higher prices, and, as a bonus, is able to squeeze out independent refiners and service stations. Government is charged by the energy industry with holding down prices (or, by consumers, with not holding them down), reducing incentives, cutting subsidies, and enmeshing industry in a thicket of agencies, standards, and regulations, causing profits to decline, capital to become scarce, and initiative to evaporate. Environmentalists are held guilty of halting the wheels of progress, of following elitist aspirations, and of shunning reality. [5] In a recent survey in the U.S.A., over 40 percent of the people felt the federal government was at fault, while about 30 percent blamed the energy industry. About 15 percent blamed the Arab countries for the energy shortages and price increases.

During the past two decades there has been an increasing tendency for industry and transportation to become more energy-intensive. Most industries responded to increased demand for production by becoming more energy-intensive and less labor-intensive. This is readily seen in the auto industry, which has become increasingly automated, thus replacing manual labor with energy-using machines. Perhaps during the next decades, there will be a decline in the use of automation and a resultant shift back to the use of labor. Nevertheless, fossil-fuel energy has been useful in multiplying man's ability to accomplish work, to move himself and his goods, and to provide physical comfort. Energy will be needed in the future to run the new sewage-treatment plant, for the recycling of materials, and for the creation of new jobs. The challenge remains to supply the energy in a way compatible with a wise use of the environment and the earth's resources.

1.6 THE ENERGY ISSUE

The three dimensions of the energy issue, as shown in Fig. 1.11, are: (1) energy sources, (2) energy processing, and (3) energy policy. In the following chapters we will examine the energy sources available now and those still to be developed, the processing and conversion of energy, energy conservation, and finally the economic, environmental, and political policy issues involving energy use.

In the next chapter we will explore the history of the use of energy throughout the world, and thus enhance our understanding of the current energy dilemma.

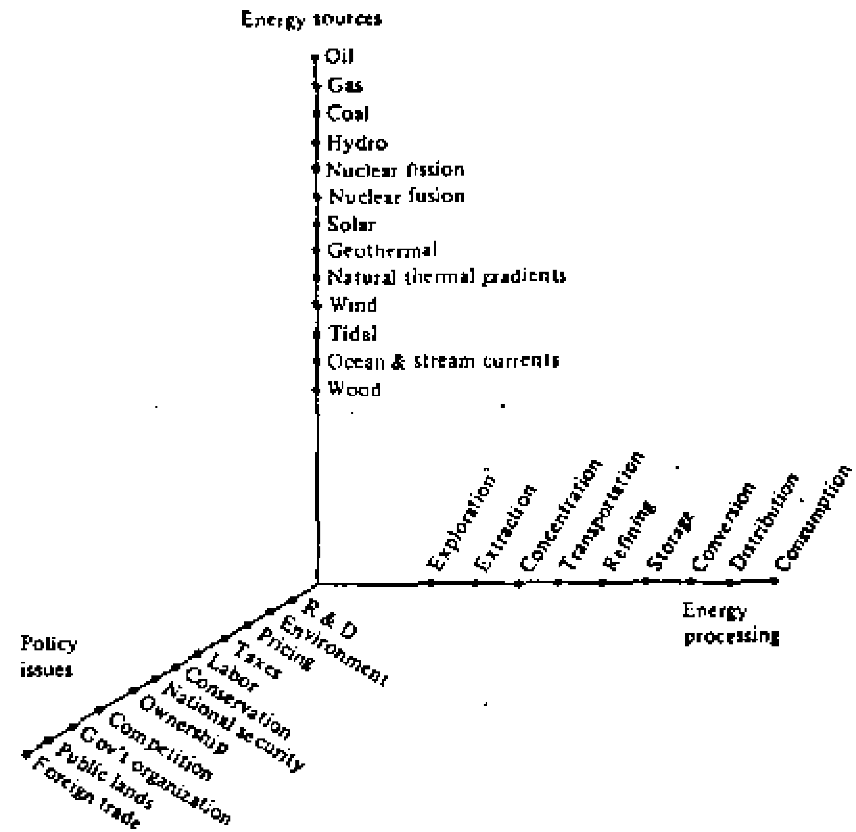


Fig. 1.11 The three dimensions of the energy issue.

REFERENCES

1. *Energy Facts*, Science Policy Research Div., Library of Congress, U.S. Government Printing Office, Washington, D.C., 1973.
2. *Social Indicators*, U.S. Government Printing Office, Washington, D.C., 1973.
3. "Pages with the editor," *Public Utilities Fortnightly*, Jan. 30, 1975, p. 6.

4. "Less energy, more dollars," *Chronicle of Higher Education*, July 15, 1975, p. 7.

5. H. H. Landsberg, "Low-cost, abundant energy—Paradise lost?," *Science*, 19 April 1974, pp. 247–253.

6. J. R. Murray, *et. al.*, "Evolution of public response to the energy crisis," *Science*, 19 April 1974, pp. 257–263.

7. J. O'Toole, *Energy and Social Change*, The M.I.T. Press, Cambridge, 1977.

8. H. S. Stocker, S. L. Seager, and R. L. Capener, *Energy: From Source to Use*, Scott Foresman and Co., Glenview, Illinois, 1976.

EXERCISES

1.1 The most fundamental energy source, without which there would be no life on earth, is ________.

1.2 Of the annual use of commercial energy worldwide, the United States accounts for:

a) almost all of it,
b) about 6 percent of it,
c) about a third of it,
d) about three quarters of it.

1.3 The use of wood as a fuel is usually not included in the statistics of commercial energy use in the world. Is this because its contribution to meeting human energy needs is unimportant or insignificant? Why is it not included in the statistics?

1.4 a) Suppose energy use is growing at a geometric rate such that it doubles every 15 years. Assuming this rate continues, how big would energy use be in 2030 compared to the 1970 use?

b) Suppose that, by means of powerful measures to reduce energy waste, the growth of energy use had been slowed down as of 1970 such that the doubling time was 30 years. If this rate continued, how big would energy use be in 2030 compared to the 1970 use?

*1.5 Obtain the population and energy consumption figures for your state during the period 1900 to 1975, and plot a pair of curves similar to Fig. 1.1. Calculate the energy per capita in your state and compare it with the national figures given in Fig. 1.2 for 1940 and 1970.

1.6 Determine the increase in the cost of energy for your college or university for the five-year period 1969 to 1974. Compare the increase at your college with the national average increase experienced by colleges during that period.

* An asterisk indicates a relatively difficult or advanced exercise.

4 Projections of Energy Consumption

Continued growth in the use of fossil fuels can occur only for a number of years before we exhaust these resources. The implications of compound growth often escape our attention until it is too late. For example, in the U.S. we have used about 100 billion barrels of our domestic oil resources, and there may be 100 billion barrels remaining as recoverable resources. Since we have used oil for about 100 years, it may be tempting to assume that the remaining oil should last for another 100 years, but the fact is that the consumption of oil has been increasing at a rate of 5 percent per year, and the remaining oil could be depleted in another 14 years.

4.1 COMPOUND GROWTH

If an amount of consumption grows from an initial value A_0 at a rate r (a decimal), then we have, after one year,

$$A_1 = A_0(1 + r), \tag{4.1}$$

where A_1 = the consumption value after one year. After the second year, we have

$$\begin{aligned} A_2 &= A_1(1 + r) \\ &= A_0(1 + r)^2. \end{aligned} \tag{4.2}$$

In general, after n years, we have

$$A_n = A_0(1 + r)^n. \tag{4.3}$$

Thus, if we consumed one billion barrels of oil in 1933 and the growth rate was 5 percent per year, we calculate the consumption, at a time 20 years later (in

1953], as follows:

$$\text{Consumption in 1953} = A_0(1 + 0.05)^{20} = 1(2.65) \text{ billion barrels.} \tag{4.4}$$

One can calculate $(1.05)^{20}$ using logarithms, a table, or a calculator.

If we ask the question, "How long will it take for a doubling of a value A_0 at a specified rate r?", we can use logarithms to write:

$$\log A_n = \log A_0 + n \log(1 + r). \tag{4.5}$$

Solving for n, we have

$$n = \frac{\log A_n - \log A_0}{\log(1 + r)} = \frac{\log(A_n/A_0)}{\log(1 + r)}. \tag{4.6}$$

Since we want to determine the number of years for doubling, we have

$$n_{\text{double}} = \frac{\log 2}{\log(1 + r)} = \frac{0.3010}{\log(1 + r)}. \tag{4.7}$$

The doubling times for several values of r are given in Table 4.1. Examining Table 4.1, we note that, as an approximation,

$$n_{\text{double}} \approx \frac{72}{r} \tag{4.8}$$

over the range $0.01 \leq r \leq 0.12$.

Table 4.1
DOUBLING PERIODS FOR SPECIFIED GROWTH RATES

r	0.01	0.03	0.05	0.06	0.07	0.09	0.10	0.12
n_{double}	69.6	23.4	14.2	11.9	10.2	8.0	7.3	6.1

The use of petroleum in the world is growing at the rate of 5 percent per year, and the consumption in 1975 was 20 billion barrels per year. Thus we may expect to be using 40 billion barrels 14 years later (in 1989) if this growth rate is sustained over the period.

4.2 EXPONENTIAL GROWTH

The growth in the consumption of oil occurs continuously, and we state that the growth is *exponential* and follows the equation

$$A(t) = A_0 e^{rt}. \tag{4.9}$$

If we replace t by n periods of time of length Δ, we have

$$A_n = A_0 e^{rn\Delta}; \tag{4.10}$$

and if, for example, $\Delta = 1$ year, we then write $A_n = A_0 e^{rn}$. Recalling that

$$e^x = 1 + x + \frac{x^2}{2} + \cdots + \frac{x^m}{m!},$$

we may use only the first two terms when r is small, so that

$$A_n = A_0(1 + r)^n. \tag{4.11}$$

Therefore, for r less than 0.10, compound growth and exponential growth yield the same result over a limited period of time.

Another approach is to reconsider Eq. (4.3). We may rewrite this equation as follows:

$$A_0(1 + r)^n = A_0 e^{[\ln(1 + r)]t} = A_0 e^{\alpha t}, \tag{4.12}$$

where $\alpha = \ln(1 + r)$. Again we note that α is approximately equal to r if $r \ll 1$, and therefore, we obtain Eq. (4.9).

Some Consequences of Growth

When consumption of a resource proceeds exponentially, we can show that the amount of a product consumed during one doubling period is equal to the total used over *all preceding time*. The total used up to time t_1, C_1, is

$$C_1 = \int_{-\infty}^{t_1} A_0 e^{rt}\, dt = \frac{A_0}{r} e^{rt_1}. \tag{4.13}$$

The total used during the doubling time t_1 to t_2, C_2, is

$$C_2 = \int_{t_1}^{t_2} A_0 e^{rt}\, dt = \frac{A_0}{r}(e^{rt_2} - e^{rt_1}). \tag{4.14}$$

Since it is a doubling period, we have $e^{rt_2} = 2e^{rt_1}$; therefore Eq. (4.14) becomes

$$C_2 = \frac{A_0}{r}(2e^{rt_1} - e^{rt_1}) = \frac{A_0}{r} e^{rt_1}, \tag{4.15}$$

and thus C_2 equals C_1; that is, the consumption over the doubling period is equal to all prior consumption. Thus, given that oil is being consumed at an exponentially growing rate, when half of that resource has been consumed, then only one doubling period is left before the resource is totally depleted.

Let us obtain an expression for the period of consumption time remaining if a resource has a finite value A_f and we have consumed C already. The remaining period of time, t, for using this resource is then

$$A_f - C = \int_0^t A_0 e^{rt}\, dt, \tag{4.16}$$

where A_0 is the rate of consumption at the beginning of the period (when $t = 0$). Therefore,

$$A_f - C = \frac{A_0}{r}(e^{rt} - 1) \tag{4.17}$$

and

$$e^{rt} = \frac{(A_f - C)r}{A_0} + 1. \tag{4.18}$$

Solving for the period t we have

$$t = \left(\frac{1}{r}\right)\left[\ln \frac{(A_f - C)r}{A_0} + 1\right]. \tag{4.19}$$

As an example, let us assume that 100 billion barrels of oil remain as U.S. resources and we continue to increase our consumption at 5 percent per year. We use our resources at a rate of 3.5 billion barrels in 1975, and we wish to calculate the number of years that the resource will last. Using Eq. (4.19) we have

$$\begin{aligned} t &= \left(\frac{1}{0.05}\right) \ln\left[\left(\frac{100}{3.5}\right)0.05 + 1\right] \\ &= 20 \ln (2.43) \\ &= 20(0.888) \\ &= 17.76 \text{ years}. \end{aligned} \tag{4.20}$$

Limits to Growth

Exponential growth cannot continue indefinitely since some natural limitation sets in. In the case of a resource such as uranium or natural gas, as consumption continues and the resource becomes scarcer, classical economic theory of supply and demand suggests that the price will increase. This price increase should dampen demand and thus lengthen the lifetime of the resource. Other factors such as environmental controls or conservation measures may also limit or alter the growth pattern of the consumption of a fossil fuel.

As an example, consider the growth in the consumption of coal in the U.S. since 1860. During the period 1860 to 1910, the consumption of coal grew at a rate of 6.6 percent per year, thus doubling every 11 years. After 1910, however, as supplies of natural gas and petroleum became available, the rate of growth in the consumption of coal slowed until the average yearly consumption became essentially constant.

The production of an exhaustible fossil fuel may follow a curve, as shown in Fig. 4.1. The production increases initially along an exponential curve, then passes through a maximum and declines eventually to a very small quantity as the fuel source approaches exhaustion.

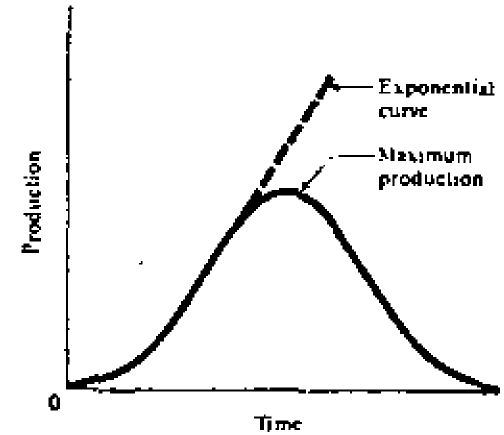


Fig. 4.1 The production of a fossil fuel in finite supply.

The cumulative production up to a time t_1 is

$$Q = \int_{-\infty}^{t_1} P\, dt, \tag{4.21}$$

where P = production rate. For a finite quantity of fuel Q_F, we have

$$Q_F = \int_{-\infty}^{t_F} P\, dt, \tag{4.22}$$

where t_F = time when the fuel is exhausted.

If we define Q_R as the proven reserves and Q_P as the total accumulated quantity of fuel removed from the ground, the cumulative discoveries Q_D represents the quantities removed from the ground plus the recoverable quantities remaining in the ground. Therefore,

$$Q_D = Q_P + Q_R. \tag{4.23}$$

Since Q_D is eventually limited to Q_F, we may represent the changes in these quantities as shown in Fig. 4.2. As the cumulative discoveries approach the finite quantity of a fuel, proven reserves drop and the price of fuel rises, thus limiting production.

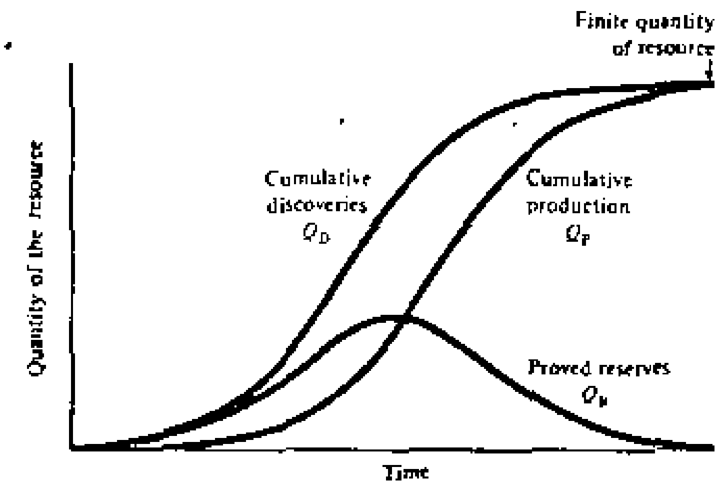


Fig. 4.2 The consumption of a limited fuel over the lifetime of the fuel.

4.3 USE OF ENERGY IN THE U.S.

As an example of a shift from exponential growth, consider the growth in per capita consumption of energy in the U.S. Historically, energy consumption has grown at a rate of about 3 percent over the 70-year period from 1900 to 1970. If we were to extend this rate of growth over the next 30-year period, we could expect a doubling of per capita consumption every 24 years. A more likely event is a gradual deceleration of the rate, so that the growth rate might reach zero by the year 2000.

For example, the rate of increase might decelerate following the equation

$$\frac{dr}{dt} = -a, \tag{4.24}$$

where $(-a)$ is the constant deceleration. Then we have

$$\int_{t_0}^{t_1} dr = \int_{t_0}^{t_1} (-a)\,dt \tag{4.25}$$

or

$$r(t_1) = r(t_0) - a(t_1 - t_0). \tag{4.26}$$

Thus, if $r(t_0) = 0.03$ and $a = 0.0015$ per year, we would expect the rate of growth to be equal to zero after 20 years.

In Fig. 4.3 the trend of the growth in energy use in the U.S. is shown for the period 1900 to 1975. The curve of the historical exponential growth* is extrapolated to the year 2020, yielding a value of 300×10^{15} Btu for that year. A

* When exponential growth is plotted against a logarithmic scale (on the vertical axis), the curve becomes a straight line.

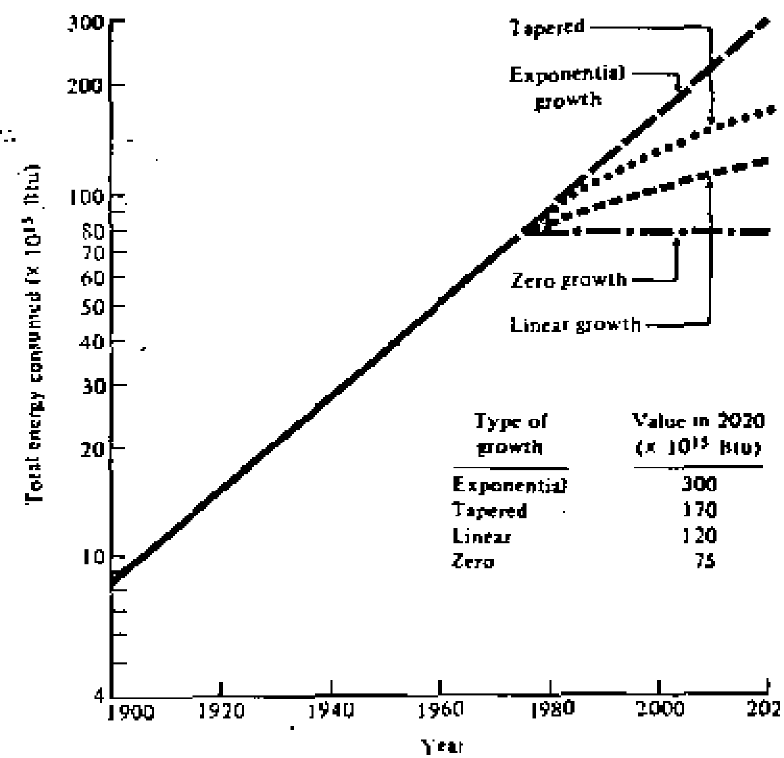


Fig. 4.3 The historical growth of energy consumed in the U.S. and several projections for the period 1975 to 2020.

curve for zero growth is also shown. The curve for linear growth following an increase of 1×10^{15} Btu's per year is also shown. We can also calculate a curve for a tapered growth resulting from a deceleration of the use of energy in the U.S. In Fig. 4.3, one curve shows a linear deceleration of the growth rate to a zero growth rate by 2025 ($a = 0.0006$ per year).

While the exponential projection yields a value of total energy consumed in 2020 equal to 300×10^{15} Btu, the value in 2020 is 170 and 120×10^{15} Btu, for the tapered and linear models respectively. Of course, the zero-growth projection remains at 75×10^{15} Btu. We can expect that many of the curves related to energy consumption in the world will experience a tapered growth as prices of fossil fuels increase and supply falls behind demand.

Forecasting

Forecasts of future energy consumption in the U.S. have traditionally turned out to be low. However, recent events have caused forecasts of energy and power trends to be highly questionable. Various forecasts of U.S. energy consumption in 1980 which were prepared in 1970 or 1971 varied from 95 to 110 × 10^{15} Btu's. [2] As we now rapidly approach 1980, we can more accurately estimate energy consumption for that year as lying in the range 80 to 90 × 10^{15} Btu's. Forecasting is an art, not a science, and variations in forecasts are to be expected.

Per Capita Use of Energy

Energy use per capita has remained a relatively low-growth item in our U.S. energy history. Considering the use of wood, and agricultural products for work-animal feed, as well as the use of coal and oil, energy per capita has not increased continuously. [3] Two jumps in our energy history occurred: early in the 20th century when agriculture became energy-intensive, and again recently because of a marked increase in the number of Americans employed. However, as the population of the U.S. levels off and the per-capita use of energy stabilizes, the nation's energy curve may flatten out over the next 40 years.

The average standard of living, L, for a nation may be expressed by the following equation: [4]

$$L = \frac{R \times E \times I}{P}, \tag{4.27}$$

where R represents the consumption of raw materials, E represents the consumption of energy, and I the consumption of all forms of ingenuity. The population of the nation is represented by P. As population stabilizes, the average level of affluence and well-being may stabilize also as long as a stable supply of energy and raw materials is available.

4.4 FORECASTS OF U.S. ENERGY CONSUMPTION

There have been many forecasts of the consumption of energy in the U.S. for the period 1975 to 2025. The projections provided in Fig. 4.3 are relatively useful and accurate. A recent study sponsored by the Ford Foundation proposed three possible growth patterns for the period 1975 to 2000, a relatively intermediate-term period. [5]

The first forecast is based on the assumption that energy use in the U.S. will continue to grow until the end of the century at about 3.4 percent annually, the average rate of growth from 1950 to 1970. Thus it assumes that no deliberate effort would be made to alter our habitual patterns of energy use, nor would higher energy prices cause a decreasing rate of growth in consumption. The curve depicting this growth is shown in Fig. 4.4, and the value of energy consumption is listed for 1975, 1985, and 2000 in Table 4.2. While the trends of energy prices cast doubt upon the likelihood that historical growth trends will persist, it is nevertheless the one trend that is often assumed by many government and industry leaders.

The second forecast is based on the assumption of a *conscious national effort* to use energy more efficiently through the introduction of energy-conserving technology, and is called the *technical fix* scenario. The Ford Foundation project

Table 4.2
THREE FORECASTS OF THE FORD ENERGY PROJECT

	Energy consumption (× 10^{15} Btu)		
	1975	1985	2000
Historical growth	75	136	187
Technical fix	78	91	124
"Zero growth"	75	93	100
Tapered growth of Fig. 4.3	78	100	132

report states that if these technical approaches were consistently applied, an energy growth of 1.9 percent per year would be adequate to satisfy our national needs. The growth of energy use in the technical-fix scenario is shown in Fig. 4.4 and the value of energy consumption is given for 1975, 1985, and 2000 in Table 4.2. Note that the energy consumption of the technical-fix response is one-third less than that of the historical response. This savings of 63 × 10^{15} Btu in 2000 is four-fifths as large as the total energy consumption in 1975.

The Ford project proposes a *zero energy-growth* scenario. While called zero growth, it actually has decreasing growth rates, eventually reaching zero after 2000. The zero-growth scenario assumes a growth rate of 1.76 percent from 1975 to 1985, and 0.47 percent over the period 1985 to 2000. The growth of energy in

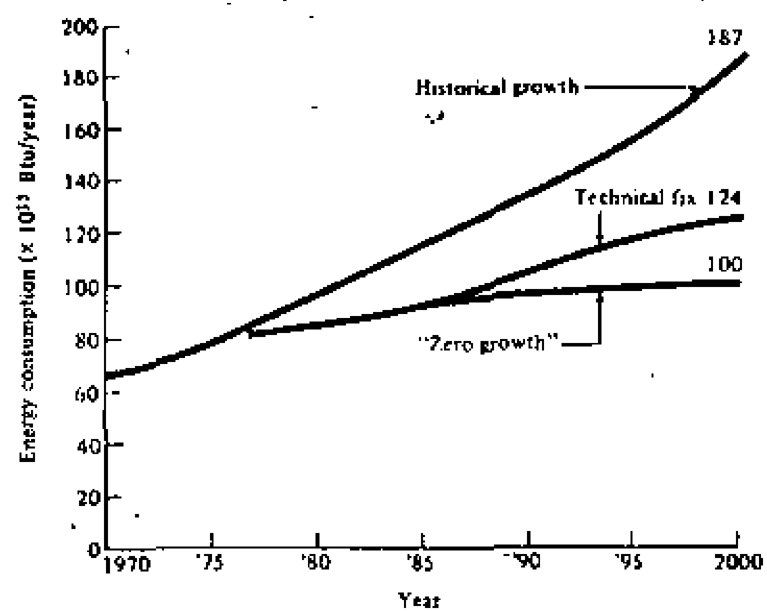


Fig. 4.4 *Three forecasts of energy consumption in the U.S. during the period 1975 to 2000. These forecasts are a result of the Ford Foundation Energy Policy Project.*

this forecast is shown in Fig. 4.4, and reflected values are listed in Table 4.2. The zero-growth response estimates a value of 100×10^{12} Btu for 2000, only 28 percent larger than the value of consumption in 1975, and 46 percent less than the value forecast for the historical response.

For comparative purposes, the *tapered growth* of energy consumption shown in Fig. 4.3 is listed for 1975, 1985, and 2000 in Table 4.2. This tapered response is only 6 percent larger in 2000 than that forecast for the technical fix case.

Only time will tell what the energy consumption will be between 1976 and 2000. In fact, whether we experience faster, lower, or zero energy growth depends upon still conjectural factors such as fuel prices, environmental controls, lifestyles, and the value attached to energy uses. [6] A conservative but unsubstantiated approach might be to assume that a response similar to the technical fix of the Ford project or the tapered growth of Fig. 4.3 is a reasonable forecast. The actual growth rate, however, will depend upon national and international policy issues yet to be settled.

One Projection for the Period 1970 to 2000

A reasonable projection for the growth of energy use in the U.S. for the period 1970 to 2000 might call for a value of energy consumption in 2000 equal to 150×10^{15} Btu. A pattern of growth yielding this value in the year 2000 is shown in Fig. 4.5, which also indicates the proportions of each of the sources of supply that would be required in order to achieve this growth.

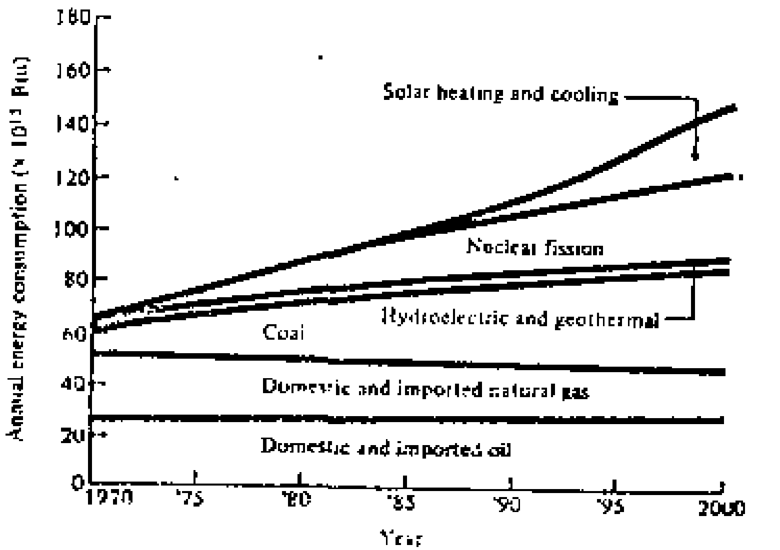


Fig. 4.5 One possible projection for the supply of energy in the U.S. during the period 1970 to 2000

It is assumed that petroleum will supply 29×10^{15} Btu's in 2000, an increase of only 15 percent during the 30-year period. This could be achieved by increasing imports of foreign oil as well as increasing domestic exploitation of U.S. resources. It is assumed that the supply of natural gas will decrease over the period 1970 to 2000 as domestic sources decline and imports prove to be unable to balance this decline. Coal, in this projection, is assumed to supply an increasing percentage of the nation's energy. Furthermore, it is assumed that hydroelectric and geothermal energy sources can be developed to yield a steadily increasing amount of energy.

Within this projection, it is assumed that energy supplied by nuclear fission reactors generating electricity will grow from 0.25×10^{15} Btu's (7×10^{10} kilowatt-hours) in 1970 to 30×10^{15} Btu's (9×10^{12} kilowatt-hours) in 2000. This use of nuclear energy over the period 1970 to 2000 assumes a rapid growth that may be unrealizable. After 1982, it is assumed that the use of solar heating and cooling systems will yield an important portion of the increasing energy consumption in the U.S.

This one projection is illustrative of the various scenarios that may be proposed. In later chapters we will consider each source of supply and determine what reasonable amounts may be obtained and what policy decisions would need to be taken in order to reach a stated level of supply.

Table 4.3
ONE POSSIBLE PROJECTION FOR THE SUPPLY OF ENERGY IN THE U.S. IN 1970 AND 1985

	1970		*1985*	
Supply	*Consumption ($\times 10^{15}$ Btu)*	*Percent of total*	*Consumption ($\times 10^{15}$ Btu)*	*Percent of total*
Oil	27	39.7	28	28.0
Coal	16	23.5	26.5	26.5
Gas	23.8	35.0	23.5	23.5
Hydro and geothermal	0.9	1.3	1.6	1.6
Nuclear	0.25	0.4	17.5	17.5
Solar	0	0	3	3.0
Total	68	100	100	100

The changes that might be achieved by 1985 are summarized in Table 4.3. Examining this table, we can see that the projected growth will only be achieved if nuclear power increases at a rapid rate and becomes 17.5 percent of the total supply by 1985. Furthermore, this projection assumes that solar heating and cooling will account for 3 percent of the total energy used in 1985. Perhaps it is more reasonable to expect nuclear power to supply only 10×10^{15} Btu in 1985, in which case we might expect the total energy consumed in 1985 to amount to 92.5×10^{15} Btu instead of 100×10^{15} Btu as previously projected for the U.S. The exploitation of nuclear fission power over the next decade will largely determine whether the projected supply (as shown in Fig. 4.5) will be achieved. An unattractive alternative would be to increase the amount of imported oil by 7.5×10^{15} Btu in 1985, in order to yield a total consumption of 100 quads. (One quad is equal to 10^{15} Btu's.) This alternative is summarized in Table 4.4.

Table 4.4
AN ALTERNATIVE PROJECTION FOR THE SUPPLY OF ENERGY IN THE U.S. IN 1985 WITH AN INCREASED DEPENDENCE UPON IMPORTED OIL

Supply	*(Quads)*	*Percent of total*
Oil	35.5	35.5
Coal	26.5	26.5
Gas	23.5	23.5
Hydro and geothermal	1.6	1.6
Nuclear	10.0	10
Solar	3.0	3
Total	100	100

4.5 ENERGY SUPPLY FOR THE WORLD

The growth of energy use by the world has followed an exponential rate of 4.5 percent over the past several decades and many expect this growth rate to continue at least until the 21st century, barring a worldwide economic depression. The growth rate for Eastern Europe and Russia may approach 5 percent over the rest of this century as these nations reach out for affluence and high productivity.

It is expected that oil production will grow dramatically in mainland China, the Middle East, and Africa, in order to supply their increasing demands for energy. One intriguing possibility is the projection of rapid industrialization of the Middle East to the point of consuming the major part of its own oil production by the year 2000.

Europe and many nations of the world are basing their future expansion of energy consumption on the availability of nuclear-fission reactor power plants by the 1980's. In 1973, Western Europe was 67 percent dependent on imported energy sources and Japan 85 percent dependent. Russia is essentially self-sufficient, while the U.S. imports about 12 percent of its energy.

The world consumed approximately 260×10^{15} Btu (78×10^{12} kilowatt-hours) in 1975, and we may expect this to grow to 800×10^{15} Btu by the year 2000 if the rate of growth is maintained at 4.5 percent per year (a questionable assumption).

The unsettled political situation in the Middle East and the rising costs of oil have been major factors in the eager development of new energy sources in all industrialized countries. The emphasis has, up to now, been put on two sources: nuclear en[illegible] and domestic oil and gas production, but a third source is al[illegible] receiving m[illegible] and more interest—the use of coal directly and for the productio[illegible] of synthetic gas. [7] The development of the Alaskan and North Sea oil fields can supply only a fraction of the U.S. and European demands.

A decade ago, nuclear fission power was presented as the answer to all future energy problems. Now, however, serious concern with environmental and safety factors is delaying full and rapid exploitation of this energy source.

Table 4.5
INCREASE IN ENERGY USE FOR 1951 TO 1969

	Energy increase ($\times 10^{12}$ *kilowatt-hours*)	*Percent increase*
World total	37.2	100%
Third World	4.1	11%
U.S.S.R. and Eastern Europe	13.0	35%
U.S.A. and Western Europe	20.1	54%

The world doubled its use of energy over the period 1951 to 1969, as shown in Table 4.5. During the remaining years of the 20th century, we can expect the rate of growth of energy consumption to rise in the Third World while decreasing somewhat in the U.S. and Western Europe. As industrialized nations increase in affluence, their per capita energy use is increased. Table 4.6 shows the increase in per capita energy use for selected regions in the world for the period 1951 to 1969. [7] It is reasonable to expect that the increase in per capita consumption will be slowed down over the next decade for the industrialized nations, while the per capita consumption in less developed nations will continue to increase at a constant or growing rate. Energy consumption per capita in the U.S. has essentially leveled off since 1968 (see Table 1.2), and we can expect this effect to continue. Energy use per capita in the U.S. increased from 225×10^6 Btu in 1951 to 325×10^6 Btu in 1969—an increase of 44 percent over the period. We might project a modest growth in per capita consumption in the U.S., from 337×10^6 Btu in 1971 to 350×10^6 Btu in 1980.

Table 4.6
INCREASE IN PER CAPITA ENERGY USE FOR CERTAIN REGIONS FOR 1951–1969

	Energy increase (megawatt-hours)
North America	23.6
South America	2.5
Western Europe	10.1
Africa	0.8
U.S.S.R. and Eastern Europe	8.0

While recognizing the increasing worldwide demand for energy, we must also work towards constraining this demand by means of energy conservation and lifestyle changes. Reduction in the rate of growth of demand in the transportation sector is discussed in Chapter 9. The conservation of energy is discussed in Chapter 21.

REFERENCES

1. R. C. DORF, *Technology, Society and Man*, Boyd and Fraser Pub. Co., San Francisco, 1974, Chapter 19.
2. J. MARTINO, "What do you do with 35 conflicting forecasts?," *The Futurist*, June 1973, pp. 134–135.
3. "Energy demand: Constant per capita," *Technology Review*, April 1974, pp. 67–68.
4. V. E. MCKELVEY, "Mineral resource estimates and public policy," *American Scientist*, Jan. 1972, pp. 32–40.
5. *A Time to Choose*, Report of the Energy Policy Project of the Ford Foundation, Ballinger Pub. Co., Cambridge, Mass., 1974.
6. *No Time To Confuse: A Critique of the Report of the Energy Policy Project*, Institute for Contemporary Studies, San Francisco, 1975.
7. L. KRISTOFERSON, "Energy in society," *Ambio*, 2, No. 6, 1973, pp. 178–185.
8. C. WILSON, *Energy Demand Studies: Major Consuming Countries*, M.I.T. Press, Cambridge, 1977.
9. G. LEACH, "Energy futures—wide open to change and choice," *Ambio*, 5, No. 3, 1976, pp. 108–116.
10. C. WILSON, *Energy Demand to the Year 2000 and Energy Supply–Demand Integrations*, The M.I.T. Press, Cambridge, Mass., 1977.

EXERCISES

4.1 If the enrollment of your college grows at a rate of 2% per year for the next decade, by what factor is the enrollment multiplied? What is the total percentage increase over that ten-year period?

4.2 The U.S. has approximately 80×10^{18} Btu of energy in coal remaining to be exploited, and currently uses 16×10^{15} Btu of coal each year. If the growth rate of coal use is 5% over the next several centuries, how long would it take to completely exhaust this resource?

4.3 Draw a curve of energy consumption in the U.S., for the period 1970 to the year 2000, that assumes a growth rate of 2% per year. What are the values of consumption for the years 1985 and 2000?

4.4 Draw a curve of energy consumption in the U.S. for a tapered growth of 3% initially in 1970, decreasing to a zero-growth rate in 2010. What are the values of consumption for the years 1985 and 2000?

4.5 Using natural logarithms and the approximation that $\ln(1 + x) \simeq x$ for small x, show that

$$t_{\text{double}} \simeq \frac{69.3}{r}.$$

Compare this result with Eq. (4.8) and explain the discrepancy.

4.6 For the curve obtained in Exercise 4.3, sketch the supply elements in a manner similar to that shown in Fig. 4.5. Decrease the reliance on imported oil and nuclear energy in your projection.

4.7 Early hunting man, with fire available but no agriculture (1610), used 5000 kilocalories per day, while early agricultural man (1700) used 12,000 kilocalories per day. Advanced agricultural man (1780) used tools and domesticated animals and consumed about 30,000 kilocalories per day. Industrial man (about 1870) used about 70,000 kilocalories per day and contemporary man uses about 230,000 kilocalories per day. Complete a plot with logarithmic coordinates for energy per capita per day as the vertical scale and years (linear) on the horizontal. Determine the rate of growth over the period 1600 to 1975. Estimate, by extrapolating the curve, what the per capita use would be in the year 2100. Is it reasonable to extrapolate this curve over this many years? Do you expect that this per capita figure will be attained?

*4.8 When a resource is first discovered, its production may rise from zero at an exponential rate. Eventually, as the resource is depleted, it is more difficult and expensive to exploit, and the rate of growth of the consumption of the resource slows down. Let the value of the ultimate resource be Q_∞ and the cumulative consumption of the resource be Q. The equation for the use of the resource will be

$$\frac{dQ}{dt} = cQ(Q_\infty - Q)$$

where c is constant. Solve the ratio $Q_{(t)}/Q_\infty$ which yields a curve called the logistics curve. Note that the rate of change approaches zero when Q approaches the ultimate value Q_∞.

* An asterisk indicates a relatively difficult or advanced exercise.

vidrio Pyrex evacuados a presiones de 10^{-2} Torr con el fin de reducir las pérdidas por convección.

d) Como sistema mecánico se escogió un motor de pistones de vapor con una eficiencia de 20%. También se probó una turbina de vapor de 1 kW, pero desafortunadamente su eficiencia fue muy baja (alrededor de 2 por ciento).

El fluido de trabajo es vapor a una temperatura de 200°C y una presión de 3 atm. Este sistema se ha hecho funcionar con una bomba de agua para tener una aplicación inmediata en pozos. (Fig. 3)

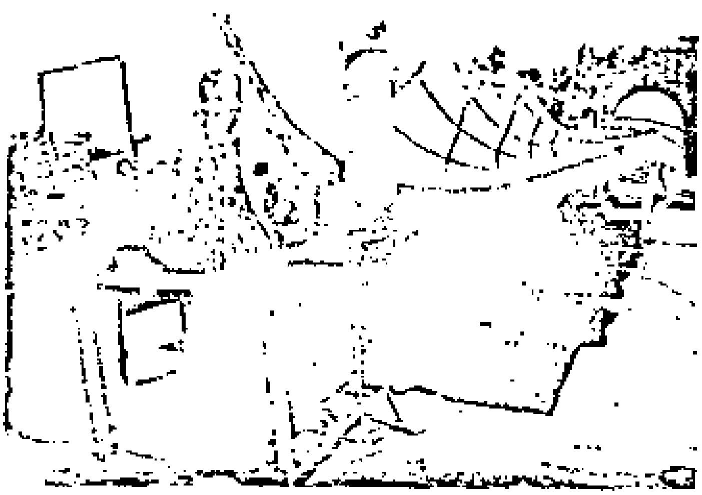


Figura 3. Sistema solar del Instituto de Ingeniería con una bomba de agua.

En el cuadro 2 se comparan los sistemas que trabajan a base de helióstatos y que en su mayoría son para potencias grandes.

En los sistemas de torre central como el de los Laboratorios Sandia de 5 MW_t los espejos están instalados sobre el suelo y orientados para reflejar la parte directa de la radiación solar hacia un absorbedor que se encuentra en la parte superior de la torre; ésta hace posible que el absorbedor reciba la radiación solar directa de todos los espejos a todas las horas del día. En el receptor, la radiación se absorbe por tubos negros por los que circula un fluido que se calienta, y que posteriormente se envía a una turbina que tiene acoplado un generador para producir electricidad. Estos sistemas deben contar con un almacenamiento de calor para asegurar la generación de potencia en los periodos de nubosidad.

En general estos sistemas constan esencialmente de cuatro subsistemas:

1) El conjunto de helióstatos orientados.

2) La torre central con un absorbedor en la parte superior.

3) El sistema de almacenamiento de calor.

4) El subsistema de conversión del calor a energía mecánica y eléctrica.

Una de las características más atractivas de estos sistemas es que todas sus partes utilizan tecnología conocida, es decir, el nivel general de incertidumbre técnica es bajo y de aquí, que en un futuro muy próximo, se puedan implantar sistemas mayores. Existen ya dos proyectos grandes que están por iniciarse: el de 10 MW_e en Barstow, California, EUA y el de 20 MW_t en Armenia, Rusia; el primero tendrá un costo del orden de 100 millones de dólares.

Factores geográficos que afectan el uso de concentradores

La temperatura en un sistema de captadores depende del balance térmico entre el calor ganado al flujo solar y las pérdidas térmicas debido a la convección y a la radiación hacia el ambiente, por lo que al emplear dispositivos de enfoque de radiación solar sería factible mejorar el balance entre ganancias y pérdidas térmicas con lo que alcanzarían mayores temperaturas. Un aspecto importante es que a fin de que los captadores de enfoque sean más eficientes, es necesario que éstos sigan el movimiento del Sol.

Existen diferentes métodos para seguir al Sol:

a) Sistemas a base de computadoras de mando central que siguen un programa fijo, debido a que el movimiento del Sol es perfectamente pronosticable.

CUADRO 2

Sistemas solares a base de Helióstatos

	Laboratorios Sandia (EU)	*Tecnológico de Georgia (EU)*	*Laboratorio White Sands (EU)*	*Odiello Francia*	*Génova Italia*	*Mitsubishi Japón*	*THEM Francia (para 1980)*
F... ia térmica total (kW_t)	5 000	400	30	1 000	130	10	3 000
... de helióstatos	222	550	356	63	271	120	–
...o de helióstatos (m)	6 x 6	1.1D	0.6 x 0.6	6 x 7.5	–	0.35 x 0.35	–
Area total de helióstatos (m^2)	8 257	532	137	2 835	136	–	–
Area de prueba (m)	2 – 3	0.3 – 1.0	0.08 – 0.15	0.25 – 1	–	–	–
Flujo (W/cm)	250	375	400	1 600	–	–	–
Temperatura máxima (°C)	2 300	2 100	2 450	3 800	800	–	–

b) Sistemas a base de sensores electrónicos ligados a servo-mecanismos usualmente a base de celdas fotovoltaicas.

c) Sistemas a base de expansión de gases con efecto peristáltico invertido; estos sistemas son autónomos pues trabajan con energía solar.

d) Sistemas a base de efectos bimetálicos.

Tomando en cuenta estos factores es importante la selección de regiones para utilizar la energía solar, en especial para los captadores de enfoque ya que éstos trabajan con la componente directa de la radiación solar; las zonas desérticas son las mejores ya que en ellas se pueden esperar grandes cantidades de radiación directa durante todo el año. En la Fig. 4 se muestra la radiación total promedio diaria durante el año en la República Mexicana en Langleys/día (cal/cm^2·día).

Costo de la generación de electricidad mediante conversión fototérmica

El principal argumento en contra de la generación de electricidad por transformación fototérmica de la energía solar, es su alto costo. Antes de profundizar en un análisis comparativo de costos conviene aclarar bajo qué condiciones es conveniente la generación de electricidad en aparatos solares.

La primera condición sería: cuando comiencen a agotarse las fuentes tradicionales y no quede más recurso que utilizar la energía solar, la nuclear y otras. Esta crisis según algunas estimaciones pesimistas se hará evidente dentro de 20 años y según los optimistas dentro de 50. En todo caso, tarde o temprano, será una realidad que tendremos que enfrentar. Las centrales nucleares serán sin duda las que remplacen en mayor medida a las tradicionales centrales termoeléctricas, pero con una interrogante muy importante que aún no se ha

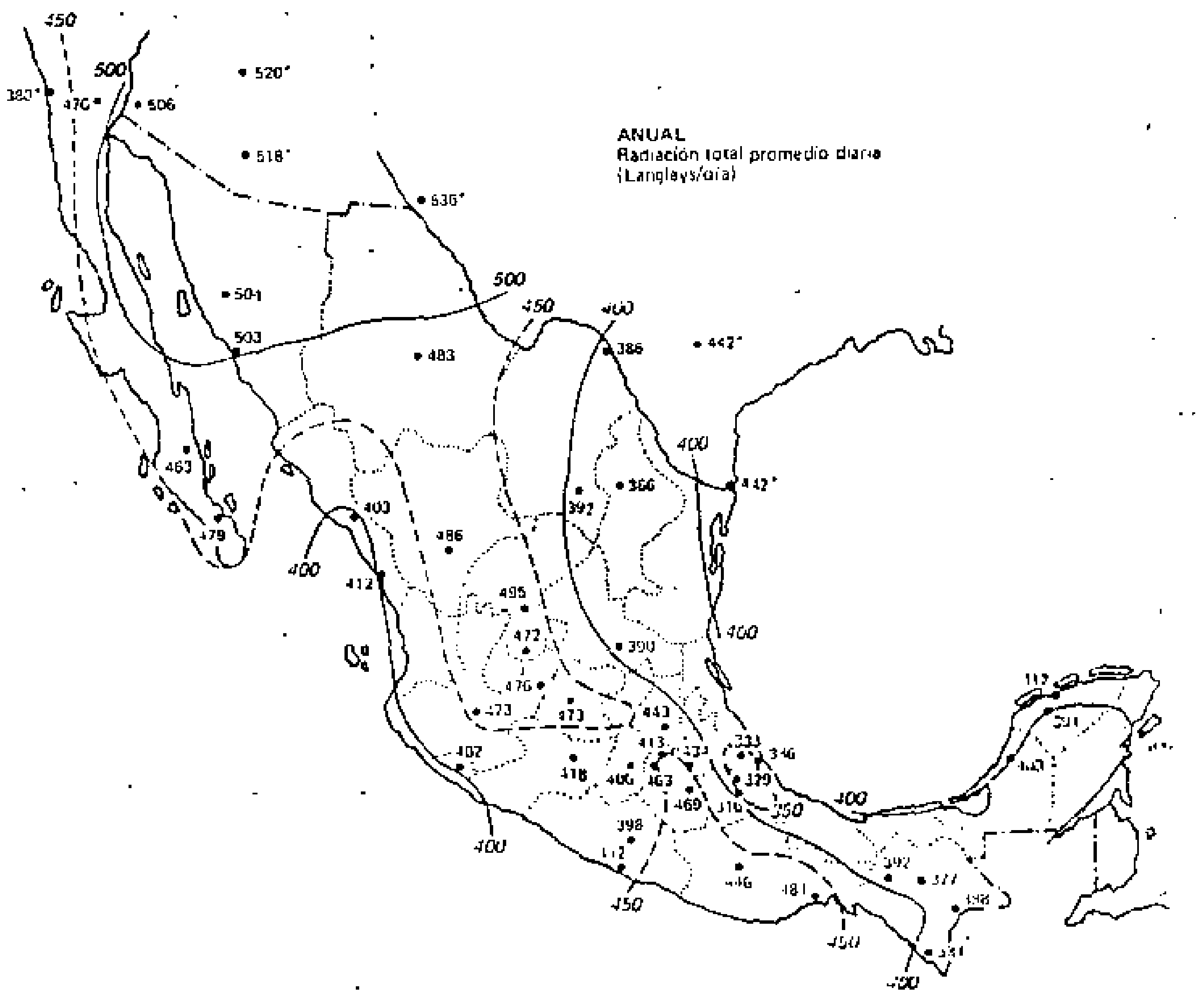


Figura 4.

definido totalmente y que es la de seguridad física (sabotaje y sus catastróficas consecuencias) y la de los desechos radiactivos. La opinión pública ha tenido una influencia creciente al respecto principalmente en Suecia y en Francia y comienza a sentirse con mayor presión en Estados Unidos. Esto hace pensar que en el futuro, dada las limitaciones que se irán imponiendo a la energía nuclear habrá una buena oportunidad para la energía solar en la forma de pequeñas centrales, del orden de 1 a 5 MW_e que suministren energía eléctrica a pequeñas poblaciones en zonas de alta insolación.

La segunda, que corresponde a los días en que estamos viviendo, es que vale la pena pensar si en un territorio de alta insolación en zonas apartadas, puede competir la generación de electricidad por transformación fototécnica de la energía solar, con un motor-generador diesel o con la electrificación rural.

A este respecto se han realizado estudios económicos para México (Ref. 36) que muestran que todavía sigue siendo más barato generar electricidad en zonas apartadas, por medio de un grupo diesel-generador que por energía solar. Pero la tendencia que muestra el costo de la generación solar a ir bajando su precio debido a nuevos desarrollos que permiten aumentar las eficiencias (lo que se traduce en menos m^2 de colector por kW generado) y que abaratan los costos de fabricación de los colectores, sumado a la fuerte influencia que el valor del combustible tiene en el costo de operación de un motor diesel, hacen evidente que llegará pronto el año en que ambos sistemas sean competitivos desde el punto de vista del costo total. Esta fecha será determinada principalmente por la razón de incremento de precio que vaya registrando año con año el petróleo diesel.

En las figuras 5 y 6 se muestra el costo de generación por kW, reducido a valores de 1978, que tendría la generación de electricidad en un poblado pequeño, apartado unos 50 km de una línea principal de transmisión eléctrica y unos 200 km del centro de abastecimiento de combustible. A continuación hacemos una comparación de tres opciones para bombear agua en dicha zona. (figuras 5 y 6).

1) Bomba solar con colector cilíndrico parabólico dirigido.

2) Planta Diesel (grupo electrógeno) convencional, con almacenamiento de combustible para un mes de operación.

3) Banco de un transformador (45 kVA) que alimente al grupo motor bomba, derivando una línea de alta tensión de la red más cercana (CFE).

Para el costo del capital y la tasa de descuento, se tomó 12, 15 y 20% de interés anual.

Para la escalación anual de precios de materiales, equipo y salarios, 7 por ciento anual.

Para la escalación anual de precios de combustible: 10 por ciento. Además, se tomaron como caso extremo valores con escalación de 20 por ciento anual para dar idea del costo a largo plazo, 20 años, según pronósticos de escasez de energéticos.

Para la vida útil (vida económica) en el ciclo de servicio, se consideró:

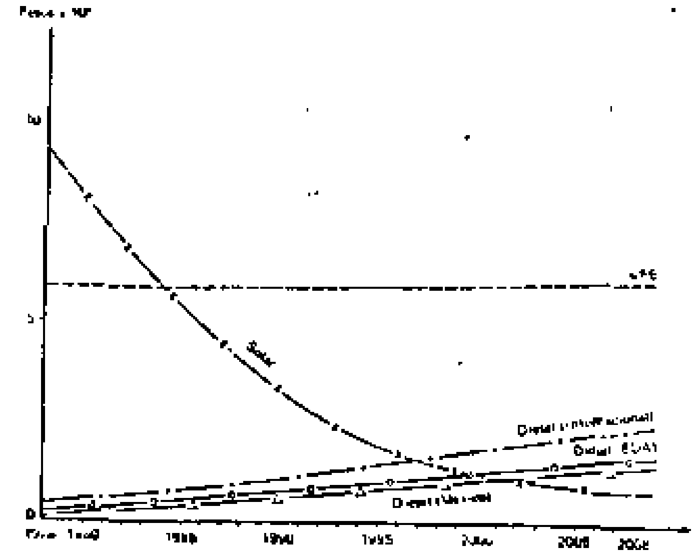


Figura 5. Costos comparativos de los sistema solar, diesel y electrificación de la CFE con una línea de 50 km, para una capacidad instalada de 35 kW, en pesos de 1978. (Escalación precio combustible de 10% anual)

Planta diesel	10 años
Planta solar	20 años
Líneas transmisión	30 años
Planta termoeléctrica	30 años

Para gastos de mantenimiento:

Planta diesel	20% anual sobre la inversión.
Planta solar	2% anual sobre la inversión.
Electrificación	valores según datos de la CFE.
Operación promedio:	6 horas por día durante todo el año.
Capacidad de la planta:	35 kW.

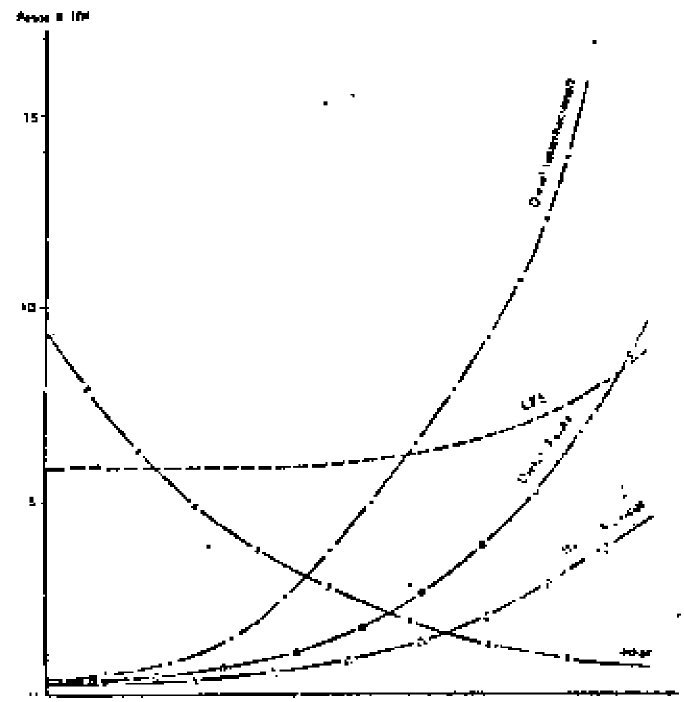


Figura 6. Costos comparativos de los sistemas solar, diesel y electrificación de la CFE con una línea de 50 km, para una capacidad instalada de 35 kW, en pesos de 1978. (Escalación precio combustible de 20% anual).

Se consideraron los siguientes parámetros y condiciones particulares para cada sistema:

a) Planta diesel: Costos actuales del mercado en México; promedio de precios de Ingeniería Electromecánica, Ottomotores, SELMEC, IGSA, y Diesel Motriz.

Promedio:	$ 5,500/kW instalado.
Consumo:	8 L/hora
Precio diesel:	$ 650/m³ en México.
	$ 2,158 m³ de EUA.
	$ 7,900/m³ dato de precio internacional.
Transporte diesel:	$ 220/tonelada.

b) Planta solar: Laboratorios Sandia (Ref. 22).

11 400 dls./kW	Precio promedio de sistemas de irrigación, con almacenamiento térmico y de agua, y colector parabólico dirigido de 10 dls./pie², capacidades de 70 kW valor medio; en varios lugares, Oregon, Arizona, Texas, Nuevo México, Nebraska, California.
4 900 dls./kW	Valor considerado para 1988, 10 años, por producción en serie, más de 1 000 unidades y mejoras en la tecnología, disminuirá el costo de producción.
1 000 dls./kW	Valor considerado para 2008, 30 años, suponiendo que se conectaría en una planta solar mayor de 1 MW con torre central Barber-Nichols (ref. 26).

1 500 a 3 800 dls./kW para 1978, valor estimado promedio.

2 700 dls./kW con diferentes tipos de colectores.

c) Electrificación rural, CFE (ref. 36). Datos de la Dirección de Electrificación Rural, CFE, México, para su programa de 1978.

Para efectos de comparación en cada sistema se calculó:

- el valor de la inversión inicial
- costo de mantenimiento
- costo de transporte (caso planta Diesel)
- costo de operación, por kW generado
- cálculo del flujo de efectivo y el valor presente correspondiente de los costos (gastos) a 30 años con la escalación de precios mencionada, sumado este valor presente a la inversión inicial. El cálculo de valor presente se hizo con factores anuales y por 30 años.

Agradecimientos. Se utilizaron datos proporcionados por el Ing. Luis Palacios Hammeken para la parte de costos. De la Gerencia de Electrificación Rural de la CFE se obtuvieron cifras para el mismo inciso.△

Referencias

1. Howell, N.R., "Unsolved Problems in Solar Thermal Energy Conversion", *Applied Mechanics Reviews*, vol. 27, núm. 8, (1974).
2. Bakus, C.E., "Solar-Energy Conversion at High Solar Intensities", *J. Vac. Sci. Technol.* vol. 12, núm. 5, (sep./oct. 1975).
3. Mattox, D.M., "Solar-Energy Materials Preparation Techniques" *J. Vac. Sci. Technol.* vol. 12, núm. 5, (1975).
4. "Electricité solaire," *Colloque International*, Tulouse, (1976).
5. Walton, J.D., Ray, A.H. y Bomar, S.H., *A State of the Art Survey of Solar Powered Irrigation Pumps, Solar Cookers, and Wood Burning Stoves for Use in Sub-Sahara Africa*, Georgia Institute of Technology, (1978).
6. Metz, W.D., "Solar Thermal Energy: Bringing the Pieces Together", *Science*, vol. 197, (1977).
7. Almanza, R. y López, S., *Radiación solar global en la República Mexicana mediante datos de insolación*, Instituto de Ingeniería, UNAM, núm. 357, México, (oct. 1975).
8. *Small Solar Power Systems*. Results of an inquiry on research and development performed in the member countries of the International Energy Agency, IEA (1976).
9. *Solar Energy Intelligence Report*, vol. 4, núm. 4, (ene. 1978).
10. *Solar Energy Intelligence Report*, vol. 3, núm. 5 (feb. 1977).
11. *Solar Energy Intelligence Report*, vol. 3, núm. 40, (nov. 1977).
12. Almanza, E., *et. al.*, "Bomba solar de 1 kW", *Informe interno* Instituto de Ingeniería, UNAM, Mexico, (sep. 1976).
13. Almanza, R., *et. al.*, "Bomba solar", *Informe de avance 1977*, Instituto de Ingeniería, UNAM, México, (ene. 1978).
14. Milter, D., *Rankine Cycle Working Fluids for Solar to Electrical Energy Conversion*, Monsanto Research Corporation, NTIS, (1974).
15. Tabor, H. y Bronicki, L., "Small Turbine for Solar Energy Power Package", *Proc., U.N. Conference on New Sources of Energy*, (1964).
16. Leonard, J.A. y Thunberg, S., "Solar Total Energy Program Quarterly Report", *SAND 74 0391*, Sandia Laboratories Albuquerque, Nuevo México, (1974).
17. Chicurel, R., "Desarrollo de un motor rotatorio de combustión" *Memoria, I Congreso Acad. Nacional Ing.*, Guanajuato, Gto., (1975), p. 306.
18. Chicurel, R., "Development of a novel rotary engine", *Proc. X Intersociety Energy Conversion Engine Conference*, Lake Tahoe, Nevada, (sep. 1976), p. 73
19. Faber, E.A., Morrison, C.A. e Ingley, H.A., "A Self Contained Powered Tracking Device", *Folleto ASME 76-WA/HT-26*, 9(1976).
20. *Ormat Solar Energy Converter and Water Pump*, Ormat Turbines Ltd., New Industrial Area, Yavne, Israel.
21. *Minto Freon Engine*, Sun Power Systems, Florida, (1977).
22. "Preliminary Economic Analysis of Solar Irrigation Systems for Selected Locations", *SAND 77-1403*, (nov. 1977).
23. Takla, Eng. Assad, "Techno-Economic Comparison between Solar Engines and Internal Combustion Engines", *University of Damascous*, (nov. 1976).
24. Palz, W., "Electricidad Solar", *UNESCO*, (1978).
25. *Solar Energy Intelligence Report*, vol. 4, núm. 15, (abr. 10, 1978).
26. Barber, R.E., "Current Costs of Solar Powered Organic Rankine Cycle Engines", Barber-Nichols Engineering Co., *Solar Energy*, vol. 20, núm. 1, (1978).
27. Caputo, R.S. y Truscello, V.C., "Solar Thermal Electric Power Plants, Their Performance Characteristics and Total Social Costs", 11th., *IECEC*, (1976).
28. Barber, R.E., "Solar Powered Organic Cycle Engines. Characteristics and Costs", 11th., *IECEC*, (1976).
29. Easton, C.R. y Raetz, J.E., "Collector Field Optimization for a Solar Thermal Electric Power Plant", 11th, *IECEC*, (1976).
30. Hopmann, H., Berdorfer, K. y Vinz, P., "Development of a 10 kW_e solar thermal power station", (1976).
31. Assad Takla, E., "Techno-Economic Comparison Between Solar Engines and Internal Combustion Engines", *United Nations Industrial Development Organization*, (1976).
32. Duffie, J.A., y Beckman, W.A., *Solar Energy Thermal Processes*, John Wiley and Sons, (1974).
33. Merrigan, J.A., *Sunlight to Electricity*, The MIT Press, (1975).
34. Meinel, A.B. y Meinel, M.P., *Applied Solar Energy. An Introduction*, Addison-Wesley, (1976).
35. Chabbal, R., *et. al.* "Solar-Thermal Power Station Delivers First Electricity", *Research 6*., Centre National de la Recherche Scientifique, France, (1977).
36. Palacios, L. y Almanza, R. "Análisis económico preliminar de un sistema de bombeo. Irrigación en localidades aisladas", *Informe interno*, Instituto de Ingeniería, UNAM, México, (1978).

Entrevista con el Ing. Juan Eibenschutz, Secretario Ejecutivo de la Comisión de Energéticos

El futuro energético de México estará basado en el petróleo.

México tiene una tasa de crecimiento para la demanda global de energía del orden de 7% anual. Esa es la situación y su característica más importante es que el petróleo y el gas satisfacen alrededor de 90% de la demanda.

En el futuro próximo esta situación no sufrirá cambios importantes. Es cierto que entre sus políticas la CFE tiene metas de diversificación de energías primarias: plantas hidroeléctricas, nucleares, carboníferas, geotérmicas, etc. A pesar de ello, seguirán preponderando los hidrocarburos.

Por lo demás, los recientes descubrimientos petrolíferos subrayan que el futuro energético del país se ve objetivamente muy petrolero.

Tales descubrimientos implican también un desafío, representan un reto para la "salud" energética de México. La abundancia de energéticos plantea una serie de opciones de políticas económicas generales.

Con la información que se tenía hace unos años sobre nuestro potencial energético, era evidente que México tenía que embarcarse aprisa en el desarrollo de fuentes alternativas. Los datos actuales, si bien no invalidan las metas de diversificación, que están presentes en el pensamiento de los altos funcionarios del gobierno, sí plantean el problema pero sin la urgencia anterior.

Esto es bueno y malo al mismo tiempo. Es bueno porque permite hacer las cosas mediante una mejor y más meditada planificación. Es malo porque al ya no urgir el desarrollo de fuentes alternativas se corre el riesgo de dejar el problema sin solución.

Hay que destinar recursos importantes para planes geotérmicos y carboníferos.

En México se está trabajando modestamente en el desarrollo de fuentes no convencionales. En mi opinión se trata aún de desarrollos incipientes y aislados que es preciso integrar y fortalecer, ya que no hemos dedicado ni suficientes recursos ni suficiente planeación al respecto. Es cierto que somos un país en desarrollo y que, a pesar de nuestra riqueza energética potencial, somos relativamente pobres. Sin embargo, hay que destinar recursos importantes para el desarrollo de fuentes no convencionales para no perder el impulso de la riqueza petrolera.

En el corto plazo, los mayores recursos deben dedicarse a programas como el de geotermia y carbón. Este último, aunque parezca raro, en México es una fuente no convencional, es decir, no se usa como energético en el sentido en que aquí estamos hablando.

Creo que algo que nos falta y que deberíamos hacer es formalizar, sistematizar los conocimientos sobre los desarrollos de fuentes no convencionales realizados en otros países. Por ejemplo, el caso de la fusión nuclear; sabemos que está fuera del alcance económico del país desarrollar esta fuente energética, pero se debe mantener un pequeño grupo que esté realmente al tanto de lo que suceda en un campo tan importante como ese.

En los países industrializados hay razones de fondo para desarrollar fuentes no convencionales de energía. La más decisiva es que la mayoría de ellos no son autosuficientes en energéticos. El caso de Estados Unidos es un ejemplo; debe importar energéticos y esto crea el interés en diversificar, en desarrollar nuevas fuentes, que le permitan hacer frente a la demanda en mejores condiciones.

Es muy difícil que los países industriales estén dispuestos a cambiar sus formas de vida.

En relación con las llamadas energías blandas, debemos advertir que implican un cambio en la estructura de vida de la sociedad moderna.

En mi opinión —y aunque por razones prácticas los países desarrollados hablan con buena voluntad de estos enfoques—, encuentro difícil que una sociedad industrial esté dispuesta a cambiar de vida, es decir, a prescindir de las ciudades modernas, a prescindir del transporte en su forma actual, de la calefacción central, de aire acondicionado, etcétera.

En los países en desarrollo la idea es también difícil de realizar. Es un tanto utópico pretender que la gente acostumbrada a vivir en la miseria y que comienza a tener acceso al "modus vivendi" de la sociedad industrial, lo abandone en favor de una vida más armónica con la preservación del ambiente.

En comunidades atrasadas y aisladas hay que comenzar por resolver el problema de la sobrevivencia.

En el caso de comunidades pequeñas, atrasadas y aisladas, en donde no hay agua potable, donde el nivel de alimentación es inferior al mínimo humano, en donde se constatan condiciones miserables, hablar de una infraestructura compleja tipo industrial parece casi una grosería.

Ahora bien, para llegar a desarrollar esas comunidades hasta un nivel de satisfacción de las necesidades elementales se requieren varias medidas que tal vez incluyan energía eléctrica; de ser así, su introducción formaría parte del "paquete" completo que tienda a resolver la situación.

El costo para un país como México de llevar electricidad en forma masiva a estas comunidades con un sistema del tipo desarrollado en tecnologías avanzadas como la espacial, es mucho mayor en el presente que los costos de sistemas convencionales. Una cosa es que se electrifiquen algunos poblados con métodos solares avanzados en plan de desarrollo tecnológico y otra muy distinta es proponer un plan de plantas solares para toda comunidad aislada de doscientos habitantes. El volumen de recursos necesarios está fuera del alcance del país, aun cuando nos volvamos muy ricos con el petróleo.

En casos especiales, la aplicación de estas tecnologías pueda ser conveniente como solución a un problema específico (radiocomunicación, enseñanza por televisión, etc.,) pero de ninguna manera puede considerarse en el presente com una solución masiva a los problemas del medio rural subdesarrollado. Por otro lado, existen otros tipos de fuentes no convencionales cuya tecnología no es compleja y cuya utilización se ha llevado a cabo durante siglos, como la energía eólica para bombeo de agua, que pueden contribuir a resolver el problema de sobrevivencia en comunidades aisladas.

Las propuestas de utilización de fuentes no convencionales se deben analizar con cuidado para no caer en aberraciones que posteriormente creen un ambiente de desconfianza hacia estas experiencias.

Fuera de la nuclear no hay hoy en día en el mundo una nueva fuente de energía de aplicación masiva.

Debemos ser claros. El problema de hablar de la introducción de una nueva fuente de energía —a nivel de utilización masiva— se reduce a la nuclear, actualmente. Yo no considero al sol como un fuente energética que pueda ser aplica masivamente ni en México ni en ningu lugar del mundo, en el presente.

Aún resta mucho desarrollo al respecto. Primero hay que convertirla en tecnología accesible. Es decir, que en términos económicos sea realmente una tecnología energética disponible. Es obvio que, por ejemplo, si las celdas fotovoltaicas se pudieran construir a un precio competitivo con respecto a la tecnología convencional, resultaría factible y hasta rápida su incorporación al sistema. Otro tanto acontece con la incorporación de sistemas eólicos a la generación energética a nivel industrial. Tales posibilidades implican el desarrollo de los estudios, la evaluación de sus resultados y después la construcción masiva de tipo de instalaciones que no son sencillas. Podemos decir que la etapa principal, a nivel de su utilización masiva, es la conversión de estas investigaciones en tecnología comercial.

El problema de las energías blandas y su utilización en el mundo moder contienen una filosofía que, en lo perso nal me gusta mucho, pero que resulta de difícil aplicación. Sería necesario que la humanidad se diera cuenta que la sociedad industrial no es el mejor modelo.Δ

Conversión fotovoltaica de la energía solar a energía eléctrica

Esteban Javier Pérez
Juan Luis del Valle P.*

Resumen

La conversión directa de energía solar en electricidad hace uso de las consecuencias del efecto fotovoltaico en un material semiconductor. Los dispositivos que realizan esta función son conocidos como celdas solares. El rendimiento de estos dispositivos depende de las características espectrales de la radiación solar así como de las propiedades y estructura de los materiales semiconductores.

Cuando una celda solar es iluminada por el sol aparece en sus extremos una diferencia de potencial de C.D. del orden de 0.5 volts y una densidad de corriente de alrededor de 30 mA/cm². La corriente total depende de la superficie expuesta a la iluminación. Así, una celda solar es inherentemente un generador de baja potencia. Para su utilización práctica es necesario asociar un gran número de celdas en serie o en paralelo para incrementar la potencia. El conjunto de celdas así asociadas se denomina módulo y generador solar. En general, para tener en cuenta la intermitencia de la energía solar se hace necesario poder almacenar la energía producida; lo que se realiza fácilmente por medio de acumuladores. Un generador solar, un banco de acumuladores, la aplicación y un sistema de control de la energía constituye lo que se llama un sistema fotovoltaico.

La conversión fotovoltaica de la energía solar en energía eléctrica es un método directo que, a diferencia de los convencionales —hidroeléctrico, nucleoeléctrico, termoeléctrico, etc.— no utiliza partes móviles ni ciclo termodinámico alguno. Como consecuencia de estas características, estos conversores tienen grandes tiempos de servicio (superior a 20 años) y su eficacia no está limitada por el principio de Carnot, sino por mecanismos de tipo cuántico y el grado de perfección de los materiales utilizados para fabricar los dispositivos de conversión conocidos como celdas solares.

Otra característica atractiva de las celdas solares es que los sistemas de potencia que las emplean pueden ser diseñados como módulos. Esto es, los sistemas fotovoltaicos pueden acoplarse económicamente a la demanda sin necesidad de emplear economías de escala, lo que permite agregar sistemas de potencia por etapas y, por ende, no partir necesariamente de sistemas de potencia relativamente grandes y esperar que la demanda los haga rentables ni, en el caso contrario, esperar que la demanda sea suficiente para instalar un sistema de potencia. Esto permitiría una flexibilidad mayor en esquemas de electrificación rural, originando un acceso relativamente más rápido a los beneficios de la electrificación de nuestras comunidades rurales, conjuntado con una mejor opción energética futura.

Desafortunadamente, aunque tal opción técnica pudiera ser factible para propósitos de electrificación rural en nuestro país, los costos actuales (que varían de 15 a 20 dólares/Watt pico) tendrían que ser reducidos a valores del orden de 0.500 dólares/Watt pico para que fueran competitivos con otras fuentes tradicionales de energía en ciertas aplicaciones de desarrollo rural, perspectiva que, por otra parte, podría ser realizada en la próxima década, dados los progresos científicos y tecnológicos actuales.

No obstante los costos actuales de los generadores fotovoltaicos en nuestro país y dadas las características de infraestructura de un gran número de comunidades rurales, existen diversas aplicaciones económicamente rentables de beneficio comunitario, tales como la televisión escolar, la radiotelefonía rural y, en los próximos años, el bombeo de agua, así como otras aplicaciones en las que es necesario una fuente de energía eléctrica autónoma y de fácil mantenimiento como es el caso de sistemas que operan en lugares remotos.

Disponibilidad de la energía solar

La energía solar recibida por la Tierra es de 5.5 kW-h/m² diario, en promedio anual y geográfico, o sea de 2×10^3 kW—h/m² anual, resultando así una insolación de 4×10^{17} kW—h para la energía solar que recibe la Tierra en un año, tal como se ilustra en la figura 1, energía que equivale a 50 000 veces el consumo eléctrico mundial durante los próximos 50 años. O bien, la energía solar que se recibe en un día promedio equivale a casi 7 000 años el consumo actual de energía.

En el área tropical y ecuatorial dentro de los paralelos 40°, la insolación anual es superior a los 600 kJ/cm², que equivale a 1666.8 kW—h/m² anuales, o sea 4.56 kW—h/m² diarios. Si el área se redujese a sólo aquella dentro de los trópicos de Cáncer y Capricornio, que están a latitudes de 27.4°, la insolación anual aumenta a un mínimo de 700 kJ/cm² (1944.6 kW—h/m² anuales, 5.32 kW—h/m² diarios).

Los países industrializados de Europa y Japón están fuera de estas regiones de alta insolación y Estados Unidos no alcanza a estar en los trópicos. Sin embargo, tales países son los que han desarrollado a un nivel comercial los generadores fotovoltaicos, generadores que claramente serán técnica y económicamente más rentables en los países en desarrollo de las áreas tropicales.

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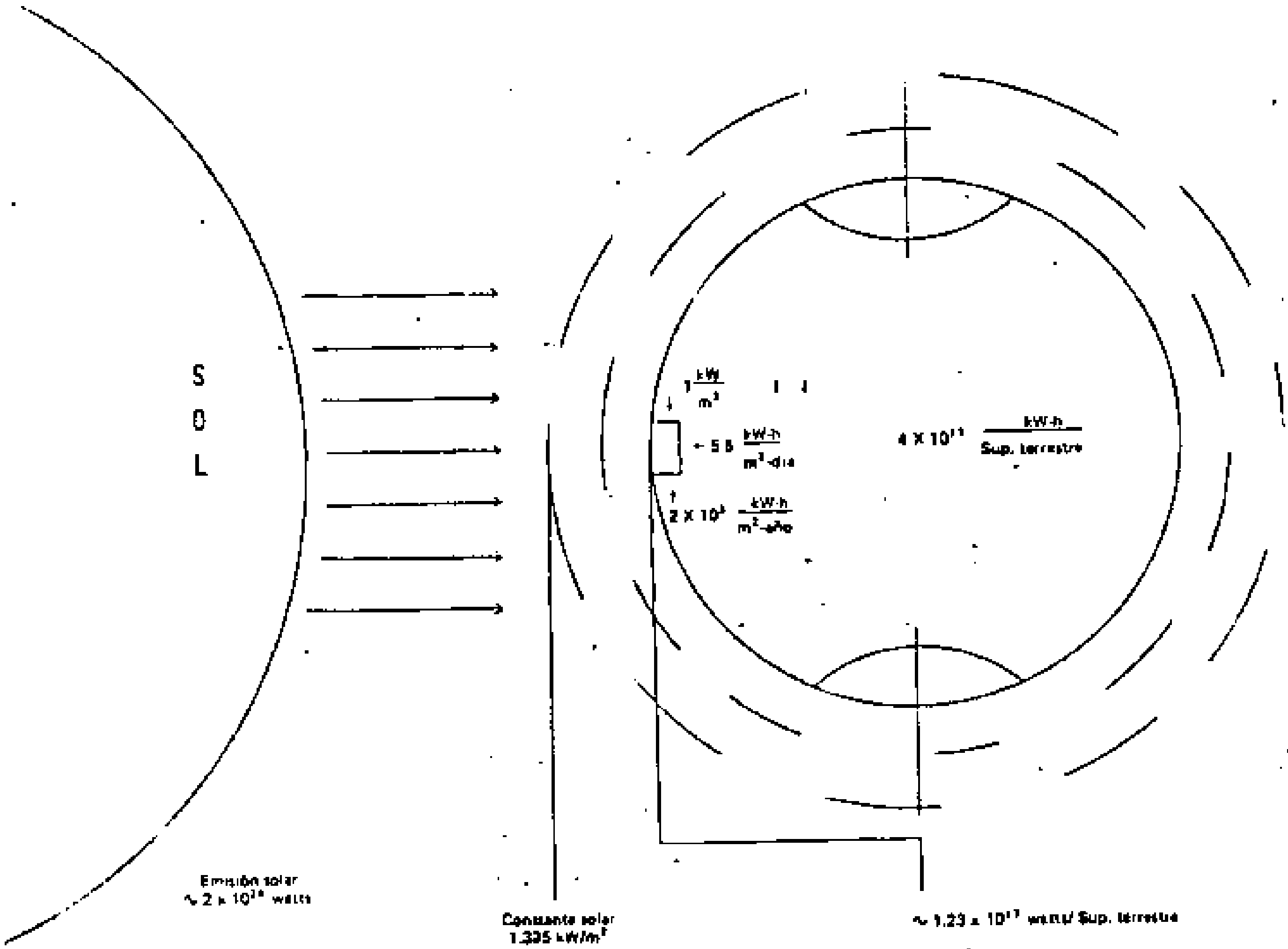


Figura 1. Características de la energía solar.

Si se usa el promedio de insolación de 2000 kW–h/m^2 anuales para las áreas tropicales, se tiene que si esta energía solar se pudiese transformar en energía eléctrica con una eficiencia de al menos 10% (lo que está completamente dentro de las posibilidades de la tecnología actual, que permite eficiencias superiores a 15%) bastaría con un cuadrado de 150 km de lado (Fig. 2) para cubrir el consumo mundial de energía eléctrica (del orden de 4.5 X 10^{12} kW–h en 1978), área que ocupa apenas 0.05% de los desiertos de nuestro planeta.

Insolación nacional

Dos terceras partes de nuestro país tienen una insolación anual superior a 700 kJ/cm^2 (≈2000 kW–h/m^2 anuales, 5.3 kW–h/m^2 diarios) y el resto, el centro y el sureste, tiene 600 kJ/cm^2. En primera aproximación, esto coincide con el hecho de que dos terceras partes de nuestro país son desérticas o semidesérticas.

Si se considera el promedio de 2000 kW –h/m^2 anuales para la mayor parte de nuestro país, se tiene que si esta energía se pudiese transformar en energía eléctrica con una eficiencia de, al menos, 10%, bastaría un cuadrado de 15 km de lado (fig. 2) para cubrir el consumo nacional de energía eléctrica (del orden de 4.5 X 10^{10} kW–h en 1978), área que ocupa apenas 0.02% de los desiertos nacionales.

Estos cálculos muestran que la energía solar es abundante aunque dispersa, esto es, de baja densidad. Así, se necesitarían grandes áreas para instalar centrales eléctricas de gran potencia, del orden de 100 000 m^2 por cada mW. Sin embargo, se necesitarán áreas tan pequeñas como 1 m^2 para suministrar energía a aparatos electrónicos tales como los de televisión educativa y radiotelefonía.

Conversión fotovoltaic

La celda solar fue obtenida originalmente como un subproducto de la investigación y desarrollo de materiales semiconductores en 1954, y desde entonces se ha beneficiado del grandísimo potencial de esa industria.

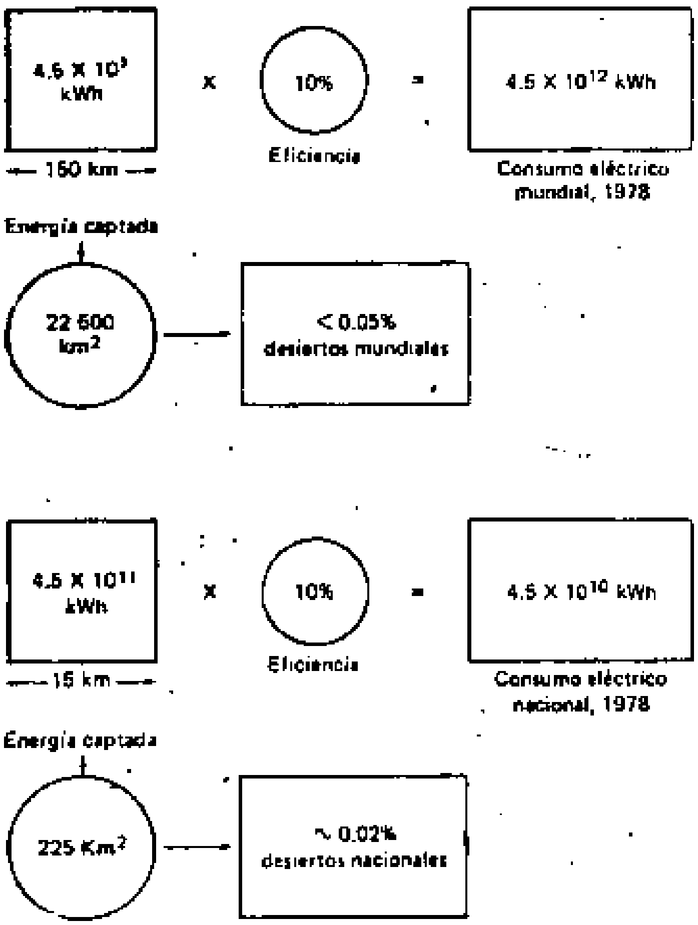


Figura 2. Disponibilidad de la energía solar a escala mundial y nacional.

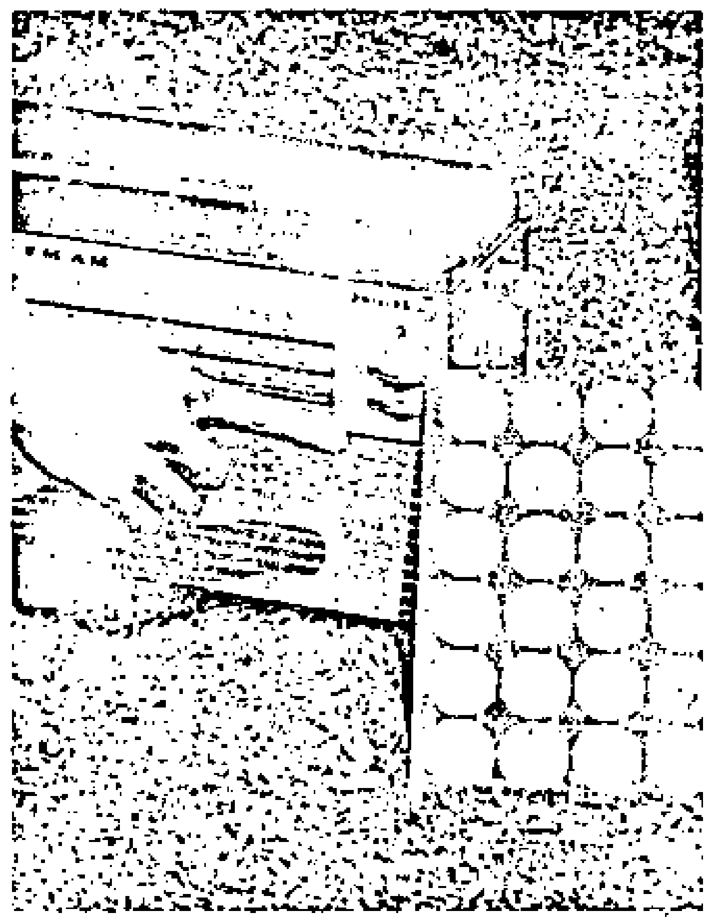


Figura 3. Radiorreceptor AF-FM operado por un módulo fotovoltaico desarrollado en el CIEA-IPN. La potencia del módulo es de 1 Watt-pico y es bastante más alta que la necesaria para la operación.

El efecto fotovoltaico puede definirse como *la generación de un potencial cuando una radiación ioniza la región cercana a la barrera de potencial de un semiconductor. Se caracteriza por una f.e.m. autogenerada y la habilidad para entregar potencia a una carga, proviniendo la potencia primaria de la radiación ionizante.*

En términos generales, la determinación del semiconductor óptimo se base en la determinación del ancho de banda prohibida E_g que proporcione la mayor potencia de salida (o sea, la máxima eficiencia que es la relación de potencia de salida a la potencia constante incidente). Desde el punto de vista de voltaje mayores E_g dan lugar a mayor energía potencial ganada por los electrones en la formación de los pares electrón-hueco y por tanto mayores voltajes de salida. Desde el punto de vista de corriente menores E_g permitirán que se aproveche mayor número de fotones, generándose así más portadores y la corriente aumentará. Surge así el compromiso en E_g y queda clara su determinación sobre el espectro solar.

Aplicaciones actuales

Las aplicaciones de las pilas solares fueron muy amplias desde 1960 en los programas espaciales y a partir de 1970 ha empezado su lenta penetración en las aplicaciones terrestres. Su precio relativamente alto (comparado con la energía eléctrica

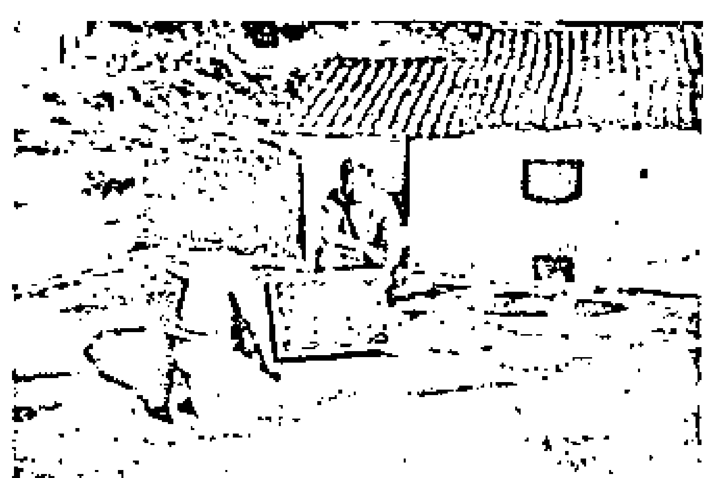


Figura 4. Módulos solares en la telesecundaria operada fotovoltaicamente, instalada por el CIEA-IPN en la sierra norte de Puebla.

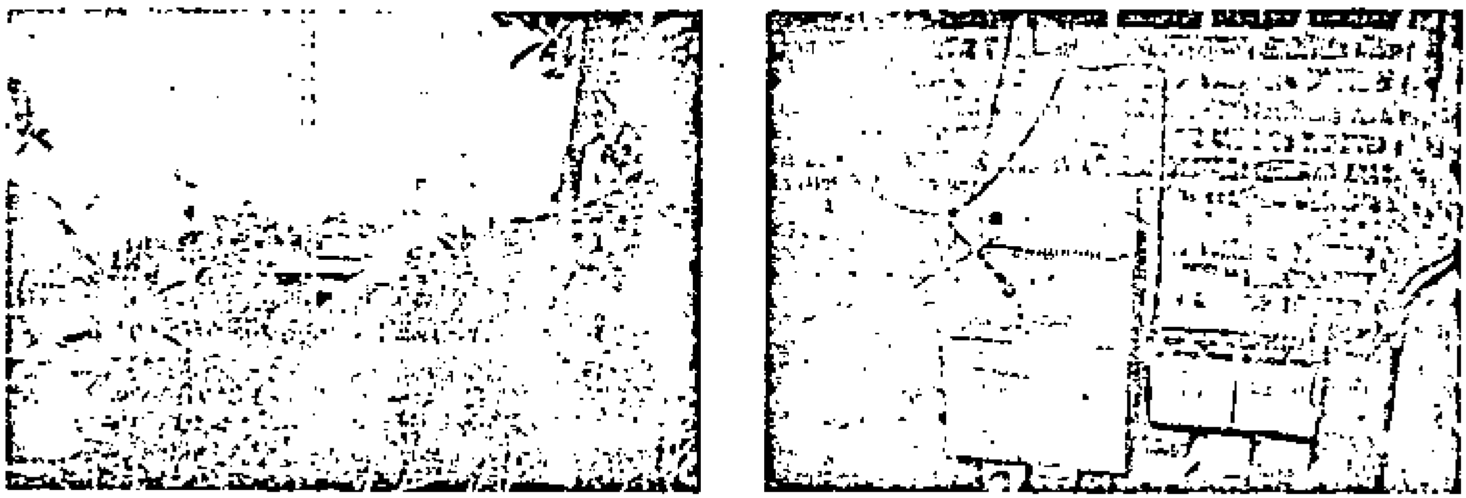


Figura 5. Sistema de radiotelefonía rural instalado en Bienvenido de Galeana, sierra norte de Puebla, por el laboratorio de Energía Solar del Departamento de Ingeniería Eléctrica del CIEA-IPN. El generador solar tiene una potencia de 28 watts-pico que garantiza una hora diaria intermitentes de operación. Los reflectores planos laterales fijos son experimentales y podrían dar hasta 40% más de energía eléctrica.

convencional en áreas electrificadas) ha circunscrito estos sistemas a las regiones aisladas y comunidades rurales. Sus características de generar energía de c.d. y de operar confiable y económicamente aun con áreas pequeñas de captación (desde unos cm^2 y con ello potencias eléctricas de algunos watts) los ha hecho ideales para equipos electrónicos tales como:

- Radiorreceptores para radiodifusión comercial y para radio profesional (Fig. 3)
- Telerreceptores para televisión comercial y para enseñanza (Fig. 4)
- Radiotelefonía rural (Fig. 5)
- Grabadoras de sonido.
- Señales para crucero en vías de ferrocarril y en carreteras
- Equipo eléctrico para acampar
- Bombeo de agua
- Plataformas de petróleo
- Transmisores de alta frecuencia
- Retransmisores de televisión y de telefonía
- Balizas luminosas y de radio
- Refrigeración
- Protección catódica para tuberías
- Juguetería

Las aplicaciones irán creciendo conforme la tecnología y el mismo mercado las hagan más económicas. Aplicaciones inmediatas potenciales incluyen transmisores y retransmisores de A.F. y T.V. y balizas de luz y radio. Debe hacerse hincapié en que todas las aplicaciones mencionadas han sido probadas y están funcionando alrededor del mundo.

Teoría del efecto fotovoltaico

El estudio de la interacción de la energía radiante (o radiación) con la materia puede estudiarse desde el punto de vista de cualquiera de las dos manifestaciones de la radiación (ondulatoria o corpuscular). Para la descripción del fenómeno fotovoltaico es más sencillo considerar el carácter corpuscular, donde cada corpúsculo con energía dada por $E = h\nu$ recibe el nombre de *fotón*, siendo h la constante de Planck y ν su frecuencia.

Un haz de radiaciones que incide en un material da origen a varios efectos según las características físicas de la radiación y de los medios de propagación e incidencia. Así, debido a la diferencia de índice de reflectividad de los medios la radiación será parcialmente reflejada y parcialmente transmitida. La radiación que se transmite puede dar lugar a tres efectos principalmente (Moss, 1961):

a) *El efecto fotoeléctrico.* La radiación transmitida la absorben los átomos del material. En este caso toda la energía $h\nu$ del fotón incidente se cede a un electrón ligado a un átomo, es expulsado con una energía cinética $E_k = h\nu - E_i$ donde E_i es el potencial de ionización del electrón.

b) *El efecto de dispersión o "scattering".* La radiación transmitida es desviada de su trayectoria sin pérdida de energía (*Efecto Thomson*) o una pérdida muy pequeña (*Efecto Com-*

pton) después de expulsar un electrón de un átomo o efectuar una colisión con un electrón libre.

c) *Generación de pares electrón-hueco o efecto fotoeléctrico interno.* Si la energía contenida por el fotón transmitido es igual o mayor que el ancho de la banda prohibida E_g de un material (generalmente semiconductor, donde E_g es pequeño), entonces un electrón de la banda de valencia absorberá la energía necesaria E_g para pasar a la banda de conducción dejando en su lugar un hueco. Así, la energía radiación se ha convertido en energía potencial del electrón y en presencia de un campo eléctrico externo se producirá un flujo de corriente que da lugar al *efecto fotoconductivo* y el material se denominará fotoconductor.

La luz del Sol, ya sea en la superficie de la Tierra o fuera de ella, tiene fotones de suficiente energía para formar pares electrón-hueco. Otro tipo de radiación usado es la radiactividad y rayos β o γ.

La barrera de potencial en las uniones p—n (Fig. 6), proporciona el campo eléctrico para colectar los portadores generados por los fotones y obtener el *efecto fotovoltaico* en dispositivos tales como fotodiodos, fotoceldas y fototransistores. Para el entendimiento del efecto fotovoltaico considérese que una radiación incide sobre la región angosta tipo p de una unión p—n y crea pares electrón-hueco, ganando cada electrón una energía potencial E_c. En presencia de la barrera de potencial ($q\downarrow$) de la unión, los electrones generados (portadores minoritarios) dentro de una distancia no mayor que una longitud de difusión a partir de la región desértica, se moverán por difusión hacia ésta, donde serán colectados perdiendo energía potencial al vencer la barrera. Los portadores colectados están así habilitados para fluír en un circuito externo, desarrollando una potencia a expensas de la energía potencial obtenida por los portadores a partir de la energía incidente, perdiéndose parte de esa potencia en vencer la barrera. Los electrones generados fuera de una cierta distancia (L_h) se recombinarán antes de alcanzar la región desértica. Fenómeno similar de colección de portados minoritarios sucede si la radiación ioniza una región delgada tipo n; en este caso, se colectarán huecos que se moverán por difusión hacia la región desértica.

Si los fotones generan los pares electrón-hueco en la región desértica, los electrones se moverán hacia la región n y los huecos a la región p debido al alto gradiente de potencial y contribuirán al flujo en un circuito externo. Por supuesto que los fotones incidentes pueden colisionar con un electrón libre o un hueco y no a un electrón de valencia y transmitirles parte de su energía (Efecto Compton) sin generar pares electrón-hueco; no obstante, aun en los semiconductores más fuertemente contaminados la concentración de portadores mayoritarios no es mayor que $10^{26}/m^3$, siendo alrededor de 1/10 000 de la concentración de electrones de valencia, tal que la probabilidad de que un fotón colisione con un portador libre y le transfiera su energía es despreciable.

Así, el mecanismo del efecto fotovoltaico se compone de tres etapas, a saber:

a) Absorción de los fotones, dando lugar a la generación de pares electrón-hueco.

b) Difusión de los portadores generados.

c) Colección de los portadores que fluirán en la carga, completándose así la transferencia de energía.

Siendo caracterizados los pasos a) y c) por correspondientes probabilidades.

Independientemente de la región de la unión p—n donde se produzca la generación de pares electro-hueco, el efecto neto es una corriente de portadores minoritarios; los huecos creados fluirán de la región n a la región p a través de la región desértica, en tanto que los electrones lo harán en sentido inverso, resultando una corriente neta de portadores positivos de la región n a la región p en el interior, o sea de la región p a la región n a través de la carga en el circuito externo.

Al circular esa corriente en la carga se desarrolla un potencial que hace al contacto con la región p más positivo respecto al contacto con la región n. De esta manera, el potencial desarrollado en la carga provoca una autopolarización directa de la unión p—n, originándose así una corriente que desafortunadamente es en sentido contrario a la generada por la luz o sea de la región n a la región p a través de la carga. Con esto la corriente que circula en la carga es menor que la generada por la radiación y en sentido contrario a la dirección normal del flujo de corriente en una unión p—n polarizada directa.

Otro posible uso del fotodispositivo aquí descrito es aplicar una polarización inversa al diodo, que da lugar a un aumento en la corriente cuando se ilumina, para operar un circuito o un interruptor. Esta es la aplicación del *fotodiodo*. Cuando aumenta la intensidad de iluminación aumenta el flujo de corriente inversa.

Estos principios básicos de la conversión fotovoltaica han proporcionado la guía para la investigación de múltiples tecnologías, materiales y estructuras, tal como sugiere la figura 6.

Tecnología

La tecnología de fabricación de celdas y módulos solares, como parte de la electrónica del estado sólido, está en una etapa de intensa evolución. Si bien existe una tecnología comercial principal más o menos definida, tiene muchas variantes y en lo que respecta a investigación y desarrollo se trabaja con una amplia variedad de técnicas, de materiales y de estructuras (Fig. 7).

Tecnología de celdas solares de silicio

Actualmente las celdas solares más baratas y eficaces se fabrican a partir del silicio. Este es el segundo elemento más abundante en la superficie de la Tierra, pero desafortunada-

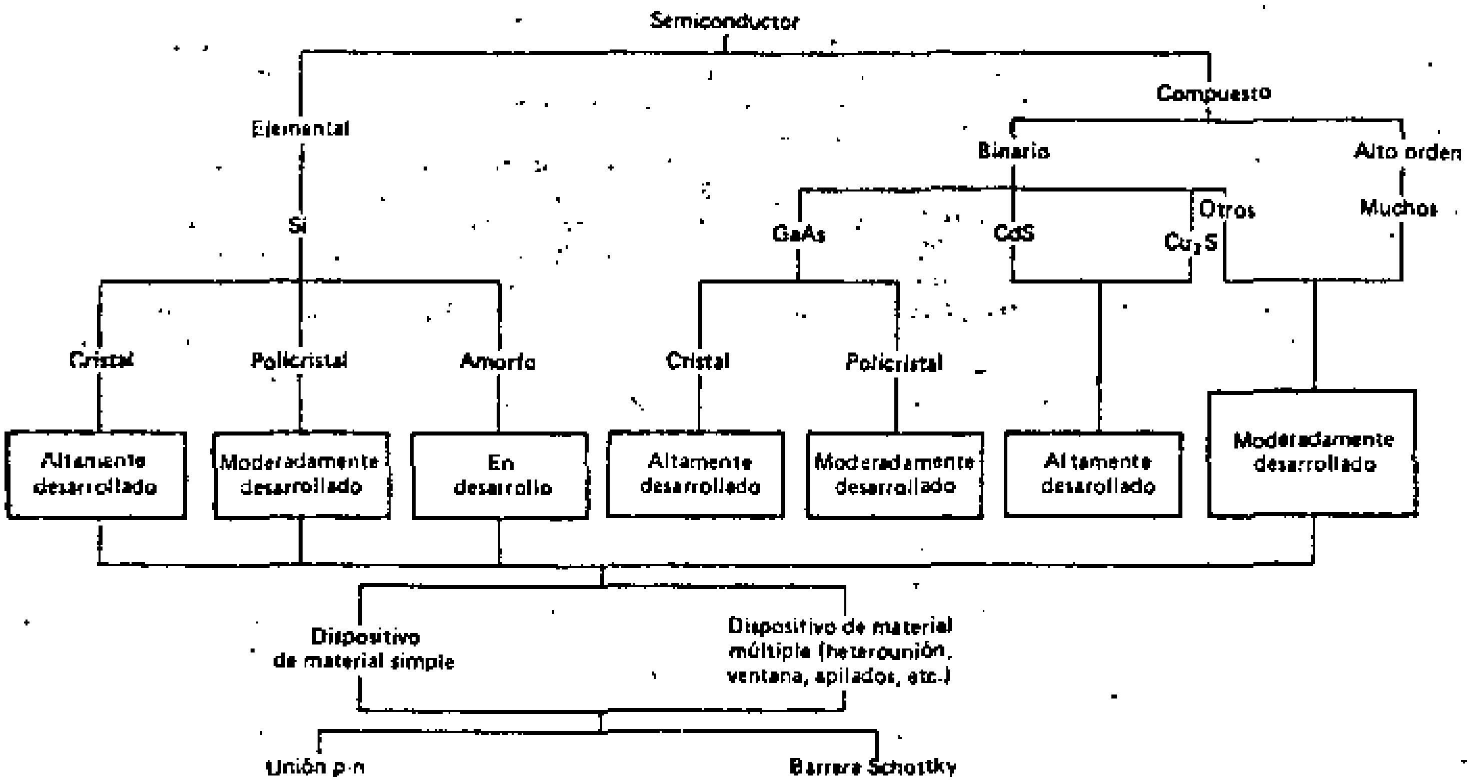


Figura 6. Clasificación de materiales y sus combinaciones para conversión fotovoltaica.

mente aparece en forma de compuestos (la arena es una buena fuente de silicio). Después de procesos de reducción y purificación, se crecen cristales de silicio en forma de lingotes que posteriormente se cortan en obleas. Este elemento es un conductor muy pobre en su forma más pura (semiconductor) y por esto se le impurifica con otros elementos para darle la conductividad requerida. Cuando se añade fósforo durante el crecimiento del cristal el silicio desarrolla cargas negativas (electrones); cuando se añade boro, aparecen cargas positivas (huecos). De esta manera se habla de silicios tipo n y tipo p respectivamente. (En la figura 7 se muestra la estructura típica de una celda solar de silicio para aplicaciones terrestres.)

Esta estructura consta de las siguientes partes:

a) Un subestrato tipo P de aproximadamente 250 micras de espesor (1 micra = 10^{-6} m).

b) Una zona tipo N de espesor aproximado de 0.5 micras.

c) Un contacto metálico posterior.

d) Un contacto en forma de reja sobre la cara iluminada que permite recoger la corriente y dejar llegar la luz hasta el semiconductor.

Los procesos tecnológicos fundamentales que intervienen en la fabricación de celdas solares de silicio son:

a) Difusión de fósforo: previa una etapa de pulido de las obleas de silicio y limpieza de las mismas, éstas son tratadas a 900°C en una atmósfera contaminada fósforo (fosfina u oxicloruro de fósforo). A esta temperatura el elemento fósforo difunde en el cristal contaminándolo tipo N. Con tiempos de operación de media hora se obtienen profundidades de unión de media micra; profundidades más cortas se controlan con la temperatura y el tiempo de difusión.

b) Contactos metálicos: para la cara posterior de la celda se realiza primero una evaporación de aluminio en alto vacío. Luego un recocido a 750°C en atmósfera inerte para asegurar una aleación silicio-aluminio y obtener sobre la cara P un contacto óhmico.

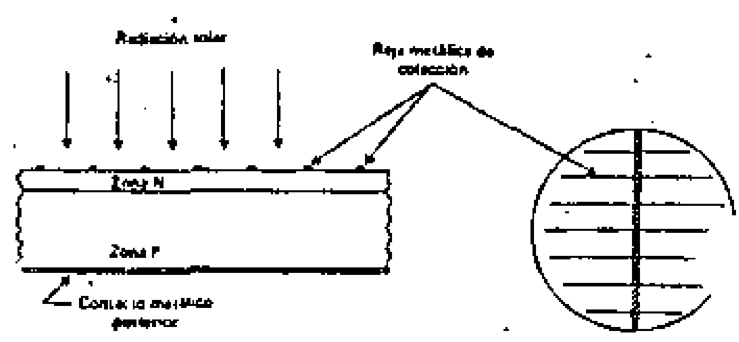


Figura 7. Estructura de una celda solar de unión p-n.

El contacto de enrejado se logra evaporando titanio y plata (en algunas ocasiones titanio-paladio-plata) a través de mascarillas metálicas. Este contacto es estable sobre silicio. Sobre el contacto de aluminio de la cara posterior también se aplica una capa de plata por evaporación para facilitar el soldado del dispositivo.

c) Capa antirreflectora: la diferencia entre los índices de refracción del silicio y del aire hace que 36% de la luz incidente sobre el semiconductor sea reflejado sin contribuir al efecto fotovoltaico. Para disminuir estas pérdidas se aplican capas antirreflectoras de índice y espesor predeterminado. Para capas de SiO_2 ($n \sim 2$) se usan espesores de aproximadamente 750 Åmstrongs.

Otros materiales y tecnologías

Aunque la tecnología de las celdas solares de silicio monocristalino es la opción más práctica y económica, actualmente existen otras que se encuentran a nivel de laboratorio y en algunos casos a nivel de producción piloto.

a) Celdas de Silicio Policristalino. Laboratorios europeos y estadounidenses han utilizado exitosamente materiales de silicio policristalino de pureza "calidad solar" fabricado por técnicas de moldeo ("casting"). Las eficiencias de conversión obtenidas se sitúan entre 8 y 10 por ciento. Dado que por ahora la fabricación del material se hace en escala piloto la reducción del costo del Watt generado no es tan importante; sin embargo, puede preverse que con la fabricación masiva del material, el costo por Watt generado pueda reducirse considerablemente en los próximos cinco años. Una mayor reducción, a más largo plazo, estaría representada por una tecnología en película gruesa (aprox. 50 micras) de silicio policristalino obtenido por deposición química en fase vapor.

b) Celdas de Silicio Amorfo. Se han fabricado en laboratorios estadounidenses e ingleses celdas solares de silicio amorfo de espesores menores a una micra con estructuras tipo p—i—n y barreras Schottky con eficiencias hasta de 5% usando descargas gaseosas de C.D. o R.F. en Silano (SiH_4). Aparentemente sus características fotovoltaicas no dependen de los mismos parámetros que se consideran en las celdas de silicio monocristalino. El hidrógeno incluido dentro de la matriz del material desordenado pudiera tener un papel importante.

Este método de fabricación podría ser uno de los métodos más apropiados para resolver a largo plazo la condición economía-eficiencia para la aplicación masiva de la conversión directa de la energía solar en eléctrica.

c) Celdas de $CdS-Cu_2S$. Estas celdas de película delgada han sido fabricadas exitosamente a escala piloto por evaporación térmica en el vacío del CdS por compañías francesas y laboratorios norteamericanos con eficiencias de conversión de 5 a 8%. Sin embargo, su fabricación masiva requiere de métodos más simples de producción de las películas de CdS tales como la técnica de Rocío Químico ("Chemical Spray"). Hasta ahora no se han podido resolver los problemas representados por la degradación con el tiempo de la eficiencia de conversión de estas heteroestructuras utilizando los métodos de fabricación simplificados.

d) Celdas de GaAs. En laboratorios de Inglaterra y de Estados Unidos se han fabricado celdas solares de Arseniuro de Galio con las eficiencias más altas informadas en estructuras fotovoltaicas: 20 a 25%. Sin embargo, su explotación comercial no ha sido posible debido a su elevado precio y su limitación en tamaño. Su empleo bajo sistemas de concentración solar, del orden de 1 000 veces, pudiera hacer factible su aplicación en la generación de potencia. Sistemas de este tipo están en operación con propósitos de evaluación en Estados Unidos.

e) Celdas de silicio en listones ("ribbons"). Con objeto de evitar la pérdida de material inherente al corte de lingotes monocristalinos en obleas y disponer de métodos de crecimiento continuo de láminas de silicio al espesor deseado, se han desarrollado métodos de crecimiento de membranas y listones de silicio. La viabilidad comercial de estos métodos todavía no ha sido demostrada respecto a las técnicas convencionales actuales (monocristal de silicio). El método en sí es una variante de los métodos de monocristalización del silicio y su ventaja potencial reside principalmente en su característica de producción masiva, y su desventaja en el alto costo energético de sus procesos.

Características de las celdas solares de silicio

Circuito equivalente de la celda solar

Una celda solar no iluminada presentará unas características corriente-voltaje correspondientes a la de una unión P—N con una resistencia serie (Fig. 8). Por medio de una teoría

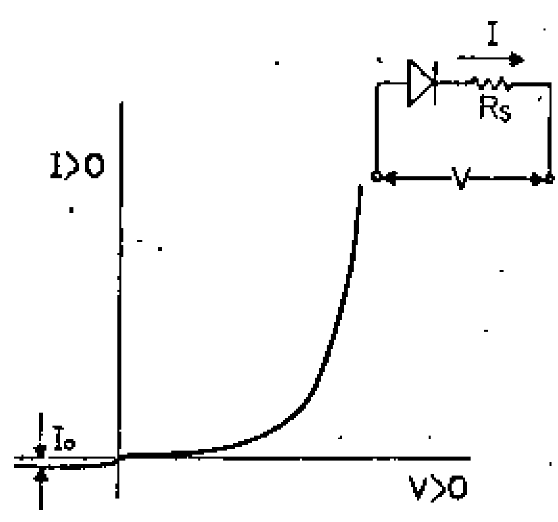


Figura 8.

simplificada puede mostrarse que estas características están dadas en forma analítica por:

$$I = I_o \, (e^{\frac{q}{AkT}(V - IR_s)} - 1)$$

Donde I es el flujo de corriente en la unión, I_o la corriente de saturación inversa y V es el voltaje aplicado (T es la temperatura en °K y k la constante de Boltzmann; a T = 25°C, kT = 0.025 eV).

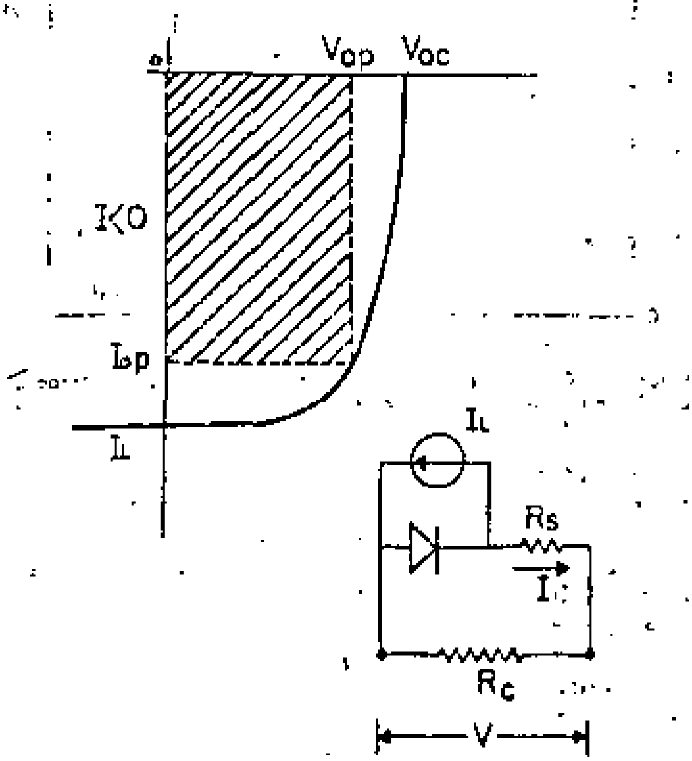


Figura 9.

La iluminación de la celda resulta en una corriente de iluminación I_L. El modelo de circuito que contiene este efecto se muestra en la figura 9. Analíticamente esta situación estará representada por:

$$I = I_o \, (e^{\frac{q}{AkT}(V - IR_s)} - 1) - I_L$$

donde I < 0, ya que físicamente se tiene que $|I| \leq |I_L|$.

Para condiciones de corto circuito ($R_c = 0$)

$$I \simeq I_L$$

ya que $V \cong 0$ e $IR_s \simeq 0$ para $R_s \to 0$.

Para condiciones de circuito abierto ($R_c = \infty$) se tiene el máximo fotovoltaje

$$V_{oc} = \frac{AkT}{q} \ln \left(\frac{I_L}{I_o} + 1\right)$$

En cualquier otra condición de carga

$$(R_c \neq 0), \ |V| < |V_{oc}|, \ |I| < |I_L|.$$

Debido a las características I vs V no lineales del dispositivo existirá un punto de potencia máxima entregada (representado por el máximo rectángulo inscrito en las características I vs V), caracterizado por la resistencia óptima

$$R_{op} = \frac{V_{op}}{I_{op}}.$$

En estas condiciones para una radiación solar incidente determinada, P_{inc} la potencia máxima estará dada por

$$P_{max} = V_{op} \ I_{op}$$

y la eficiencia de la celda solar será

$$\eta = f_c \frac{V_{oc} \ I_{op}}{P_{inc}}$$

Tanto V_{op} como I_{op} dependerán de las características I vs V de la celda (I_o, A, R_s) y del valor I_L de la corriente de iluminación. Para tomar en cuenta este hecho, es útil y conveniente definir un factor experimental f_c, factor de curva, como:

$$f_c = \frac{V_{op} \ I_{op}}{V_{oc} \ I_L}$$

así, la eficiencia de la celda podrá expresarse:

$$\eta = f_c \frac{V_{oc} \ I_L}{P_{inc}}$$

De esta manera una celda será más eficiente conforme crezca f_c, ($V_{oc} = \frac{AkT}{q} \ln [\frac{I_L}{I_o} + 1]$) y la relación $\frac{I_L}{I_o}$ o sea lo más grande posible.

Aunque aparentemente un factor A ("factor adicional de curva") grande aumentaría V_{oc}, este no es el caso, ya que puede mostrarse que un coeficiente A mucho mejor que la unidad es indicio de mecanismos de transporte no ideales que aumentan la corriente de saturación I_o.

En general se caracterizan las celdas por medio de lr siguientes factores, que permiten evaluar y controlar l procesos:

$I_L \to$ densidad de corriente de corto circuito (mA/cm²). Control: el espesor de la capa superficial y acabado superficial de las celdas.

V_{oc} → voltaje de circuito abierto (mV). Control: Densidad de corriente de saturación.

f_c → factor de curva. Control: R_s, I_o, A.

R_s → resistencia serie (ohms). Control: máximo punto de potencia.

A → factor de curva adicional. Control: uniformidad de la difusión, procesos de recocido, precipitación de elementos metálicos.

η_e → eficiencia eléctrica: $_e = \frac{I_{op}}{I_L} \times 100$. Control: pérdidas por drenaje de corriente en la unión p–n.

η → eficiencia global.

La densidad de corriente de saturación, el factor de curva adicional y la resistencia serie pueden evaluarse experimentalmente determinando las características reales de la unión p—n, por medio de una técnica de iluminación variable.

Módulos y paneles fotovoltaicos

Dado el estado actual de desarrollo técnico-económico de las celdas solares para aplicaciones terrestres, se considera generalmente que los generadores fotovoltaicos (módulos y paneles de celdas solares) están hechos a la medida para los países de fuerte insolación y que la mayor parte de las aplicaciones económicamente rentables necesitan potencias pico de algunas decenas o centenas de Watt o hasta kilowatts.

En la sección anterior se vio que una celda solar es un dispositivo que genera potencia eléctrica a valores relativamente bajos:

- El voltaje óptimo para potencia máxima se sitúa alrededor de 0.450 volts.

- La corriente óptima para la misma potencia, o mejor la densidad de corriente óptima es alrededor de 30 mA/cm^2

- La potencia máxima proporcionada por una celda será de alrededor de 13.5 mW/cm^2 (Fig. 10).

La iluminación correspondería a una condición de iluminación AM1 (1 $Kw-m^{-2}$).

Ya que la corriente proporcionada por la celda es proporcional a su superficie (igual a densidad de corriente por superficie total [cm^2]), en tanto que el voltaje es independiente de ésta (según se vio en la sección anterior) la potencia máxima total proporcionada por una celda será proporcional al área de la misma.

Así, para obtener las potencias necesarias para las aplicaciones presentes se diseñan arreglos serie o serie-paralelo de celdas solares (*módulos*) adecuados para proporcionar una potencia pico dada a un voltaje determinado, en general, por los rangos de operación de las baterías en flotación de los sistemas (en particular las baterías comerciales comunes trabajan a múltiplos de 6 y 12 volts). El arreglo serie-paralelo de estos módulos (*paneles*) proporcionará el voltaje y la corriente necesaria para la aplicación deseada.

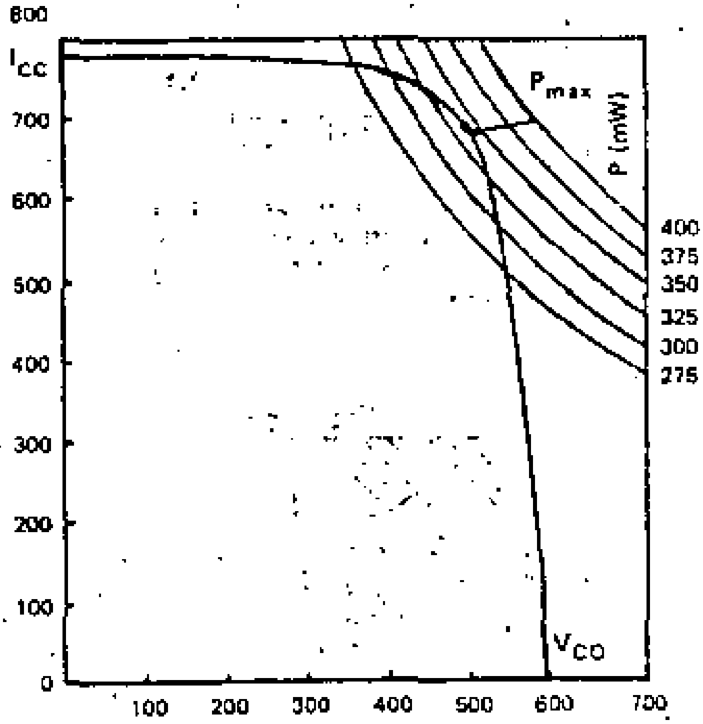


Figura 10. Características eléctricas corriente-voltaje de una fotocelda de 57 mm de diámetro, a una intensidad de 1 $kW\text{-}m^{-2}$.

Así por ejemplo un módulo solar que será utilizado en conjunción con una batería de 12 volts nominales, deberá generar potencia a un voltaje de cuando menos 14.5 volts: 13.6 volts representan el voltaje terminal a plena carga de la batería y 0.7 volts la caída en el diodo de bloqueo. Para tener este voltaje se necesitará un número de celdas igual a 14.5/0.45 = 32.2 celdas, esto es, 33 celdas. Sin embargo, para periodos de insolación débil o por efectos de la temperatura de operación ($\sim$ 60°C, dependiendo del tipo de soporte y protección ambiental del módulo) el voltaje por celda puede disminuir a 95% (el voltaje disminuye como una función logarítmica de la intensidad solar), deberá preverse un número de celdas del orden de 14.5/0.43$\simeq$34 celdas. En general los módulos para aplicaciones con baterías de 12 volts nominales se diseñan con 36 celdas en serie con el fin de que el generador solar funcione como fuente de corriente, con la batería como carga reguladora, o con el fin de prolongar la vida útil de las baterías.

Características físicas de los módulos solares

Un generador fotovoltaico se compone de: una estructura mecánica que sirve de soporte, de celdas solares, de interconexiones y de una encapsulación. El conjunto e interacción de estas componentes deberá asegurar durante un gran período (10 años como mínimo) el comportamiento normal del generador fotovoltaico, con mínima o nula degradación de sus características eléctricas, bajo las condiciones ambientales de su utilización.

La concepción de generadores fotovoltaicos deberá considerar, entre otros, los siguientes aspectos ambientales:

- Humedad; oxidación de los contactos.
- Esfuerzos térmicos; integridad de las conexiones.
- Esfuerzos mecánicos; efecto del viento y de diversos impactos.
- Depósitos de diversa naturaleza: pérdidas de potencia evitables o permanentes resultantes de estos depósitos.

Diseño de sistemas. Un ejemplo

Se describe aquí someramente la experiencia del Centro de Investigación del IPN en el diseño y operación de un sistema fotovoltaico para una telesecundaria. El sistema presenta las conexiones de la figura 11, en la que un diodo de potencia evita la descarga de las baterías sobre el módulo solar en las noches.

A continuación se hace una descripción de los elementos básicos del sistema: el módulo solar, la batería y el televisor.

El televisor

Se adquirieron dos televisores de 19 pulgadas de pantalla, ya que este tamaño y el de 21 pulgadas son los recomendados por la Dirección General de Telesecundarias.

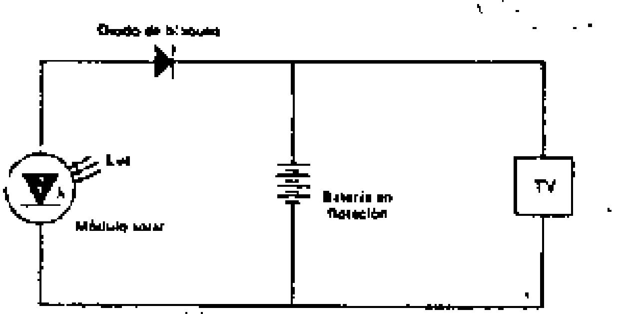


Figura 11. Sistema fotovoltaico para la televisión escolar.

Este televisor fue seleccionado por su menor consumo de potencia en relación con su tamaño de pantalla. El criterio de menor consumo de potencia eléctrica es decisivo en un sistema fotovoltaico como el aquí experimentado, ya que menor potencia eléctrica consumida implica menor inversión en los módulos de generación fotovoltaica, los cuales representan alrededor de 75% del sistema total de telerrecepción.

El consumo de potencia en corriente alterna de este televisor es del orden de 50 Watts, dependiendo del nivel de audio y la brillantez de la pantalla.

Sin embargo, puesto que los módulos fotovoltaicos generan energía eléctrica del tipo de corriente directa (también se la llama corriente continua), fue necesario adaptar la televisión para este propósito. Esta adaptación requiere la eliminación de la etapa de rectificación y estabilización de la corriente y, además de simple, tiene la doble ventaja de: 1) consumir una potencia significativamente menor que la de c.a., y 2) permitir prever un menor costo del televisor debido a la ausencia de la etapa de rectificación y estabilización. Es posible también la adaptación simple de un conmutador de perilla (o deslizable) para su uso ya sea en c.a. o c.d., el cual se está adaptando ahora.

El consumo de potencia en corriente directa es del orden de 20-24 Watts, dependiendo del nivel de audio, la brillantez y el nivel de voltaje de c.d. El voltaje nominal de trabajo de c.d. es de 23 volts; sin embargo, voltajes tan bajos como 16 volts (con un consumo de 12-13 watts) permiten aún un trabajo satisfactorio del TV, aunque cabe aclarar que a 18 volts se empieza reducir la dimensión *horizontal* (ancho) de la imagen y que a 16 volts se empieza a perder el control de la estabilidad de la imagen.

La adaptación del televisor a un suministro único de c.d. incluyó la incorporación del filamento del tubo de imagen que trabaja nominalmente a 6 volts. La adaptación completa, que incluye tanto la electrónica de procesamiento de la señal de audio y video como el filamento, fue hecha para 24 volts nominales con un consumo de 1 ampere para máximos brillantez y audio, o sea un consumo de 24 watts máximo.

Las baterías

Estas son de 24 volts, que es el voltaje de adaptación del televisor. Su capacidad de carga almacenada (Watts-hora) queda determinada por el consumo del televisor, los días de autonomía del sistema (número máximo de días en que se prevé tiempo nublado y por lo tanto una recarga despreciable de las baterías), la disponibilidad en el mercado y, muy importante, el precio que se esté dispuesto a pagar.

Estas consideraciones muestran una cierta ventaja técnico-económica para las baterías del tipo plomo-ácido. De hecho, el sistema alemán para los televisores educacionales solares instalados en Egipto y la India, favorece esta decisión.

Se seleccionaron dos acumuladores de automóvil plomo-ácido, de 12 volts cada uno, para usarlos en serie y proporcionar el voltaje deseado, con una capacidad de 90 A.h., que proporciona 90 horas de autonomía ya que el televisor consume 1 ampere. Considerando que las jornadas de clase de telesecundaria son de 6 horas diarias, la autonomía por carga almacenada es de 15 días hábiles o sea de 3 semanas calendario con 5 días hábiles cada una. Debe hacerse notar en este contexto, que la autonomía será mayor en la práctica porque aun en días lluviosos o nublados se logra captar una cierta energía solar y transformarla en eléctrica; esta parte está sujeta a evaluación en este Programa.

El módulo solar

Se usaron dos módulos fotovoltaicos con dimensiones externas de 63 cm por lado y 2 cm de espesor

Considerando así la potencia máxima de 21.8 watts por módulo a 56°C (temperatura fácilmente alcanzada por las celdas al exponerse a la insolación directa) se nota que esta potencia instalada por módulo solar puede proporcionar la energía necesaria si se hace un balance energético semanal, ya que el módulo genera energía los 7 días dando: 21.8w x 5hs/días x 7 días/sem = 903 watts–h/sem en tanto que la telesecundaria trabaja sólo 5 días consumiendo 144 watts-hora/día x 5 días/sem = 720 watts-hora/sem. Aun considerando 90% de eficiencia de captación de energía y 90% de eficiencia en almacenamiento y fugas en el acumulador la energía generada y almacenada será de 0.9 x 0.9 x 903 = 731.43 watts-hora/sem y superior a la demandada por el televisor.

Sin embargo esta potencia generada efectiva de 731 watts-hora/sem por cada módulo es sólo disponible trabajando al voltaje óptimo de 12-15 volts, o sea cargando un acumulador de voltaje nominal de 12 volts. Puesto que el televisor seleccionado opera a 24 volts, sería necesario el uso de un convertidor c.d.-c.d. para cambiar de 12 a 24 volts. Desafortunadamente un convertidor de este tipo y para esta potencia tiene una eficiencia de entre 50 y 60% y un precio del orden de 7 500.00 pesos, que hacen a esta solución inaceptable.

Basados en estas consideraciones, se optó por colocar dos módulos en serie y obtener el voltaje deseado de 24 volts tanto para el acumulador como para el televisor.

Este estudio muestra que la selección del módulo es bastante crítica y limitada a aquéllos disponibles en el mercado. Las consideraciones anteriores muestran que, idealmente, era necesario un módulo de la misma potencia pero al doble del voltaje de operación (y consiguientemente a la mitad de la corriente) que el disponible. En términos de las celdas solares que los componen, el módulo solar ideal para este televisor debería tener el doble de celdas con la mitad de área individual (6.3 cm de diámetro) para obtener la misma potencia que el disponible. Esta conclusión se está poniendo en práctica en los módulos que se están desarrollando en nuestro laboratorio.

Investigación en México

De las instituciones activas en energía solar sólo 4 lo son en el área fotovoltaica.

1) El Departamento de Ingeniería Eléctrica del Centro de Investigación y de Estudios Avanzados del IPN. Desde 1964, realiza investigación y desarrollo experimental en celdas solares de silicio, originalmente bajo contrato con la Comisión Nacional del Espacio Exterior. Ha desarrollado una tecnología de celdas de silicio por difusión hacia un prototipo de 15 watts-pico, con 10% de eficiencia. La tecnología es susceptible de industrialización previa adaptación que puede desarrollarse en un año y con un valor de alrededor de un millón de pesos. Una fábrica pequeña requeriría un capital inicial del orden de 5 millones de pesos para una producción inicial anual de 50 kW.

Este laboratorio tiene también investigadores trabajando en investigación de celdas de $CdS-Cu_2S$, celdas de silicio amorfo, celdas de silicio policristalino y celdas Schottky, así como en el crecimiento de lingotes y listones de silicio.

En el área de aplicaciones se ha desarrollado un sistema de telesecundaria fotovoltaica, descrito anteriormente, así como dos estaciones de telefonía rural, todos ellos en la Sierra Norte de Puebla.

Se tienen contratos con la CFE, la Secretaría de Comunicaciones y Transportes y con la Secretaría de Educación Pública.

2) El Centro de Investigación de Materiales de la UNAM Desde 1973 realiza investigación básica en celdas de sulfuro de cadmio por evaporación al vacío. Han obtenido hasta 4% de eficiencia y se busca resolver el problema de este tipo de celdas que es la degradación. Este centro tiene apoyo de la OEA.

3) El Departamento de Física del CIEA-IPN. Desde 1975 realiza investigación básica en celdas con barrera Schottky del tipo electrólito-semiconductor (CdTe). Tiene apoyo de la NSF (EUA).

4) El Departamento de Química del CIEA-IPN. Es el grupo más nuevo y más pequeño. Trabaja en los aspectos electroquímicos fundamentales de la estructura mencionada para el grupo anterior.Δ

Bibliografía

Memorias (proceedings) de las "Photovoltaic Specialist Conference" publicadas por el Institute of Electrical And Electronics Engineers de EUA. (La 13ava. reunión se celebró del 5-9 de junio de 1978 en Washington).

Memoria del Coloquio Internacional "Electricité Solaire" celebrado en Tolosa, Francia, del 1-6 de marzo de 1976, y publicada por el Centre National d'Etudes Spatiales (Francia) por medio de su Département des Affaires Universitaires.

Memoria de la "Photovoltaic Solar Energy Conference" celebrada en Luxemburgo, del 27 al 30 de septiembre de 1977 y publicada por la D. Reidel Publishing Co. de Holanda y EUA.

A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future (2 volúmenes), documento ERDA 76-1, Energy Research and Development Agency, EUA.

E.J. Perez y J.L. del Valle, *Diseño e instalación de sistemas fotovoltaicos*, (en prensa), Editorial [illegible] México, 1978.

Joseph A. Merrigan, *Sunlight to Electricity*, MIT Press, EUA, 1975

Harold J. Hovel, *Solar Cells*, vol. 11 de la serie Semiconductors and Semimetals, Academic Press, 1975.

Energy and Man: Technical and Social Aspects of Energy, ed. por M. Granger Morgan y la IEEE Press de EUA, 1975.

Wolfang Palz, *Solar Electricity*, editado por Butter Words, UNESCO, 1978.

Satellite power stations: a new source of energy?

Solar cell power, converted to microwave power, is beamed to earth and reconverted

William C. Brown Raytheon Company

The rapidly increasing demand for electric energy[1,2]—coupled with the inability of conventional means of electric power generation to keep up with that demand—makes urgent the need for new prime energy sources for future electric power generation. In addition to nuclear fuels, there are many potential sources of energy that are not now being used in appreciable amounts: wind and tidal energy, geothermal energy, temperature differences in the ocean, and solar energy. This article will be concerned with solar energy.

For each possible energy source, including nuclear fission and fusion, there is some factor that limits the degree of optimism. Either the source is too small to qualify as a major energy source, hard-to-assess pollution and ecological hazards are unavoidable, the technology has not yet been reduced to practice, or there is an economy barrier. Solar energy falls into the last category.

The amount of solar energy intercepted by the earth is at least 10 000 times the projected consumption of electric energy in the year 2000. Because the sun's energy has such a low density at the earth's surface, any earth-bound power generation scheme based on the sun as energy source would require relatively large areas devoted to devices that either convert the sun's energy directly into electricity or function as boilers for a system employing turbogenerators. Moreover, the day-night cycle, atmospheric attenuation, cloud coverage, and other factors reduce the amount of solar energy falling on a given location to a small fraction of that falling on the same area in space. In December, for example, the sunniest locations in the United States, located in the Southwest and in Florida, receive only 11 percent of the energy that a similar area in space would receive.[3] In New York and Seattle, by contrast, the percentages would be 4.5 and 2.2 respectively. The impractical result of these poor duty cycles is an excessive investment in solar energy devices[4] to capture a given amount of energy. And an equally excessive investment in storage facilities must be made if the captured energy is to be used as a reliable base-load source of electric power.

To overcome the problems resulting from this poor duty cycle, Dr. Peter Glaser of Arthur D. Little, Inc., proposed, in 1968, that we put large arrays of solar photovoltaic cells into space in near-equatorial synchronous orbit where the sun would shine upon them nearly 100 percent of the time.[5] The dc power obtained from the photovoltaic arrays would then be converted into microwave power, beamed to the surface of the earth, and there converted back into dc power. Because the rotation of the solar satellite would be synchronous with that of the earth, the microwave link would be fixed and operative at all times. This concept has become known as the Satellite Solar Power Station (SSPS).

Dr. Glaser's proposal was received with considerable interest because of the concept's inherently low thermal pollution; because of the absence of any form of particulate, chemical, or nuclear pollution; and because of its association with a dependable, inexhaustible source of energy—the sun. This interest has led to a series of studies of the technology and associated economics of the system in stages of increasing depth.[5-7] The latest study was performed by a four-company team, with Dr. Glaser as its leader, consisting of personnel from A. D. Little, Inc., the Grumman Aerospace Corp., Raytheon Co., and Textron, Inc.

After a six-month study of all aspects of the SSPS, the team reached the conclusion that the satellite solar power station concept, as proposed by Dr. Glaser, is technically feasible.[7,8] The present cost projection—based upon solar cell costs derived from an automated version of today's conventional silicon solar-cell technology and upon space transportation costs as represented by a first-generation space shuttle—is too high to be cost competitive with established methods of power generation. Because of the 15 to 25 years projected time frame for the SSPS to become operational, it is entirely possible that breakthroughs in cost will occur.

A preferred way to view the SSPS system concept is hat it is a pollution-free, resource-conserving approach to the solution of our energy problem in the time frame 1990-2000 and that it is based upon an inexhaustible prime energy source, our sun. Although not currently cost competitive, it is an option that should be considered carefully and kept open in the event cost breakthroughs occur and unexpectedly severe problems arise in the development of other approaches.

System configuration and characteristics

The overall configuration and principal characteristics of the SSPS to be presented make up a "baseline" design.[7] It is not intended as a final design but rather to serve as a starting point for further study and the evolution of improved designs.

The system is shown on the front cover of this issue. The SSPS is placed in an equatorial, synchronous geocentric orbit 35 800 km above the earth's equator so that its position with respect to any other position on the earth's surface is fixed. Two large solar photovoltaic cell arrays, always pointed toward the sun, convert the sun's radiant energy to dc power, which is then transferred to a large, active phased array mounted by means of two rotary joints between the two solar arrays. The active phased arrays' functions are to convert the dc power into microwave energy at a preferred wavelength that will penetrate the earth's atmosphere and to focus that energy into a narrow beam pointed toward the receiving point on the earth's surface.

The microwave beam in space is unattenuated and arrives at the earth's atmosphere with the same power level as at launch. The microwave energy then penetrates the earth's atmosphere and reaches the earth's surface where it is efficiently converted back into dc power by a device known as a "rectenna," which simultaneously absorbs and rectifies the incoming microwave energy.

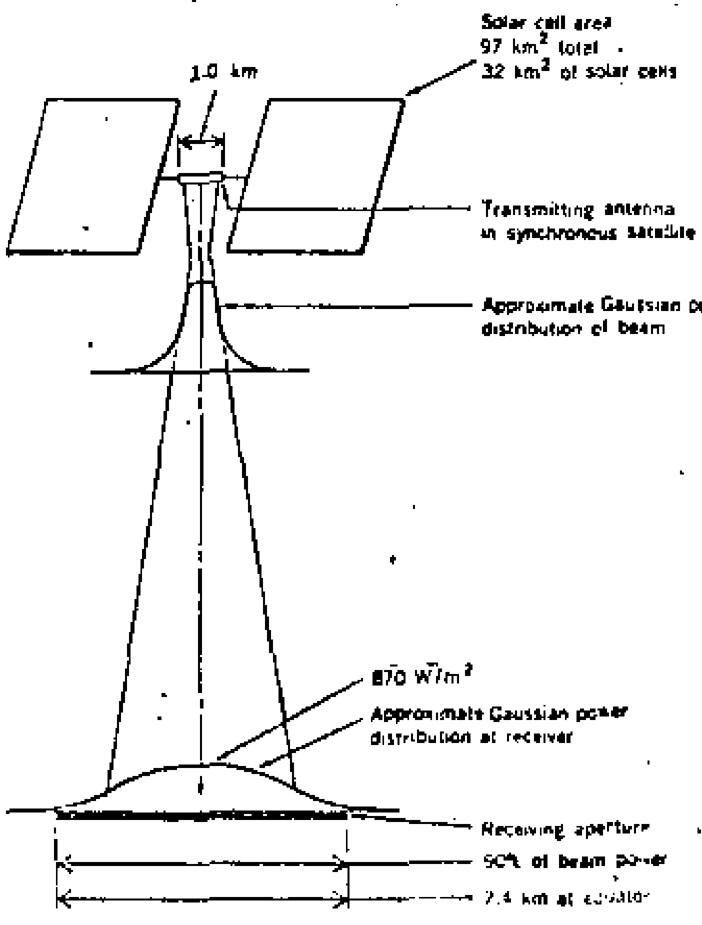
An important characteristic of the SSPS system is its high duty cycle. Because of the 23-degree tilt of the earth's axis with respect to the ecliptic plane, and the fact that the satellite is at a distance of 35 800 km (22 400 miles) from the earth in equatorial orbit, the SSPS is continuously illuminated during the winter and summer months and well into the spring and fall months. For 22 days before and after the vernal and autumnal equinoxes the satellite is eclipsed for periods of time ranging up to a maximum of one hour and 14 minutes. If the satellite and ground rectenna are located at the same longitude, the eclipse period will center around midnight. The average duty cycle for the entire year is slightly more than 99 percent.

The proposed electrical size of a single SSPS is in the range of 3000 to 15 000 MW. To place this power level in perspective, 10 000 MW represents about 3 percent of the electric generating capacity in the United States today but only 0.5 percent of the projected capability in the year 2000. The electrical size of the system is determined primarily by the power level at which the construction cost per kilowatt of output is at a minimum. Although many parameters are involved, the most important ones appear to be the area of the transmitting antenna aperture required for efficient transmission of power, the most efficient utilization of this area for radiation of waste heat, and the bus losses associated with the transmission of dc power from the solar cell array to the transmitting antenna.

The choice of frequency for the microwave transmission of power, from a strictly technological point of view, involves several factors: how the attenuation and scattering of electromagnetic energy in the earth's atmosphere behave as a function of the wavelength of the energy; the physical size of the transmitting antenna and receiving rectenna; and the efficiency of the components that interchange dc and microwave energy. A study of atmospheric attenuation versus wavelength shows that a wavelength of 7.5 cm (4 GHz) or longer is necessary to avoid excessive attenuation (>1 dB) during a heavy rainstorm, the form of atmospheric disturbance having greatest impact upon microwave propagation. Atmospheric scattering and attenuation effects become much more pronounced at millimeter and optical wavelengths and prevent serious consideration of this part of the spectrum for efficient power transmission.

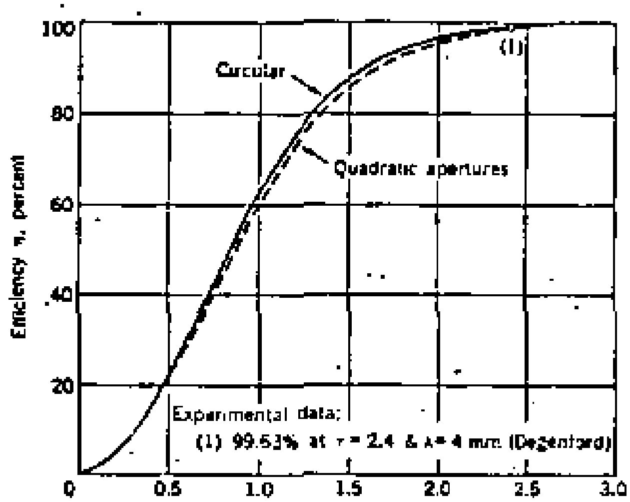
From the viewpoint of keeping aperture sizes small, a short wavelength is preferred since the total area of the two apertures is proportional to wavelength for a given efficiency. However, substantial aperture areas are necessary for disposal of any waste heat resulting from any inefficiencies in energy conversion, particularly in space. Energy conversion components presently have better efficiency at the longer wavelengths.

[1] Dimensions of essential physical features of the SSPS for a 10 000-MW system.



The net result of these considerations is that at the present time, and from a strictly technological point of view, the best compromise appears to be in the relatively narrow range of 7.5 to 15 cm. In the SSPS design, a wavelength of 10 cm has been assumed.

The proposed physical size of the present base-line design is shown in Fig. 1 for a 10 000-MW system. The solar energy collecting array has an area of 97 km^2; one third of that area is made up of solar cells and the remaining area consists of inexpensive solar concentrators made from thin-film material treated to have a reflecting surface. The transmitting antenna is 1 km in diameter, and the rectenna array to capture 90 percent of the transmitted energy is 7.44 km in diameter. The antenna dimensions are derived from the relationship between efficiency and physical parameters given in Fig. 2.



[2] Theoretical transmission efficiency for a microwave beam radiated from an aperture with a spherical phase front whose radius is equal to the distance D. A_t and A_r are the areas of the transmitting and receiving apertures, λ is radiation wavelength, and D is the distance between transmitting and receiving apertures. Aperture illumination is unique for each value of efficiency but approximates a slightly truncated Gaussian distribution for high efficiencies. One point of experimental data is given.

The overall efficiency of the SSPS system is the product of the efficiency of the solar cell array and the microwave power transmission system. The solar cell conversion efficiency is limited, primarily because of the distribution of the sun's energy over a very broad frequency spectrum. The conversion efficiency of today's silicon solar cells is in the range of 12 percent. It is expected to improve to 18 percent[6] but never to exceed 25 percent. The use of concentrators reduces the cost and weight of the array but the resulting higher temperature of the cell also reduces the projected efficiency of the solar cell to 11.5 percent.[7]

By contrast, the overall efficiency of the microwave power transmission system is projected to be in the 65 to 70 percent range. Figure 3 shows the various power flows and losses in the SSPS system using the dc power input to the active phased array as the 100 percent reference point.

The specific weight of the satellite portion of the SSPS system, important because of space transportation costs, has been estimated to be 2.5 kg/kW of output.[7] More than half of this weight is associated with the solar cell array.

The satellite solar power station would be placed into orbit with the space shuttle[7] or perhaps a second-generation shuttle that would transport material from the earth's surface to near-earth orbit and a space tug utilizing high-specific-impulse electric propulsion to go from near-earth to synchronous orbit.

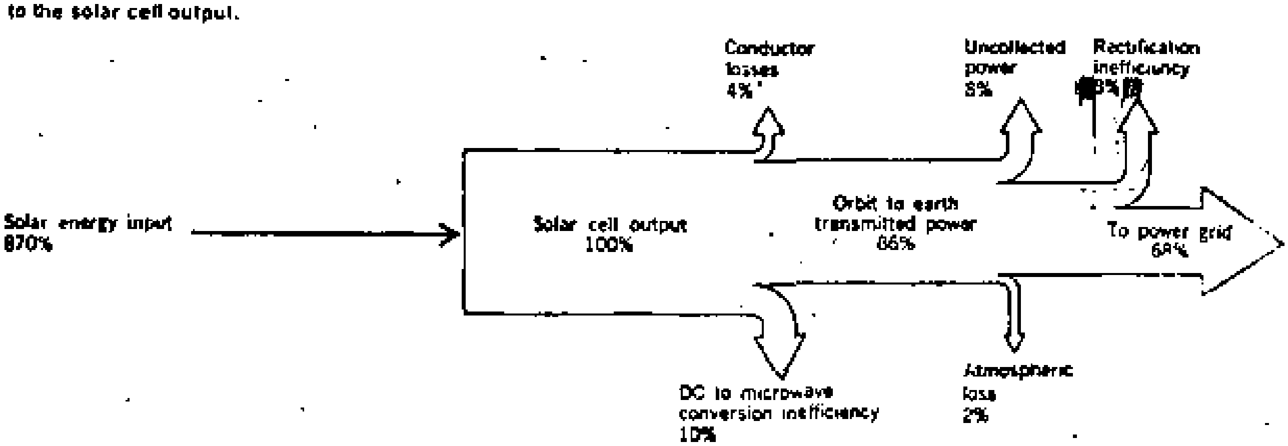
Solar photovoltaic cell array

In the SSPS the sun's energy is converted into electric power by a large photovoltaic array optimized for this purpose. Its design uses construction techniques extrapolated from present practices but the scale far surpasses anything yet constructed or contemplated.

The principle of operation of the solar photovoltaic cell is shown in Fig. 4. If made from silicon, as most solar cells are, there is an abundant and cheap source of material for its construction. It has an extremely long lifetime, although in a space environment it may lose some of its initial efficiency. In a terrestrial application, it will need special coatings to prevent erosion. It will tolerate a load that is either open-circuited or short-circuited. It is potentially capable of a very high ratio of power output to weight.

Although the conventional photovoltaic cell will always be limited in efficiency because of the sun's

[3] Projected flow of power in the SSPS system indicating various losses. The power flows and losses are referenced to the solar cell output.



...ad spectrum of energy), an efficiency of 18 percent reportedly achieved with a cell based on gallium arsenide[19] represents about half the efficiency of conventional or nuclear generating plants using fossil or nuclear fuels. Solar cells also have the advantages that their prime source of energy, the sun, is inexhaustible and cost-free and that there are no residual wastes to dispose of.

The solar cell, in spite of its advantages, has not moved into serious contention as a source of large amounts of electric power because of its relatively high cost and poor duty cycle when terrestrially based. In space, however, it has been used widely and now represents the major source of power for satellites that are required to operate reliably for long periods.

As the result of the growing concern over future energy sources, there has been a renewed interest in improving the solar photovoltaic cell in terms of efficiency and reduced manufacturing cost. A recent study sponsored by the National Academy of Sciences[9] has indicated that an increase in efficiency of the silicon solar cell from its present nominal value of 12 to 18 or 20 percent is a reasonable objective. Meanwhile, an efficiency of 18 percent for a solar cell based on gallium-arsenide material has been reported by the laboratories of International Business Machines.[10]

One of the most likely areas for cost reduction is in growing silicon crystal material for the cells. The chief projected cost of automated silicon solar cell production is that brought about by sawing the crystal material as grown into thin wafers whereby a substantial amount of crystal material is lost in the saw kerf. Some crystal materials are now being grown commercially in thin sheet or ribbon form.[11] If this method could be adapted successfully to the continuous growth of silicon crystals, it would not only cut drastically the cost of the crystal material but would also make possible an uninterrupted process flow of the silicon material from the molten state to the finished silicon solar cell.[12] A resultant cost of $375 per kilowatt has been projected from a study[14] based upon an assumed successful adaptation of the ribbon process to silicon solar cells.

Microwave power transmission system

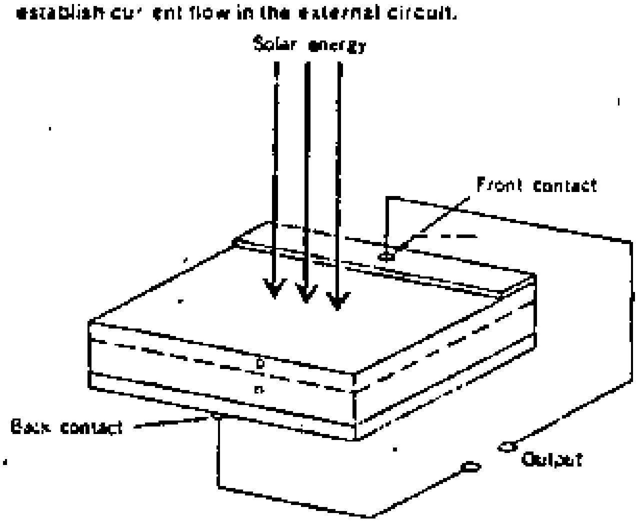
The proposed use[3-14] of a microwave beam for efficient transfer of large amounts of power over long distances is a radical departure from the traditional use of microwaves in radar and communications. A considerable amount of effort in the experimental development of microwave power transmission systems has been supported by private and Government agencies[15-17] and this effort, in addition to advances in component technology and our understanding of microwave beams, makes it possible to evaluate critically the use of a microwave beam to transmit power in the SSPS system.

The forming of the microwave beam. A properly launched beam can be an extremely efficient means of transporting energy in microwave form from a transmitting to a receiving aperture. Such beams have been investigated theoretically and experimentally in considerable depth.[19-22] The transmission efficiency in the vacuum environment of space is independent of distance, although the transmitting and aperture areas must increase in proportion to the distance. The relationship between efficiency η, transmitting and receiving apertures A_t and A_r, transmission distance D, and the wavelength λ of the radiation is shown in Fig. 2.[19] One experimental data point of 99.6 percent[22] is shown in Fig. 2.

The application of Fig. 2 to the problem of transferring power from a synchronous satellite over a distance of 35 800 km using a radiation wavelength of 10 cm shows that for 90 percent power transfer efficiency the product of the receiving and transmitting apertures must be 34.1 km⁴. If the transmitting aperture is 1 km in diameter, then the receiving aperture will be 7.44 km in diameter, as shown in Fig. 1. The relationship provided by Fig. 2 requires that for each value of efficiency there must be a specific distribution of illumination at the transmitting antenna. For high efficiency values, this illumination approaches a slightly truncated Gaussian.

The gain of the transmitting antenna will be very high, of the order of 90 dB for the present base-line design of the SSPS transmitter. The proposed rectenna diameter of 7.44 km required to intercept 90 percent of the beam represents an arc segment of 0.7 minute. To maintain a given spot size around a given point on the earth's surface, and to maintain low scattering losses from the transmitting antenna, phase deviations over the phase front of the beam must be held at launch to within a small fraction of a wavelength—typically within 5 mm for a transmitted wavelength of 10 cm. Since it would be impossible to maintain the physical alignment of the surface of the antenna to this tolerance, some beam launching method must be employed that uses one of the fast-acting, self-phasing concepts.[23] These methods maintain the proper phase over the entire transmitting aperture by sensing electronically the physical displacement of local areas and compensating for any displacement by changing the phase of the microwave radiation at the point of launch. To be effective in the

[4] Salient features of standard solar cell. Basic material is single-crystal, n-type silicon. Thin layer of p-type material is formed on one surface. Enough energy is transferred from the incoming solar rays to the holes and electrons in the silicon to overcome the junction barrier voltage and to establish current flow in the external circuit.



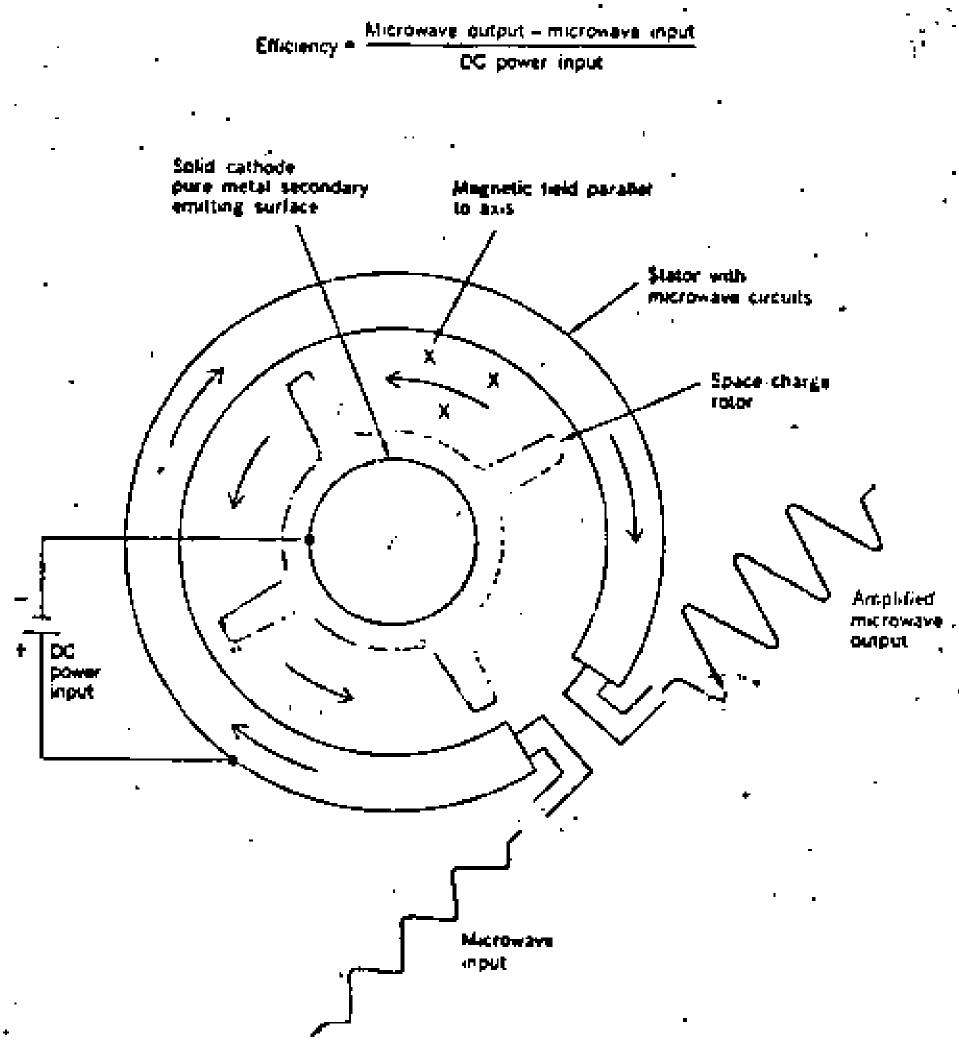
SSPS, these self-phasing concepts would require that the transmitting antenna be subdivided into a large number of smaller arrays so that the phase of the radiated output from each subarray could be controlled independently. The reference phase front, with which the output phase of each subarray is compared, would be established by an independent transmitter located on earth at the center of the receiving location for the power beam.

The overall efficiency of a microwave power transmission system depends upon the conversion efficiencies at both ends of the system as well as upon the launching and beam efficiencies. Conversion devices have already exhibited highly efficient operation and even greater efficiencies are possible if advantage is taken in device design of newly available materials.

Conversion of dc to microwave power. In the SSPS system, the space environment imposes unusually severe requirements upon the conversion of dc power to microwave power. Waste heat disposal, the need for extremely long life and high reliability, and the demand for light weight assume an importance far above that encountered in a terrestrial environment. In the base-line design, one promising device, the crossed-field electron tube, was selected for examination to see how well it would meet the stringent requirements if integrated into the overall system. It will not necessarily be the final choice.

The crossed-field device is the most efficient converter of dc power to microwave power in the wavelength range of interest. In both its oscillator form (magnetron) and amplifier form (Amplitron) it has exhibited overall conversion efficiencies of between 85 and 90 percent.[25] With the aid of the recently developed permanent magnet material, samarium cobalt, the device can also be made very light in weight.

In both the magnetron and the Amplitron, as shown schematically in Fig. 5 for the Amplitron, there is a rotor consisting of spokes of space charge that induce high-frequency alternating currents in a stator composed of a microwave circuit. The electric fields from the energy in the microwave circuit, in turn, exert a force against the spokes of space charge. The torque required to spin the rotor comes not from external mechanical torque, as in the 60-Hz alternator, but from the motion of charged particles in static electric and magnetic fields oriented at right angles to each other. Unlike the mechanical rotor of the alternator, the space-charge rotor of the crossed-field device has very little mass and rotates at extremely high speed—perhaps 100 000 000 times that of a 60-Hz alternator. Since the power generated by any device is



[5] Principle of operation of the Amplitron. Rotating spokes of space charge induce currents into the microwave circuit and provide efficient amplification of the microwave input signal. DC to microwave conversion efficiencies of over 85 percent have been obtained from the cross-field device.

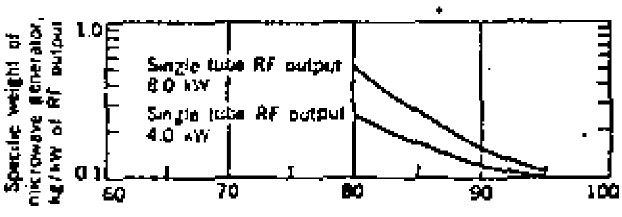
proportional to the product of torque and angular velocity, the capability of the small, lightweight microwave device to generate large amounts of microwave power becomes evident. This inherently lightweight mechanism, in normal practice, is highly disguised in conventional tubes because of the mass of the magnet required for operation and the mass of the glass and metal envelope required in the terrestrial environment. In space, the envelope is not required and the new samarium-cobalt magnet material can reduce the magnet weight by a factor of at least ten.

In the SSPS system, the power-handling capability of the device and its weight are directly related to disposal of the waste heat that results from any inefficiency in operation. Weight and reliability considerations require that waste heat be disposed of by direct radiation into space so the generator must have an efficient radiator fin attached to it. Fortunately, the large area of the transmitting antenna allows these radiators to dispose of a large amount of waste energy if the generators are uniformly distributed over the antenna's area. At 300°C, for example, a disk 1 km in diameter has a black-body radiation capability of 4.45×10^6 kW from each of its faces.

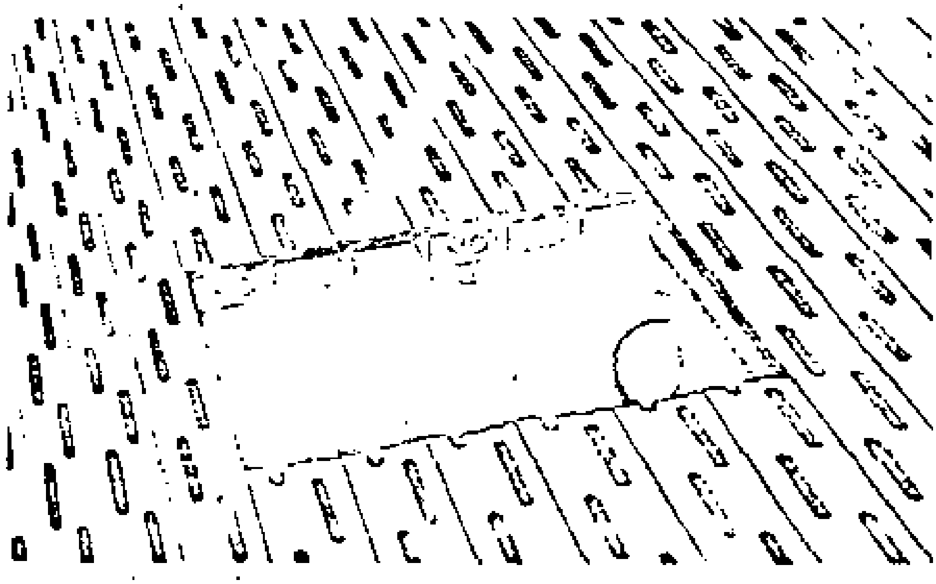
A study has been made of the specific weight of the crossed-field generator together with its permanent magnet and its pyrolytic graphite radiator as a function of Amplitron efficiency and power-handling capability. The results are given in Fig. 6. The specific weight of the combined generator and cooling fin, as measured in kg/kW of output power, is sensitive to both efficiency and power level primarily because the weight of the cooling fin approximates the 2.5 power of the quantity of waste heat it must radiate. This consideration places a practical upper power bound of about 10 kW on the microwave generator. Microwave tubes with power ratings that are nominal by present standards would be used in the SSPS.

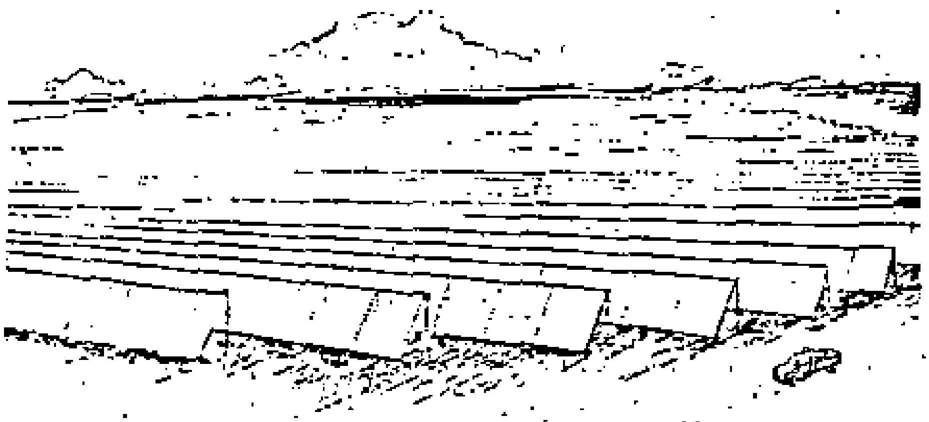
Use of microwave power amplifiers with a nominal power rating of 5 kW would require a quantity of two million such tubes to produce a 10 000-MW microwave beam. The problems associated with the microwave excitation of such a large number of tubes, and the efficient coupling of them into a phased array, are resolved by a cascade arrangement of tubes and slotted waveguides, as suggested by the artist's rendering in Fig. 7. The output of each Amplitron flows into a section of slotted waveguide where most of the power is coherently radiated and becomes part of the microwave beam. Enough power is left over to excite the next Amplitron. The cycle is then repeated for the next section of waveguide and the next Amplitron, etc. Not within the scope of this discussion are the methods of phase correction and other controls that integrate the cascaded arrangement into the antenna subarray and insure proper overall behavior of the transmitting antenna.

The high reliability and long operating life demands of the SSPS system require all components to have this capability. They must be used in a redundant manner to minimize the impact of component failure upon system performance. In the case of the microwave generator, long life is made possible by the use of a layer of pure metal, usually platinum, on the surface of the cathode to supply electrons by secondary emission. The flow of electrons from the cathode is initiated by the normal injection of microwave



[6] Specific weight of microwave generator and associated magnet and cooling radiator as a function of generator efficiency and power rating of tube. Radiation from both sides. Average fin temperature is 300°C, temperature rise in fin is 50°C, temperature of tube edge is 325°C, radiator material is pyrolytic graphite, and heat sink is space 0°K.


[7] Cutaway section in earth-facing section of transmitting antenna showing the slotted waveguide radiators and two Amplitrons coupled into the waveguides by means of probes. The Amplitron disposes of its waste heat to space by means of a circular cooling fin made from pyrolytic graphite.



[8] Artist's sketch of the SSPS rectenna, the electronic device that captures the energy from the microwave beam and simultaneously converts it into dc power for distribution on a conventional power grid. The rectenna need not be accurately pointed toward the transmitting antenna for efficient operation and its operation is independent of any distortion of the microwave beam as it passes through the earth's atmosphere.

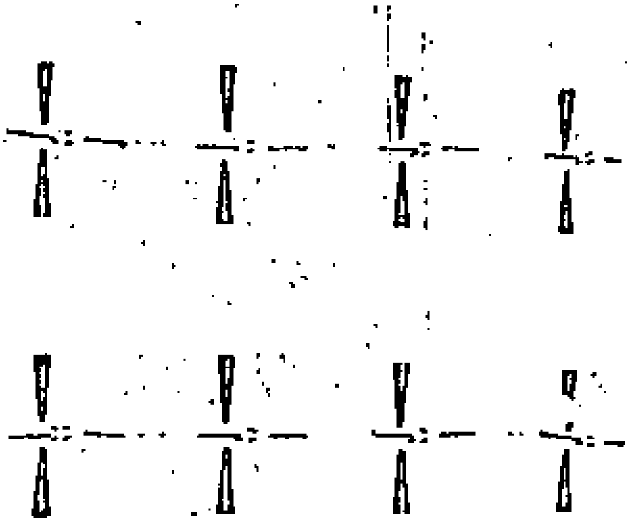
energy (see Fig. 5) into the microwave input terminal of the tube so that no initiation of electron flow by thermal means is needed. This technique eliminates the need for a cathode heater that not only has a limited life but, in this application, would impose an additional complication because of its separate power supply requirement. There is no known life limitation to the secondary emission process from a pure metal cathode other than erosion from sputtering, and this is expected to be negligible in the high vacuum of space. The use of pure metal cathodes, and starting them with RF injection, is a standard procedure in many terrestrial applications.

The efficient capture and rectification of the microwave power over such a large receiving area would probably not be practical if it were not possible to combine these two functions in the rectenna[25] and thereby simultaneously achieve high collection and rectification efficiency, insensitivity of the array to amplitude and phase perturbations of the incoming beam caused by atmospheric phenomena, insensitivity to the direction of the incoming radiation over a considerable angle, economical construction, and disposal of waste heat by passive radiation.

Structurally, the rectenna consists of many independent receiving elements, each of which is terminated in a rectifier. The dc outputs of the rectifiers feed into a common load. If the receiving element is a half-wave dipole, then the directivity of the array, no matter how large, approximates that of the relatively broad-patterned, half-wave dipole. The absorption efficiency of the rectenna is theoretically 100 percent and the microwave efficiencies of the better types of Schottky-barrier diodes, which may be used as rectifiers, are over 80 percent. The rectenna is expected to have an overall collection and rectification efficiency of 85 or possibly 90 percent when optimum diodes are designed and the rectifier circuits are refined.

Although the rectenna is relatively new, it has been used successfully in applications[26] and has been made in a number of physical formats.[27] It is currently undergoing intensive investigation to maximize its efficiency.

An artist's concept of the appearance of the rectenna array in the SSPS system is shown in Fig. 8. The detailed format of the array has yet to be developed. Some appreciation of the detail may be obtained from a laboratory-model of the rectenna shown in Fig. 9. Printed circuit techniques would undoubtedly be used in production designs.



[9] Laboratory model rectenna made of elements consisting of a half-wave dipole and solid-state rectifiers. Elements are mounted in a plane one quarter wavelength above a reflecting metal surface. Overall capture and rectification efficiency, experimentally achieved, is 63 percent. Potential overall efficiency is 85 to 90 percent.

Microwave power transmission efficiency

The overall efficiency of a microwave power transmission system is defined as the product of the three individual efficiencies associated with dc-to-microwave power conversion, microwave transmission, and microwave-to-dc power conversion. In the SSPS system, an overall efficiency of 65 to 70 percent has been projected. How does this compare with various efficiency measurements in the laboratory?

With excellent dc-to-microwave conversion efficiency already well established,[24] laboratory effort has concentrated on output of the microwave generator to the dc output of the rectenna. Recent results[18] have given an efficiency of 60.2 percent for this portion of the system. Recent improvements in rectenna design, making use of improved Schottky-barrier diodes and improved rectifier circuits, will soon raise this figure to 70 percent. If this efficiency is multiplied by a credible generator efficiency of 85 percent, already obtained in some magnetrons and Amplitrons,[24] an overall efficiency of 59 percent is obtained, which is approaching the 65 to 70 percent projected for the SSPS.

The achieved efficiencies and those expected in the future are given in Table I. It shows an eventual laboratory overall dc-to-dc efficiency of 77 percent. The principal reason for this high efficiency is that in the laboratory nearly all of the beam can be intercepted whereas in practice this may be uneconomical.

Projected costs for the SSPS system

Table II gives the estimated capital costs of SSPS power generation in dollars per kilowatt.[8] Various confidence levels are reflected in the three different estimates of total cost and principal-components cost.

The estimates for the solar array were based on a straightforward extrapolation of existing manufacturing techniques into a highly automated format justified by the huge production volume. They did not take into account possible breakthroughs in manufacturing techniques, such as those already discussed.

The cost for the microwave transmitting antenna (designated "microwave" in Table II) and the rectenna were arrived at by a consideration of the basic materials involved and a highly automated production line, again justified by the huge number of identical units to be produced. The cost of the microwave generators was based on the very low cost of already mass-produced electronic-oven magnetrons whose material and assembly labor content is similar to the proposed generator. The cost of the Schottky-barrier diodes in the rectenna was projected on the basis of the basic material content and the use of experience curves typical of the semiconductor device industry.[24]

The estimate of transportation costs is based upon a completely reusable space shuttle to transport material from the ground to near-earth orbit and the use of space tugs equipped with high-specific-impulse electric propulsion to transport material from near-earth to synchronous orbit. The estimate given in the "low" column of the table is associated with a second-generation earth-to-near-earth-orbit system.

All component and system costs are assumed to be an average cost associated with the tooling for and the manufacture of 20 or more nearly identical systems. The development costs of the first prototype cannot now be estimated accurately but it is assumed that this cost spread over a production of 20 or more systems represents only a small fraction of the costs listed in Table II.

Number of SSPS systems and land use

The number of SSPS systems that might be deployed is dependent upon their economic viability. Any discussion of the number deployed and land use must be placed in the context of the year 2000 or thereabouts. At that time, the projected requirement is for two million megawatts of electric power generation.[1] This requirement is staggering but it still does not take into account such distinct possibilities in that time period as electric propulsion of automobiles or forced abandonment of fossil fuels for heating purposes. If the requirement were to be met by conventional generating stations rated at 1000 MW each, a quantity of 1000 such plants would be required. If these were all located offshore so as to minimize impact upon the land environment, there would be an average of one generating station approximately every 5 km along the entire U.S. coastline, exclusive of Alaska and Hawaii. This absurd example illustrates not only the magnitude of the requirement but the necessity of a variety of approaches to the energy problem.

The terrestrially based portion of the SSPS system, by virtue of its low pollution and no need for a coolant, is well suited to the inland areas of a country. There is, then, a desire to find land areas that are either wasteland, or at least marginal from an economic use point of view. To such land areas may be added low-cost land that may be located within a reasonable distance of even our most populous areas. Without some drastic reversal of the present declining birth rate and the present flow of the population from rural regions to urban centers, many sparsely populated land regions will remain available as sites for rectennas in the year 2000. This is particularly true of the arid regions of the Southwest and the Great Plains.

To be an important factor in supplying the base-load requirements in the year 2000, the SSPS system

I. Microwave power transmission efficiencies

	Efficiency Presently Demonstrated*	Efficiency Expected with Present Technology*	Efficiency Expected with Additional Development*
Microwave power generation efficiency (η_g)	76.7†	85.0	90.0
Transmission efficiency from output of generator to collector aperture (η_t)	94.0	94.0	95.0
Collection and rectification efficiency (rectenna) (η_r)	64.0	75.0	90.0
Transmission, collection, and rectification efficiency ($\eta_t\eta_r$)	60.2	70.5	85.0
Overall efficiency ($\eta_g\eta_t\eta_r$)	26.5‡	60.0	77.0

* Frequency of 2450 MHz (12.2-cm wavelength)

† This efficiency was demonstrated at 3000 MHz and a power level of 300 kW CW.

‡ This value could be immediately increased to 45 percent if an efficient generator were available at the same power level at which the $\eta_t\eta_r$ efficiency of 60.2 percent was obtained.

II. Estimated capital costs of SSPS power generation ($/kW)

Cost Element	Low $p = 0.25$	Medium $p = 0.50$	High $p = 0.75$
	Confidence Factor		
Solar array	610	1100	1870
Microwave	60	120	190
Rectenna	30	50	70
Transportation	190	450	810
Land	*	*	*
Total	890	1720	2940
Probability estimate	1400	2100	2600

*Negligible

would have to supply about 500 000 MW. This figure corresponds to a quantity of fifty 10 000-MW systems, each requiring about 40 km^2 for the rectenna and a protective guard ring. The total land requirement would be 2000 km^2. This is an insignificant portion of the marginally useful land that is still expected to be available in the year 2000.

Side effects of the SSPS system

The freedom of the SSPS from any pollution in the form of chemical, particulate, or nuclear wastes has been mentioned. It also has a very low thermal pollution as the result of the very high efficiency of the rectenna, the only terrestrially based part of the system. Three possible side effects whose seriousness should be evaluated, however, are biological effects, RFI, and weather modification.

From the viewpoint of general biological effects[29,30] of microwave energy upon man and other forms of life, the only effect that has been established after many years of investigation and observation is the heating effect, now used beneficially in the home electronic oven and in industrial processing. The heating effect is relatively benign biologically and man has the relatively high continuous-exposure tolerance of 10 mW/cm^2. The continuous exposure standard in the U.S. is set at that level.

The maximum power density of microwave radiation in the base-line SSPS system is at the center of the rectenna and its value is a little less than 100 mW/cm^2—less than that of solar radiation but ten times the density of the U.S. continuous exposure standard. The intensity level falls rapidly near the skirts of the microwave beam and reaches levels of a few μW/cm^2 within a few kilometers of the outer edge of the rectenna. A reasonable guard ring and fence around the rectenna should prevent any damage to humans or wild life in the general area. Within the confines of the rectenna area, wild life would probably be excluded and maintenance personnel would take suitable precautions.

The impact of the beam upon metal-skinned aircraft that fly through it should be minimal because almost all of the energy impinging upon the aircraft would be reflected. For fabric-covered planes and plastic-cockpit helicopters or airplanes, the occupants would be exposed to the beam for the period of time required to fly through it. The impact upon birds is a special problem that needs to be studied. Location of the rectenna in comparatively desolate areas and away from the migration lanes of birds should minimize this aspect.

In concluding this brief discussion of biological effects of the SSPS, it should be noted that despite the lack of identification of any effects of microwave radiation other than thermal, there is agreement that the study of biological effects of microwaves should be continued, particularly with respect to any long-range or delayed effects. This concern has been recognized by the U.S. Government and is identified with a proposed Government-supported comprehensive study of the nonionization aspects of microwave radiation. The results of this and other studies that may be made would determine the extent of the guard ring around the rectenna and the range of choice of geographical area for rectenna installation.

The side effects associated with RFI are expected to be more important than the biological effects. Since the microwave beam portion of the SSPS system is not intended to handle information, no bandwidth is required for that purpose. However, a transmitter of this power level will inherently generate a large amount of noise, which would be scattered physically outside of the microwave beam. The intensity of this noise would be greatest near the frequency assigned to the SSPS system, just where the use of filters is the least effective. It would be desirable, therefore, to assign a frequency band—perhaps 100 MHz wide—to the system. Initial calculations based upon the measured noise properties of the type of microwave generator proposed for the system and the use of a moderate amount of additional filtering indicate that the CCIR flux density limitation requirement that protects earth-based microwave receivers can be met if a band of 100 MHz is assigned. However, this aspect of the SSPS operation needs a great deal more study.

In the minds of many, it may seem that the proposed use of space for the transmission of power represents a potential intrusion into an area long reserved for the transmission of information and should be permitted only if our future energy problem becomes so great that power transmission through space is an overriding consideration in our system of priorities. But the coexistence of power and information transfer in space should be examined in terms of what communication practices will be in 1990 and 2000—reasonable dates for the first operational SSPS system and for full-scale deployment. The low-frequency end of the microwave spectrum, in which the SSPS would probably be located, is already becoming too restrictive for the large mass of information to be conveyed and, by 1990, almost all land-based communication may be handled in ducted systems using millimeter waves or light waves and spaced-based systems may be using millimeter waves.

It is also observed that, in the past, power and communication have been able to take advantage of a common transmission medium, notably wire transmission, and to resolve the mutual interference problems that have arisen. There may also be a clue to a solution in case interference problems do arise by observing the palliative action that has been taken to override man-made interference in the AM broadcast band by increasing the power level of the transmitter. It is even possible that the synchronous SSPS satellite may become attractive as the physical location for the transmitters of advanced communication systems because of the easy availability of power.

The issue of the microwave beam's impact upon atmospheric disturbances and weather has also been raised. Upon examination, however, it is found that the density of power input to the atmosphere resulting from absorption of microwave energy is typically 20 watts/m^2. This level is small compared with the density of power absorbed from solar radiation and reradiative processes from the earth. It is doubtful if the beam could produce a significant local disturbance. On a global scale the total energy input to the atmosphere from 100 SSPS systems would be minuscule compared with natural processes.

Any proposed time scale for the SSPS development must be made in the context of the possible need for the system, when it may be needed, and the difficulty of the development and deployment. From a strictly technological point of view, the development of the SSPS system may well be less of an undertaking than was the Apollo project when it was first initiated in 1961. Most, but certainly not all, of the basic technology and know-how involved are at hand, either from the Apollo project or from other sources.

Will there be a need for the system? This depends upon whether the approach can be made more cost competitive and upon the experience with other approaches to satisfying our future electric power needs. And here the picture is very clouded. Even nuclear fission has a relatively near-term fuel problem whose solution is dependent upon the successful development of the breeder reactor. In the long term, the bulk of all our energy—including electric energy—must come either from a concentration of the sun's diffuse energy or from nuclear fusion.

If needed, when will it be needed? It is clear that the approaches to achieve our electric power needs for the next two decades have already been set in motion. It should become much clearer in the 1980 time frame whether these approaches will also meet our needs in the 1990 to 2010 time frame and whether nuclear fusion will have progressed to the point where we will have confidence in its capability to help supply our energy needs into the future. It appears that it will be the 1980s, when the SSPS option will be picked up, if there is a need for it.

With this discussion as a background, the appropriate near-term action is clear. A thorough systems study of the SSPS should be made to determine the critical and weak points in the system and to assess if they can be dealt with successfully. If the study continues to indicate a viable system, some development effort on a few long-lead-time items should be initiated. Concurrently with the systems study, development effort should go forward in some of the already established critical areas that have a broader range of application than just the SSPS. Two specific technological areas are solar photovoltaic cells and microwave power transmission. With such a near-term program as a background, the 1980 time frame should be arrived at with a well-organized, well-thought-out program to mobilize our resources efficiently and to build and deploy the complete SSPS system ,if it should be desirable to do so.

REFERENCES

1. Szego, G. C., *et al.*, "The U.S. energy problem," Report for RANN-NSF, No. C645, Intertechnology Corporation, Warrenton, Va., Nov. 1971.

2. *World Energy Supplies*, United Nations.

3. *Handbook of Geophysics*. New York: MacMillan, Sec. 16, 1961, pp. 28-29.

4. Rink, J. E., and Hewitt, J. G., Jr., "Large terrestrial solar arrays," *Proc. 1971 Intersociety Energy Conversion Eng. Conf.*, pp. 15-23.

5. Glaser, P. E., "Power from the sun: its future," *Science*, vol. 162, pp. 857-861, Nov. 22, 1968.

6. *J. Microwave Power*, vol. 5, special issue on "Satellite solar power station and microwave transmission to earth," Dec. 1970.

7. Mockovciak, J., Jr., "A systems engineering overview of the satellite solar power station," *Proc. 1972 Intersociety Energy Conversion Eng. Conf.*

8. Briefings before the Task Force on Energy of the Committee on Science and Astronautics, U.S. House of Representatives 92nd Congress, "Satellite Solar Power Station, An Option for Power Generation." Testimony by: A. D. Little, Inc., Grumman Aerospace Corp., Raytheon Co., Textron Inc.

9. *Ad Hoc* Panel (Paul Rappaport, Chairman) on Solar Cell Efficiency, National Research Council for National Academy of Sciences, "Solar cells: outlook for improved efficiency," available from Space Science Board.

10. Woodall, J. M., and Hovel, H. J., "High efficiency $Ga_{1-x}Al_xAs$–GaAs solar cells," *Appl. Phys. Letters*, vol. 21, p. 379, Oct. 15, 1972.

11. LaBelle, H. E., Jr., "Growth of controlled profile crystals from the melt: Part II. Edge-defined, film fed growth (EFG)," *Materials Res. Bull.*, vol. 6, pp. 581-590, 1971.

12. "Development of thick film silicon growth techniques," JPL contract No. 953365 with Tyco Labs, Inc., Waltham, Mass.

13. Currin, C. G., Ling, K. S., Ralph, E. L., Smith, W. A., and Stern, R. J., "Feasibility of low cost silicon solar cells," *Proc. Ninth IEEE Photovoltaic Specialists Conf.*, Johns Hopkins University, Silver Spring, Md., May 4, 1972.

14. Brown, W. C., "Transportation of energy by microwave beam," *Proc. 1971 Intersociety Energy Conversion Eng. Conf.*, pp. 5-13.

15. Okress, E. C., *Microwave Power Engineering*, vol. 1 and 2. New York: Academic, 1968.

16. Okress, E. C., Brown, W. C., Moreno, T., Goubau, G., Heenan, N. I., and George, R. H., "Microwave power engineering," *IEEE Spectrum*, vol. 1, pp. 76-100, Oct. 1964.

17. Robinson, W. J., "Wireless power transmission in a space environment," *J. Microwave Power*, vol. 5, Dec. 1970.

18. Brown, W. C., "Progress in the efficiency of free-space microwave power transmission," *J. Microwave Power*, vol. 7, Sept. 1972.

19. Goubau, G., "Microwave power transmission from an orbiting solar power station," *J. Microwave Power*, vol. 5, Dec. 1970.

20. Goubau, G., and Schwering, F., "On the guided propagation of electromagnetic wave beams," *IRE Trans. Antennas and Propagation*, vol. AP-9, pp. 248-256, May 1961.

21. Li, T., "Diffraction loss and selection of modes in maser resonators with circular mirrors," *Bell System Tech. J.*, vol. 44, pp. 917-932, May-June 1965.

22. Degenford, J. E., Sirkis, M. D., and Steir, W. H., "The reflecting beam waveguide," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-12, pp. 445-453, July 1964.

23. Special issue on "Active and Adaptive Antennas," *IEEE Trans. Antennas and Propagation*, Mar. 1964.

24. Brown, W. C., "High power microwave generators of the crossed-field type," *J. Microwave Power*, vol. 5, Dec. 1970.

25. Brown, W. C., "The receiving antenna and microwave power rectification," *J. Microwave Power*, vol. 5, pp. 279-292, Dec. 1970.

26. Brown, W. C., "Experiments involving a microwave beam to power and position a helicopter," *IEEE Trans. Aerospace and Electronic Systems*, vol. AES-5, pp. 692-702, Sept. 1969.

27. Brown, W. C., "Progress in the design of rectennas," *J. Microwave Power*, vol. 4, pp. 168-175, 1969.

28. *Perspective on experience*, Boston Consulting Group, Boston, Mass.

29. Michaelson, S. M., "Human exposure to nonionizing radiant energy—potential hazards and safety standards," *Proc. IEEE*, vol. 60, pp. 389-421, Apr. 1972.

30. Special issue on "Biological Effects of Microwaves," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-19, Feb. 1971.

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1. The background

The radiant energy which reaches earth from the sun is our sole continuing supply, in the longterm. All the other world energy resources, whether they be fuels for burning, uranium for fission or even hydrogen for fusion, are finite in extent. In the long run, if civilization survives, those limited resources of stored energy will become exhausted. But when that day comes, sunlight will still be falling on earth with undiminished strength, we believe: at a rate, on the earth's surface, of one kilowatt per square metre of area normal to the direction of the sun.

In the very long term therefore the direct conversion of solar energy to man's use will be an important element of our civilization. In this chapter we are concerned with electronic conversion techniques, in which the solar energy interacts directly with electrons in solids. The two effects with which we are concerned are known as the photovoltaic and the thermoelectric effects.

As incoming solar energy is available to all, and free, we might well ask why it is that no great use is already made of solar energy as an energy resource. We know of some limited technical applications, it is true, which we will discuss briefly below, and of course all farmers and foresters are strongly dependent on solar energy for the growth of their crops. But why is it that relatively slight use is made of this "free" source of energy in fulfilling our requirements, particularly its potential to contribute to our usage of electricity by means of a direct interaction with the electrons in solids?

Direct electronic conversion of solar energy to electricity has other potential advantages also. It is silent and static; it involves no working fluid other than the electrons contained within the semiconductors, and it generates no waste products which require to be disposed.

There are however two principal aspects of solar energy which have limited its economic usefulness in direct conversion to electricity. In the first place it is incident at rather low power density (1 kW/m^2), so that energy must be collected over quite a large area to obtain a contribution which is appreciable in terms of our industrial electricity usage. More importantly, perhaps, is the discontinuity of its supply. The costs of the large-scale storage of electricity generated during daylight hours only, and even then intermittently during cloudy conditions, rule out for the moment the large-scale "central" generation of electricity by direct conversion of solar energy. As we shall see later, there are also the costs of the conversion devices, the "solar cells", to be taken into account.

In spite of such cost barriers there nevertheless exist applications for silicon solar cells in which they are quite economical. In the case of satellite communication systems they are indeed essential. As was shown in the first satellite communication experiments with a passively reflecting satellite in 1960, it is necessary for continuity of communications that the satellite carry a "repeater" which will receive amplify and re-transmit the signal from and to earth. The electronic equipment involved in this procedure requires a supply of electrical power to perform its function, but because of the limitations on satellite launcher payload it is not possible to launch with the satellite a supply of fuel or other stored energy which would maintain the repeater in operating condition for the many years of its life. Consequently the satellite must draw its energy supplies from its environment, and solar energy is the only realistic source. Silicon solar cells are at present the preferred means of carrying out the conversion to electricity which is required; they are more reliable and cost-effective than any other known means. We note that no energy storage is required, since a satellite in synchronous orbit is in almost continuous sunlight.

There is an increasing number of terrestial applications in which silicon solar cells are economically attractive in conjunction with storage batteries, even at their present cost levels of \$25 and above per peak watt generated. These include many electronic and other forms of equipment which are required to operate remotely, in situations where total power requirements are only a few watts and it is difficult to maintain a supply of more conventional fuel. Examples of such equipment are remote radio-telephone subscribers' installations, lighthouses and other navigational aids, terrestial broadcasting and communications repeater stations, and networks of data collection installations such as rainfall and river-height gauges.

The increasing usage of solar cells in such applications will undoubtedly lead to reductions in the cost of cells, quite apart from the possibilities inherent in the research and development into new forms of solar cell currently under way. The time has come, then, for us now to look into the physics of the operation of solar cells, so-called photovoltaic devices, so that we may identify the problems and obtain a better understanding of their exciting future prospects, from a technical point of view. It will also be possible for us at the same time to study another electronic technique for the direct conversion to electricity of incoming solar radiation, namely the use of thermoelectric effects (thermocouples). Both photovoltaic and thermoelectric effects have been recognized empirically for decades, but it is only in the past 20 years or so that clear prospects for the large-scale application of these effects have emerged as the result of technological advances in materials.

2. Semiconductors

Since both forms of interaction of sunlight with electrons with which we shall be concerned involve semiconductors, it may be appropriate to refresh our minds on some aspects of such materials. We need to know more about their properties to understand the photovoltaic effect, in which sunlight falling on a single crystal of semiconductor with an internal barrier can generate an electromotive force (emf) in the crystal, which can then dissipate electrical energy in an external load. We also need to know why heat applied to one junction between two dissimilar semiconductors can cause a current to flow, again doing work in an external load. Both these effects can be understood in terms of quite a simple model of a semiconductor.

Silicon is by far the most commonly used semiconductor material today, and we shall therefore focus on the element silicon in our basic discussions. It is one of the most commonly occurring of the elements, but our interest is in a highly processed form, in which the silicon is purified to an extraordinary degree of purity (less than one impurity atom for every 10^{10} silicon atoms).

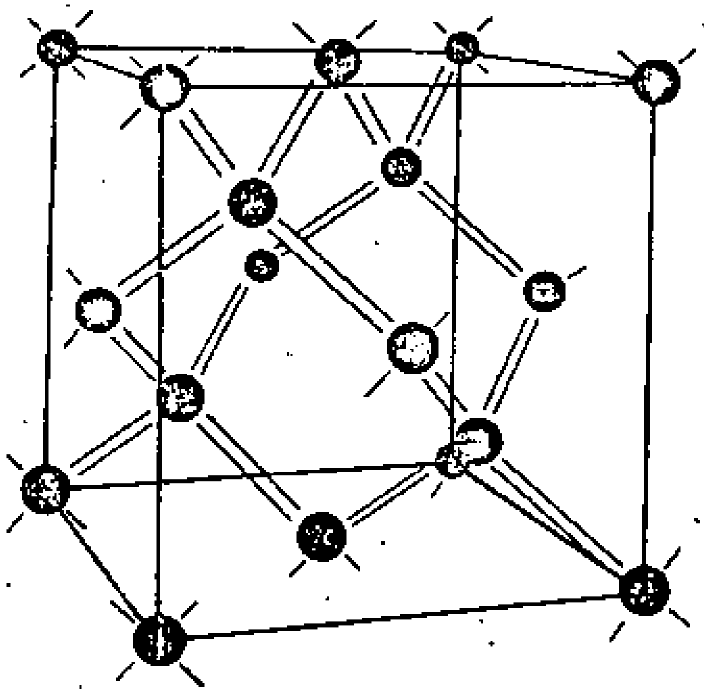

Figure 1. Spatial arrangement of atoms in crystal of silicon.

A perspective view of the arrangement of atoms in a crystal of silicon is shown in Figure 1.

The mode of crystallization shown, which occurs when molten silicon is solidified, arises from the fact that each silicon atom has 4 valence electrons. Consequently a crystal form is adopted in which each silicon atom has 4 nearest neighbours, as in Figure 1, with each of which it can share one of its valence electrons. The crystal lattice arrangement of Figure 1 is incidentally identical with the arrangement of carbon atoms in diamond, so that the crystalline structure of Figure 1 is sometimes referred to as a 'diamond lattice'.

The structure of Figure 1 is shown in a schematic 2-dimensional form in Figure 2. Here again we see each atom

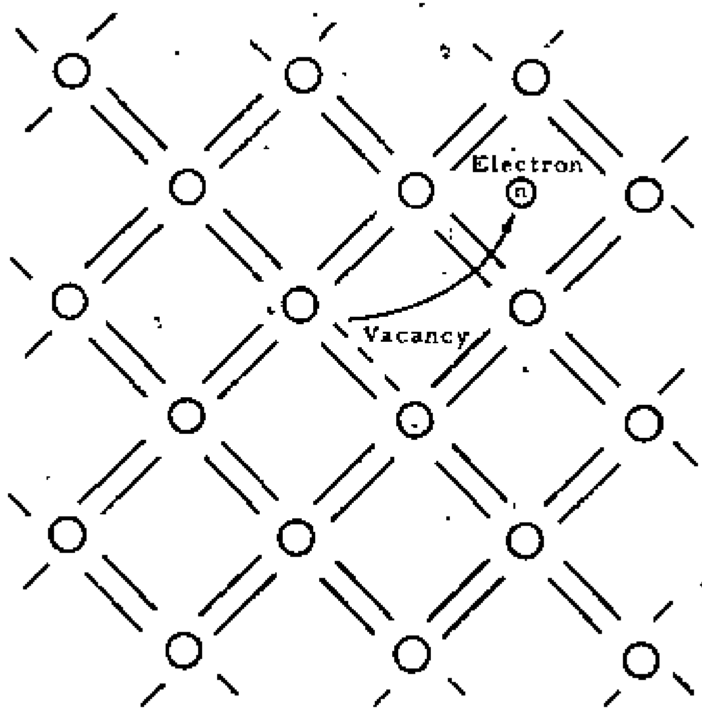

Figure 2. Schematic two-dimensional model of silicon crystal, showing creation of electron-hole pair.

with 4 nearest neighbours; the two lines drawn between each atom represent the 2 valence electrons, one from each atom. These pairs of valence electrons constitute the covalent bonds, which are in effect the binding links which hold the atoms of the crystal together.

At the absolute zero of temperature all covalent bonds in a crystal of pure silicon remain unbroken. However, as the temperature is raised, the thermal vibrations of the atoms of the lattice are sufficiently intense to disrupt some of the covalent bonds, as shown for one such bond in Figure 2. The disruption of valence bonds in crystals of semiconductor at ambient temperature has some important consequences for the electrical properties of the crystal. These are the properties of greatest interest to us when we seek explanations of the photovoltaic and thermoelectric effects.

From Figure 2 it is clear that the breaking of a valence bond gives us a free electron, free to move throughout the crystal and to take part in conduction processes. The 'missing' electron in the broken valence bond can also take part, quite independently of the newly-created free electron, in electrical conduction; it does so by successive replacement of the missing electron from neighbouring bonds.

As a consequence, when an electric field is applied to the crystal the free electrons tend to drift in a direction anti-parallel to the field, while any vacancies in the valence bonds tend to drift in the opposite direction, i.e. parallel to the field. The vacancies thus tend to behave like positively charged particles. Semiconductor physicists as a consequence are accustomed to thinking of semiconductors as materials in which electrical conduction occurs by two quite independent mechanisms: the movement of free electrons, and the movement of conceptual positively-charged particles, which we call 'holes' to remind us that each one represents a missing valence electron.

The prefix 'semi' in the word "semiconductor" arises from the fact that there are relatively few electrons and holes (in equal numbers, in a pure crystal) when compared with conductors such as the metals. In pure silicon, in equilibrium at room temperature, for example, there is one electron-hole

pair for every 10^{12} atoms approximately. This compares with one electron for each atom in many metal crystals.

In a silicon crystal under equilibrium conditions at a given temperature the electron-hole pair density is determined by steadystate balance between the rate at which electrons and holes are created by the thermal vibration processes of the lattice, and the rate at which they annihilate each other by recombination when they approach sufficiently closely to each other.

It is also possible for incoming electromagnetic radiation to disrupt the valence bonds. Provided the photon of incoming radiation is sufficiently energetic, it will create an electron-hole pair at the point at which it is absorbed. The energy required to form an electron-hole pair is a well-defined quantity; it is 1.1 eV in silicon at room temperature. It follows that any photon of energy greater than 1.1 eV, i.e. of wavelength less than 1100 nm (in the infrared region of the spectrum) can create electron-hole pairs in silicon. In particular, the greater portion of the spectrum of incoming solar radiation is capable of creating electron-hole pairs by absorption in silicon.

Such charge carriers will be in excess of equilibrium, and we shall see in the next section how they may lead to the generation of an emf and the direct conversion of solar energy to electricity. However, we must first look at the important effects which impurity elements incorporated in silicon can have on its electrical conductivity. The whole of silicon technology is based on these relatively "impure" crystals, rather than the pure crystals which we have discussed to this point.

In Figure 3 we show an atom of arsenic incorporated in a silicon crystal, grown for example from a melt containing a small additional amount of arsenic as an impurity. Arsenic atoms have 5 valence electrons. Consequently when they take up a substitutional position in the crystal lattice there is one valence electron left over, after 4 of the 5 valence electrons have been shared with the 4 nearest neighbour silicon atoms. At ambient temperatures the relatively weak binding forces which hold this fifth electron to its parent arsenic atom are

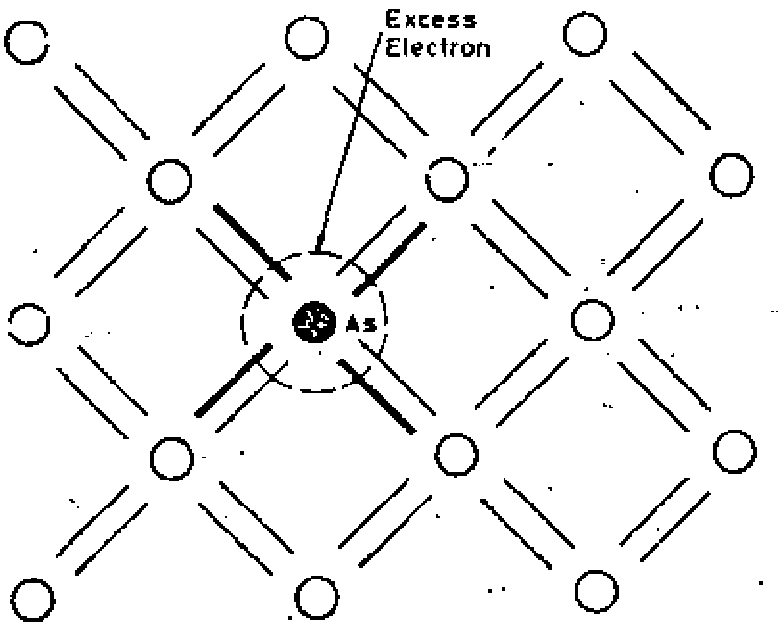

Figure 3. Arsenic impurity atom in silicon crystal, about to 'donate' free electron.

overcome, and we are left with a situation in which the arsenic atom 'donates' a free electron to the silicon crystal. The positively-ionized arsenic atom remains fixed in the crystal, while the electron which it donated can move throughout the entire crystal, and take part in electrical conduction processes if an electric field is present.

Since arsenic (and other pentavalent) atoms behave in this fashion in crystals of silicon, it is clear that additions of 'donor' impurities, as they are called, can modify the electrical properties of silicon in two important ways. In the first place, if donors are added in amounts greater than 1 part in 10^{12} (a very low level of impurity) they will increase the electrical conductivity of otherwise pure silicon. Secondly, whereas electrons and holes contribute to the conductivity in roughly equal proportions in pure silicon, conduction will be almost entirely by

the movement of the more numerous electrons in a crystal containing donors. (The positive charges, ionized donor impurities, remain fixed in the lattice and unable to contribute to conduction). Because electrons carry a negative charge, we call such crystals N-type.

Not surprisingly, there is a corresponding effect when 3-valent impurities such as boron or gallium are added to silicon. In this case, however, each impurity 'accepts' an electron from the valence bonds giving rise to a hole which can take part in conduction, and an immobile negatively charged impurity ion. Since holes are positively charged, we refer to crystals containing a majority of acceptor impurities as P-type. Once again, the conductivity of pure or 'intrinsic' silicon can be increased by many orders of magnitude (powers of ten) by the addition of appropriate amounts of acceptor impurity.

3. The photovoltaic cell

Because the relative amounts of impurity involved are so small, it is quite possible to have a single crystal of silicon which is P-type at one end, and N-type at the other. We show such a crystal containing a P-N junction in Figure 4(a). It should be pointed out, in passing, that the many millions of silicon semiconductor devices (transistors and integrated circuits) manufactured daily each contain such P-N junctions. Their properties are well understood, and widely applied.

Suppose that sunlight is allowed to fall on the silicon P-N junction, as also shown in Figure 4(a). We have already seen that each photon of solar radiation whose energy is greater than 1.1 eV is capable of creating an electron-hole pair in silicon. In the arrangement of Figure 4(a), we find experimentally that the electron-hole pairs are somehow separated, so that the P-region becomes positive with respect to the N-region. If an external load, a resistor for example, is connected to the irradiated P-N junction as shown in Figure 4(b), a current is found to flow: there is then direct electronic conversion of the incoming solar radiation to the electrical energy dissipated in the load resistor. To understand how this sequence of events can take place, we give some thought to the properties of P-N junctions.

In the N-region of the P-N junction of Figure 4(a) there are many electrons. In the P-region, by contrast, there are very few. Yet this is a monocrystal of silicon at room temperature, in which any electrons and holes present are taking part

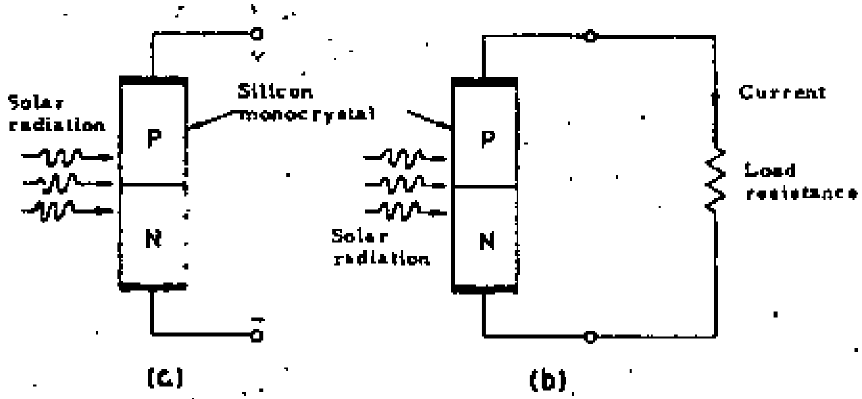

Figure 4. (a) the photovoltaic effect in silicon (b) direct electronic conversion of solar energy to electricity.

in the ceaseless migration processes which are characteristic of thermal equilibrium. The electrons in the N-region would tend to diffuse, as a consequence of their random thermal movements, into the P-region of the monocrystal. They are clearly prevented from doing so, and the restraining mechanism is a contact difference of potential between N-type and P-type silicon which is of such polarity that the P-type material is negative with respect to the N-type. Thus the electrons encounter a potential barrier at the junction : only the most energetic electrons are able to surmount it, and in equilibrium (when there is no net current flow) they are offset exactly by electrons which are thermally generated in the P-region and then accelerated through the junction to the N-region. This barrier is shown as the full line in Figure 5(a).

The polarity of the contact potential difference at the junction is such that it also acts as a barrier to constrain the positively-charged holes in the P-region, thus being more negative than the N-region. Thus in equilibrium we have zero net electron

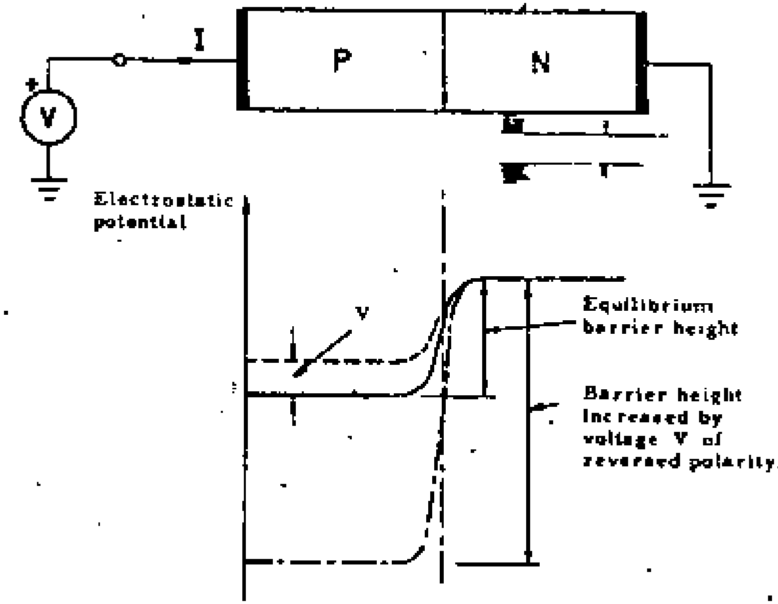

Figure 5(a). Determination of current-voltage characteristic of P-N junction.

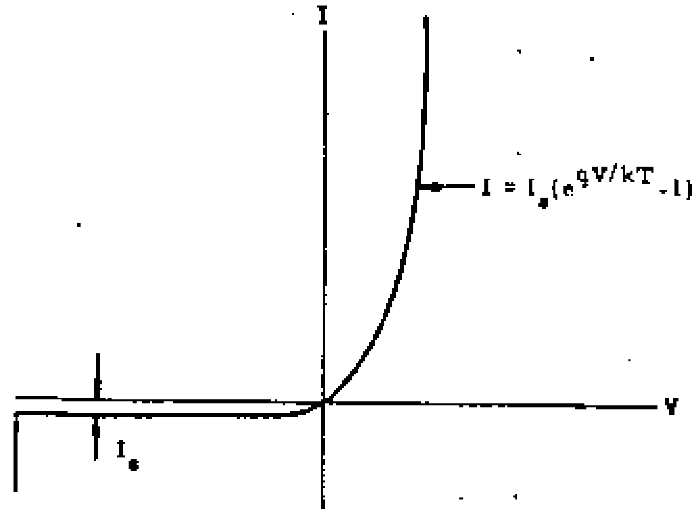

Figure 5(b). Current-voltage characteristic of P-N junction.

and hole currents through the junction, with each type of charge-carrier restrained for the most part to its respective side of the barrier.

It is possible to change the height of the barrier in two ways. We may apply an external voltage source to the junction, or we may illuminate it with photons of sufficient energy to create electron-hole pairs. Let us look at these two possibilities in more detail.

In the first instance, application of a voltage source of the polarity shown in Figure 5(a) will lower the height of the barrier, enabling increasingly large currents of electrons and holes to flow as the barrier height is further reduced. The junction current indeed increases exponentially with voltage, as shown in Figure 5(b). When we reverse the polarity of the external voltage source V, however, we increase the height of the barrier and rapidly reach a situation in which no charge-carriers of either variety can surmount the barrier. We are left only with a small saturation current I_S, corresponding to the thermal generation of electrons and holes in the vicinity of the junction. The complete current-voltage characteristic of the junction, which is highly non-linear (a "rectifier"), is shown in Figure 5(b). We note that it also exhibits a rapid increase in current for large negative values of V, when the junction undergoes a form of internal avalanche breakdown, but this need not concern us further.

Suppose that a silicon P-N junction is now illuminated while disconnected from any source of voltage, as shown in Figure 4(a). As we see from the equilibrium curve of Figure 5(a) there is in existence at the junction a potential barrier which will separate any electron-hole pairs created by light in its vicinity. The holes are accelerated into the P-region and the electrons into the N-region, so that an electromotive force (emf) is set up, of the polarity indicated in Figure 4(a).

The magnitude of the emf is in principle determined by the rate at which electron-hole pairs are being separated by the incoming radiation; in the steady state, the reduction in height of the potential barrier allows a current to flow within the junction which just balances the rate of separation of photon-created charge carriers. In practice, because of the

exponential nature of the current-voltage characteristic of P-N junction, the voltage under illumination is approximately 0.6V.

The efficiency with which the photovoltaic process for direct conversion could take place would be quite remarkably high, if only solar energy were monochromatic at a wavelength close to the electron-hole binding energy of a suitable semi-conductor! This is not the case however, we must face the fact that each photon of solar radiation with energy above 1.1 eV will create one electron-hole pair, regardless of the amount by which its energy exceeds 1.1 eV. Consequently there is a wide departure from perfection on this count alone; in silicon, maximum conversion efficiencies of 20 per cent are envisaged.

However, on this basis a one-square-metre array of silicon solar cells would generate 200 W when the axis of the array is directed at the sun.

In principle other semiconductors, particularly intermetallic compounds, should offer the prospect of higher conversion efficiencies than silicon. In practice, however, the technology of silicon processing is so advanced that silicon cells are likely to be the principal ones of interest for some time to come. The established reliability of silicon devices also mitigates against other forms of photovoltaic generator such as metal-semiconductor (Schottky) junctions in silicon or in other materials.

It is possible to consider likely increases in cost-effectiveness by concentrating or "collecting" the incident solar energy and bringing it to a focus on a smaller area of relatively expensive solar cell. The detailed economics of this procedure have to be evaluated in each application, however, as in general the concept of concentration/collection carries with it the need for a mechanical steering arrangement to ensure that the axis of the optical concentrator is always directed at the sun.

4. Thermoelectric conversion

Recently there has been a renewal of interest in the possibility of using thermoelectric generation as a means of directly converting incoming solar energy to electricity.

To understand the physics of this effect, first discovered by Seebeck 150 years ago, we refer to Figure 6 and to our earlier discussion of P-type and N-type semiconductors. In an N-type semiconductor, it will be recalled, almost all the free charge-carriers are electrons. For each electron there is a positively charged donor ion, fixed in the lattice.

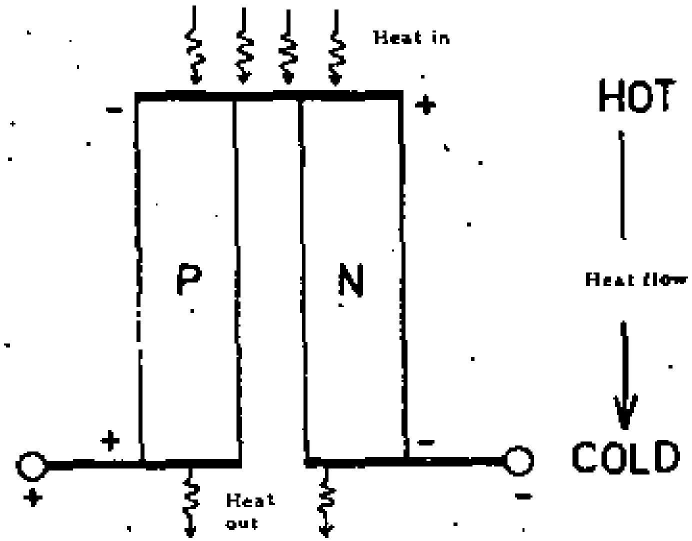

Figure 6. Thermoelectric generation of emf (Seebeck effect).

When we heat an N-type semiconductor crystal both the atoms of the crystal and the electrons move more vigorously, with increased thermal energy. If the crystal is heated locally, for example at the top of the N-type crystal shown in Figure 6, then the electrons there will move with greater thermal energy than the electrons at the cooler end of the crystal. But the electron "pressure" must be uniform throughout the crystal in a steady-state situation, and therefore, since electron pressure is proportional to the product of their density and temperature, there will be fewer electrons at the heated end. The density of positively ionized donors is fixed; however, and so the relative movement of electrons away from the

heated end leads to the generation of an emf between points in the path of the heat flow in an N-type crystal.

By means of a parallel argument it can be seen that an emf is similarly set up in a locally heated P-type semiconductor, but of opposite polarity, as shown in Figure 6. This difference enables the heated ends of the crystals to be connected with a metallic link, placing them in series, without interfering with the heat flow.

Thus we see that the thermoelectric generator of Figure 6 is also electronic in character; it is a heat engine in which electrons are the working fluid. As is the case for heat engines, its conversion efficiency is related to the Carnot efficiency appropriate to the temperature difference of hot and cold junctions, and is generally a few percent at most.

In seeking semiconductor material which will have the highest conversion efficiency, or figure of merit, we face two conflicting requirements. On the one hand we require a high resistance to the flow of heat (i.e. low thermal conductivity), but on the other a low resistance to the flow of electrical current when an external load is connected to the thermocouple. Low thermal and high electrical conductivities are most readily obtained in relatively high purity "mixed" crystals of such material as germanium and silicon, or of bismuth telluride and selenide; an economic compromise is the use of lead telluride (PbTe), which is the most used material in commonly encountered fossil-fueled thermoelectric generators of capacity 10 W and above.

In searching for possible applications to solar energy conversion for thermoelectric generators we should keep one advantage in mind. The discontinuities in the incidence of sunshine, to which reference was made at the beginning of this chapter, can be surmounted with an auxiliary fuel supply to heat the thermoelectric generator when solar energy is unavailable. In this case, in principle, there would be no need for the storage of electrical energy as with solar cells.

Recently, however, there has been speculation that this latter disadvantage of photovoltaic solar energy conversion systems may be avoided by placing the system as an earth satellite in synchronous orbit. In this case it would be continuously irradiated with sunlight except for the relatively rare occasions on which it is eclipsed. There are very great difficulties, however, in arranging for the energy generated to be transported to earth from the satellite!

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

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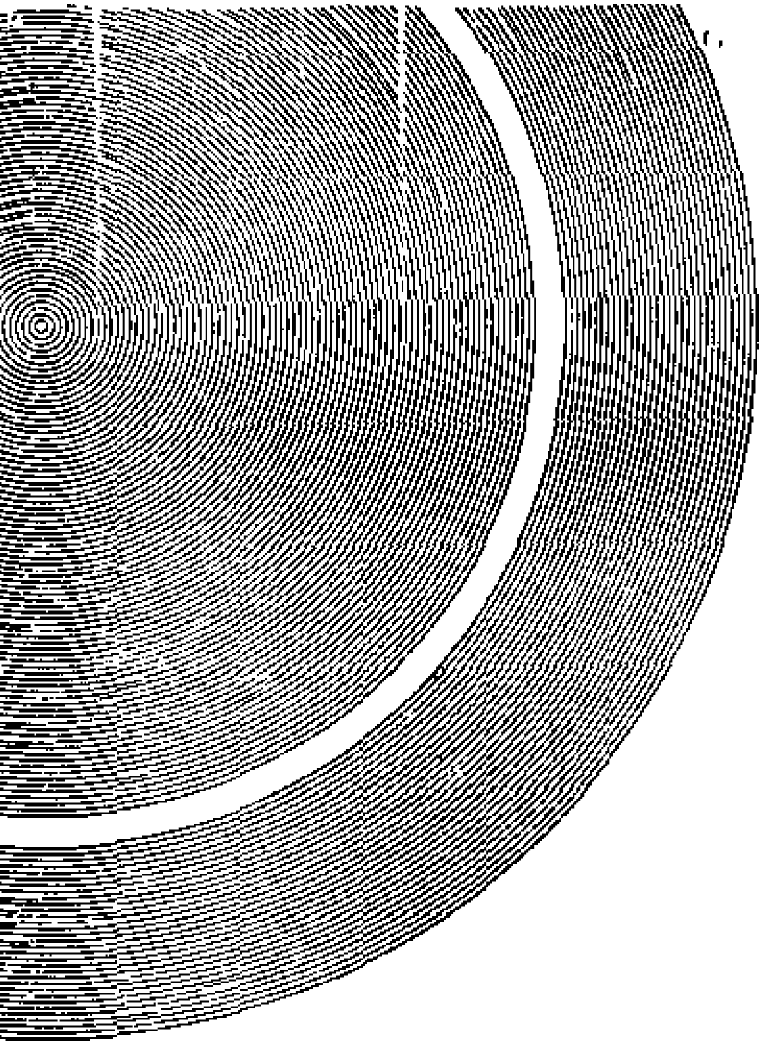
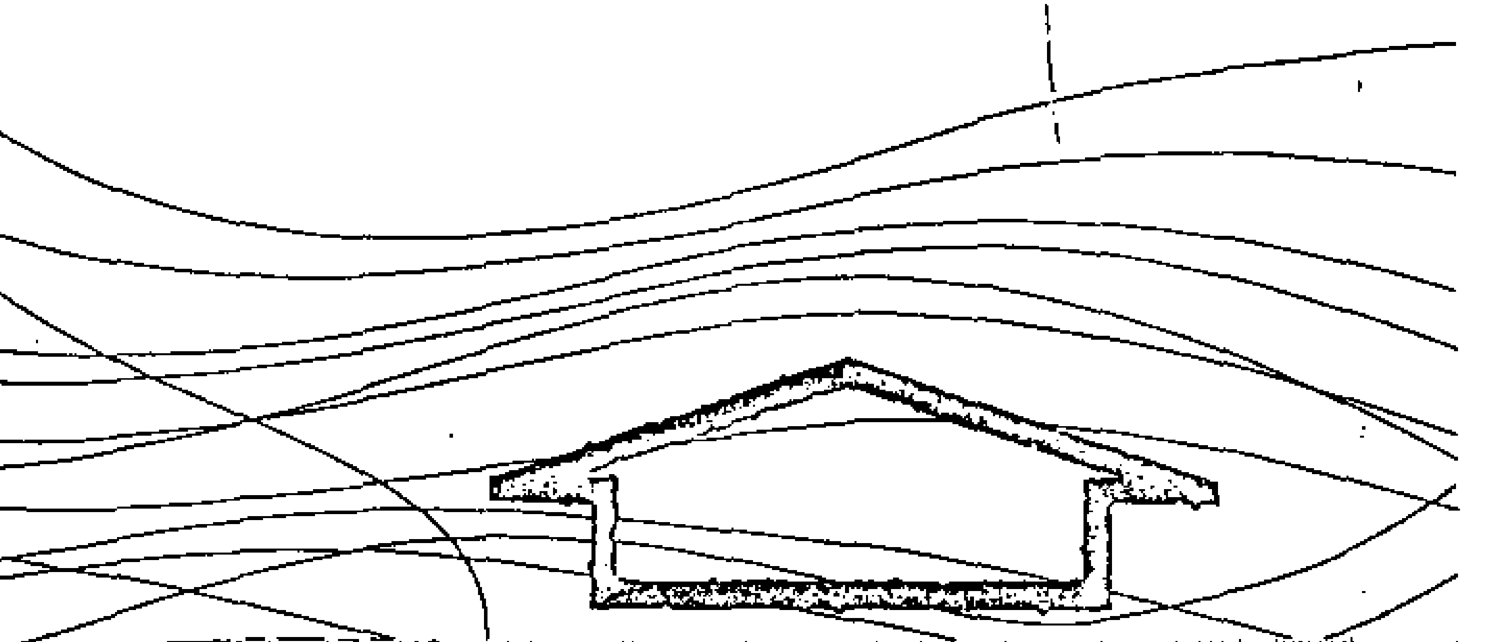


climatización eólico - solar de escuelas en climas cálido - húmedos

Everardo Hernández H.*



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INTRODUCCION

El sol, elemento fundamental de nuestro sistema ecológico, es una fuente natural de energía que, en la actualidad, el hombre busca afanosamente aprovechar para mejorar sus condiciones de vida.

De acuerdo con los lineamientos que el CONESCAL ha definido respecto a la difusión de nuevas tecnologías o nuevos enfoques de viejas ideas para el aprovechamiento de nuevas alternativas energéticas, este artículo pretende continuar con la filosofía planteada en el número 44 de esta revista, en la que se inició una serie de artículos enfocados a la difusión de criterios para la optimización del confort térmico en el interior de los recintos escolares. En ese sentido este trabajo ejemplifica cómo, mediante la conversión fototérmica de la energía solar, es decir mediante la transformación de radiación solar en calor, es posible alcanzar la sensación de bienestar higrotérmico a través del diseño de sistemas de climatización natural, en los que el sol y el viento proporcionan la fuerza motriz para el acondicionamiento adecuado del aire.

1. CLIMATIZACION NATURAL HABITACIONAL

Un área de exhaustiva investigación de la energía solar es la arquitectura solar o helio-arquitectura. Esta, a partir de la información sobre la intensidad y duración de la radiación solar global, directa y difusa y otros elementos climatológicos locales –temperaturas, humedad y vientos predominantes– permite diseñar viviendas con los requerimientos necesarios para resolver problemas de climatización, tales como ventilación, enfriamiento y calentamiento.

Los diseños helio-arquitectónicos deben realizarse de acuerdo al tipo de clima y con materiales de propiedades térmicas adecuadas, para que de esta manera, la construcción misma sea capaz de actuar como un envolvente autoregulador de las variaciones térmicas diarias y estacionales del exterior. Se ha podido comprobar que mediante sistemas de climatización pasiva –los que por su naturaleza prescinden de sistemas electromecánicos– es factible alcanzar condiciones de confort térmico humano, evitándose así el empleo de sofisticados y costosos dispositivos de aire acondicionado, calefacción y otros. Latinoamérica, al igual que todas aquellas regiones del mundo situadas en las zonas tropicales, subtropicales y de latitudes medias (hasta el paralelo 55°) cuenta con un caudal energético solar anual (Figs. 1 y 2) que permite, mediante el diseño helio-arquitectónico idóneo, el funcionamiento eficiente de sistemas de solarización pasiva, ya que éstos operan, la mayoría de las veces, tanto en condiciones de cielo despejado como nublado.

Otras características positivas de los sistemas de climatización pasiva son su baja inversión inicial, rápida amortización, mínimo mantenimiento, integración estructural a la vivienda, larga durabilidad y el no propiciar alteraciones de la salud. Esta última característica es muy importante, ya que por el contrario los sistemas electromecánicos convencionales de aire acondicionado, sufren frecuentes averías en sus mecanismos de regulación de temperatura, además del "shock térmico" que el individuo experimenta cuando sale del local acondicionado artificialmente.

Puede decirse que los sistemas pasivos ofrecen una respuesta más natural a los requerimientos de confort térmico, aunque cabe aclarar que ante el empleo de los sistemas electromecánicos, el hombre moderno se ha vuelto demasiado exigente y las condiciones proporcionadas por un sistema pasivo pudieran parecerle insuficientes con respecto a su estándar de comodidad. Sin embargo, debemos recordar que el aire acondicionado es un producto tecnológico relativamente reciente, y que el hombre ha podido prescindir de él a través de los tiempos. Es fácil constatar que culturas ancestrales ya basaban el diseño de sus viviendas en función de un profundo conocimiento de su habitat y de la problemática climatológica local. El diseño bioclimático resultante conjuntaba, además, la integración de materiales locales que empíricamente mostraban las propiedades térmicas adecuadas a sus requerimientos de aislamiento o almacenamiento de calor.

La capacidad de los sistemas pasivos para proporcionar condiciones favorables de bienestar térmico, dentro de límites razonablemente aceptables para el ser humano, está condicionada a la disponibilidad de energía solar –que como ya se apuntó es cuantiosa en Latinoamérica– y al diseño helio-arquitectónico apropiado, resultante del análisis de variables locales y del cálculo que permita el dimensionamiento apropiado y eficiente del sistema seleccionado.

Dado que los sistemas pasivos de climatización basan su funcionamiento en fenómenos de convección y advección de fluidos, así como en intercambios de radiación solar y terrestre, cuya descripción fisicomatemática quedaría fuera del contexto del nivel de divulgación científica con el cual está enfocado este artículo, la exposición se centrará sobre la descripción operativa de los sistemas de climatización y los diseños que, en mi opinión, pudiesen dar una solución práctica a un problema de climatización de un edificio escolar. En particular he considerado de interés abordar el problema de la ventilación de aulas en climas húmedo-calientes. El por qué de la selección de este caso prticular se fundamenta en la circunstancia de que este tipo de clima corresponde a extensas regiones de Latinoamérica y del Caribe, donde las escuelas presentan serios problemas de ventilación matutina, vespertina y nocturna.

Considero que los sistemas y diseños que se describirán ofrecen, por su bajo costo, una solución de alto beneficio social, y representan una alternativa económicamente factible a los problemas de climatización que sufre la población escolar mayoritaria en las regiones tropicales húmedo-calientes de Latinoamérica y la región del Caribe.

2. ANALISIS CLIMATOLOGICO DE LA LOCALIDAD SELECCIONADA

Como ejemplo de la problemática a resolver, he escogido la localidad de Martínez de la Torre, Estado de Veracruz, que se encuentra a sólo unas decenas de kilómetros del litoral del Golfo de México, a una latitud de 20° 04' N.; longitud 97° 03' W.; altitud: 152 m.s.n.m. Su clima se clasifica como tropical lluvioso (clima de selva), húmedo - cálido.

Temperatura del aire.

En la tabla I podemos observar los valores de las temperaturas:

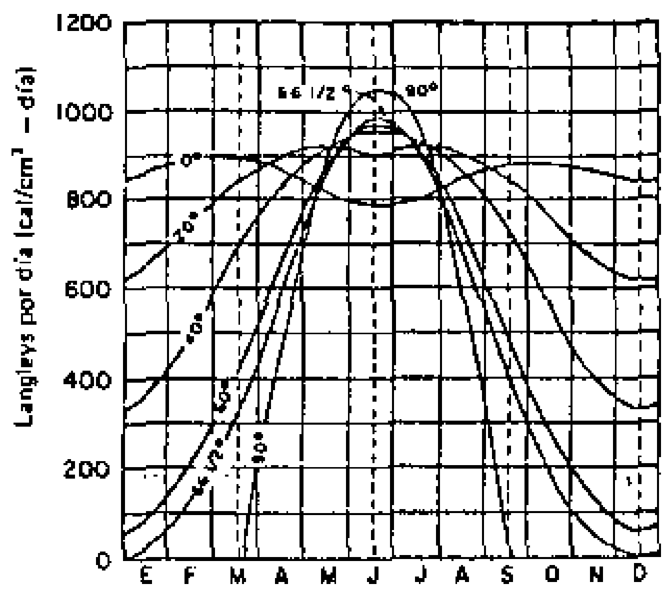


FIGURA 1

Insolación en varias latitudes del Hemisferio Norte.

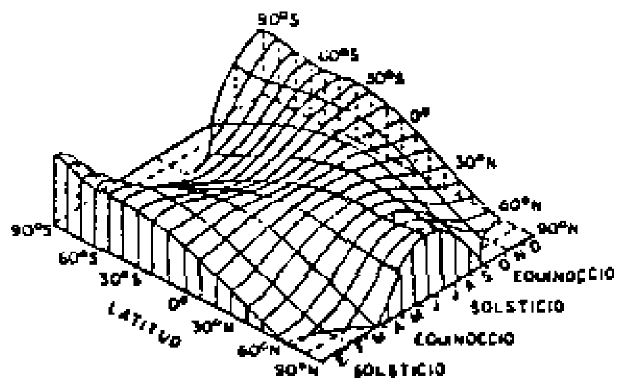


FIGURA 2

Insolación en varias latitudes y épocas del año.

TABLA I   Temperaturas °C (1945 – 1970)

	E	F	M	A	M	J	J	A	S	O	N	D	A
Máxima extrema	38.5	37.0	41.0	43.2	43.6	39.6	39.0	40.0	39.8	38.0	34.0	36.5	43.6
Promedio de máximas	23.8	25.2	27.2	30.9	33.1	33.0	31.9	33.1	31.5	29.6	26.2	24.0	29.1
Media	18.6	19.8	22.0	25.5	27.5	27.7	26.7	27.4	26.4	24.5	21.3	19.0	23.6
Promedio de mínimas	13.5	14.5	16.8	20.1	22.0	22.4	21.5	21.7	21.4	19.5	16.4	14.1	18.6
Mínima extrema	0.9	2.0	6.0	8.0	14.5	16.1	16.0	18.0	14.0	11.0	7.0	3.0	0.9
Oscilación	10.3	10.7	10.4	10.8	11.1	10.6	10.4	11.4	10.1	10.1	9.8	9.9	10.5

Podrá observarse que el promedio de máxima oscila durante el año entre 23.8°C en enero (invierno del hemisferio norte) y 33.1 °C en mayo y agosto (verano). Hay que recordar que la temperatura máxima, generalmente ocurre entre las 14:00 y 15:00 hrs, mientras que las temperaturas mínimas ocurren al amanecer. Estas últimas oscilan entre 0.9°C en enero y 18.0°C en agosto. La temperatura media, según podemos observar del histograma de la figura 3, oscila de 18.6°C en enero a 27.7°C en junio.

La oscilación media diaria durante todos los meses permanece casi constante, fluctuando entre los 9.8°C y 11.4°C.

Dado que las temperaturas máximas y mínimas extremas (record) han ocurrido solamente en una ocasión durante los 26 años (1945-70) de registro, para propósitos de diseño es recomendable basarse en los promedios mensuales de máxima y de mínima.

Humedad relativa

Como la humedad relativa representa la cantidad de vapor de agua contenido en un momento dado en el aire, respecto a la cantidad máxima que pudiese contener a la temperatura ambiente, se infiere que una humedad relativa del 100% correspondería al aire completamente saturado y, en consecuencia, imposibilitado de aceptar más vapor de agua sin que se produzca la inmediata condensación del exceso de vapor presente. Las consideraciones anteriores son importantes, ya que en la localidad de Martínez de la Torre, la humedad relativa media mensual fluctúa durante todo el año entre el 70 y 80%, lo que significa que es una atmósfera demasiado húmeda en la cual se propicia la formación de rocío matutino, cuando la humedad relativa aumenta al 100% al disminuir la temperatura del aire al tiempo de la salida del sol. En la tabla II puede observarse cómo aproximadamente en poco más de un tercio del año se presentan días con rocío.

La presión de vapor de agua fluctúa entre 25 y 30 milibarios, lo que ya produce sensaciones de incomodidad y de bochorno al aumentar la temperatura en las primeras horas de la mañana.

Al sobrepasar la presión de vapor el valor de 20 mb., ya se nota cierto grado de incomodidad.

Precipitación

La tabla III muestra la distribución anual de la precipitación, donde podemos apreciar que llueve durante todo el año. Las precipitaciones más intensas ocurren durante el verano, otoño y principios del invierno. El histograma de la Fig. 4 muestra la distribución anual del total de lluvia (media mensual).

Condiciones del cielo

Examinando la tabla IV y el histograma de la Fig. 5, donde se muestra la distribución anual de la cubierta de nubes de la localidad en cuestión es fácil percatarse de que el cielo está permanentemente nublado. Casi la mitad del año presenta nublados cerrados en un 50% del mes. La suma de días completamente nublados y parcialmente nublados es mínima durante fines del invierno y primavera que, como se describió anteriormente, es la época de menor precipitación pluvial.

Puesto que en este estudio se trata de aprovechar la radiación solar, el conocimiento de la nubosidad resulta fundamentalmente importante. La nubosidad porcentual y el tipo de nubes repercute cuanticualitativamente en la radiación solar que, finalmente, alcanza a llegar a nivel del suelo después de ser atenuada en su trayecto atmosférico.

En la misma Tabla IV se observa que el número de días con niebla es mayor en invierno. Esto se debe a que las más bajas temperaturas características de esta estación, favorecen la condensación del vapor de agua, formándose así nieblas matutinas o vespertinas. Por el contrario, durante el verano, las temperaturas son más elevadas, y aunque la humedad relativa permanece alta, no llega a alcanzarse fácilmente la temperatura de punto de rocío. De mayo a agosto se observan a lo sumo dos días con niebla. Afortunadamente, las nieblas se disipan durante las primeras horas de la mañana, reduciéndose así, una posible atenuación adicional de la radiación solar.

Radiación solar

Como se señala en el párrafo anterior, las nubes tienen un efecto determinante en cuanto a la intermitencia e intensidad de la radiación solar disponible. Las nubes constituyen el elemento que mayor reducción produce sobre la cantidad y duración de asoleamiento o insolación. Sin embargo, a la latitud geográfica en la que se encuentra el sitio escogido, la radiación solar anual es cuantiosa respecto a latitudes mayores. Esto puede apreciarse en la Fig. 2. No obstante, por efecto de las nubes, la radiación global resultante (directa + difusa) es predominantemente difusa. (Figs. 6 y 7).

Los principales fenómenos de atenuación de la radiación solar pueden clasificarse en tres: reflexión, dispersión y absorción. El primero repercute negativamente en la disponibilidad de radiación solar, ya que las nubes generalmente presentan una alta reflectividad a la radiación solar de onda corta, especialmente en la región del espectro electromagnético de la luz visible. Debido a esta alta reflectividad, o albedo como se acostumbra llamarla en el léxico meteorológico, una gran cantidad de radiación solar es reflejada directamente hacia el espacio exterior (Tabla 5).

El segundo de los fenómenos produce esencialmente la difusión en las regiones del espectro solar correspondientes al visible y al cercano infrarrojo. El efecto neto del fenómeno de dispersión por los gases atmosféricos y las nubes consiste en la difusión de la radiación solar. Esta difusión puede ser tan intensa que llega a producir, con frecuencia, situaciones molestas por el deslumbramiento que produce.

La intensidad de la radiación difusa en latitudes ecuatoriales y subtropicales, generalmente es cuantiosa, a menos que existan nublados demasiado cerrados como los que anteceden a las tormentas tropicales (Fig. 7).

La Fig. 8 muestra la intensidad de la radiación solar en varios tipos de atmósferas, pudiéndose observar que en las atmósferas consideradas como "húmedas" la intensidad no deja de ser importante.

El fenómeno menos importante respecto a la atenuación de la radiación solar es el de la absorción. En efecto, dentro del intervalo de longitudes de onda que corresponden al espectro solar, la absorción por los gases de la atmósfera, y en especial por el vapor de agua y el bióxido de carbono, es mínima. Sin embargo, esta absorción puede ser de importancia en atmósferas urbanas o suburbanas contaminadas, ya que la presencia de aerosoles (partículas sólidas o líquidas suspendidas) incrementa la absorción de la radiación solar.

En contraste, el vapor de agua es opaco al paso de radiaciones electromagnéticas de mayor longitud de onda que las del espectro solar; las radiaciones del lejano infrarrojo procedentes de cuerpos o gases a temperaturas terrestres son absorbidas por el vapor de agua atmosférico, particularmente por las nubes. Esto favorece el llamado efecto invernadero atmosférico, mediante el cual las radiaciones solares pasan a través de las nubes como por analogía lo hacen a través de un vidrio común,

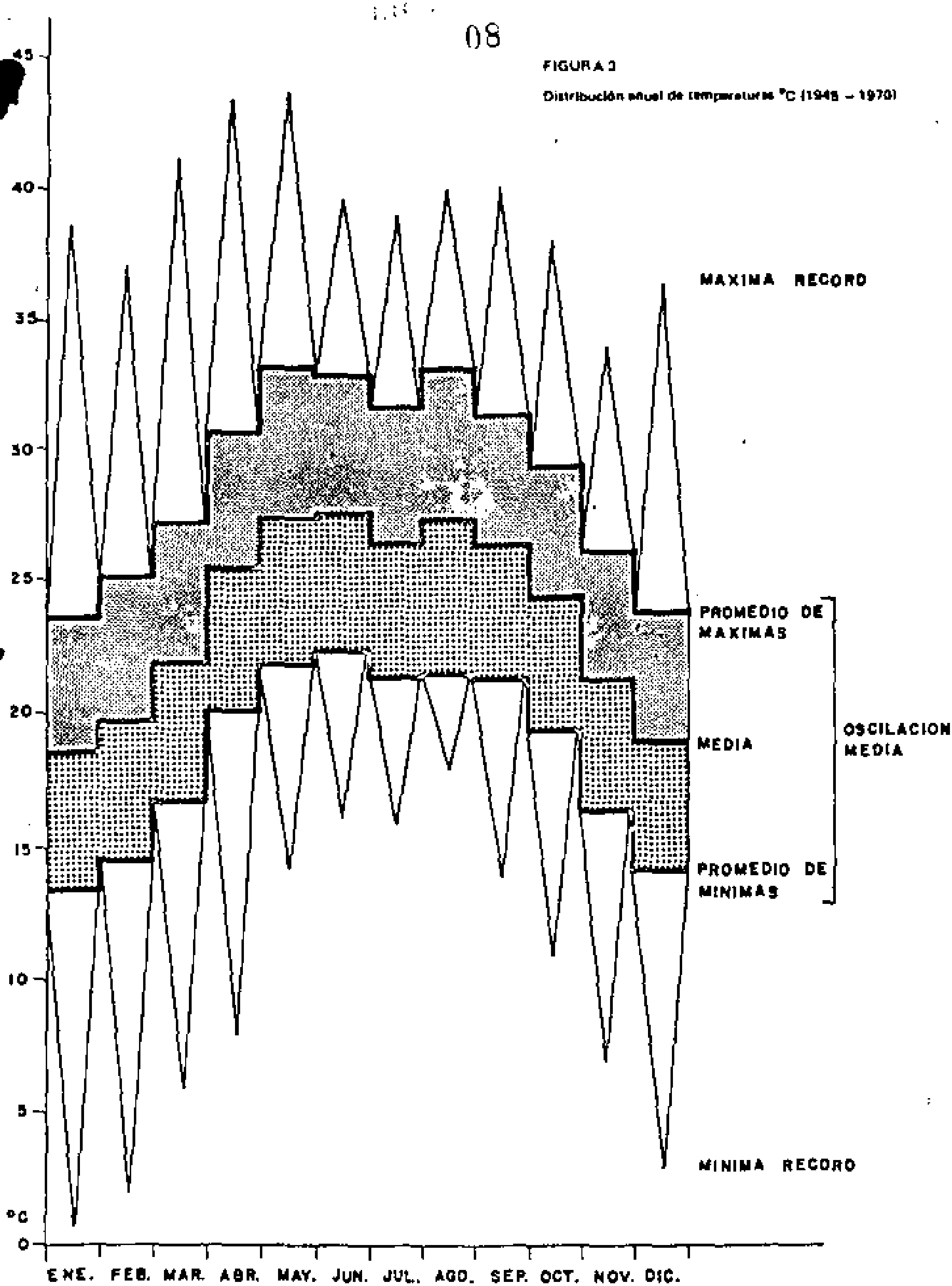


FIGURA 3

Distribución anual de temperaturas °C (1945 – 1970)

TABLA II

Días con rocío

E	F	M	A	M	J	J	A	S	O	N	D	A
10.4	12.0	11.7	11.1	12.7	12.0	11.4	13.8	10.9	11.5	10.6	12.3	140.4

TABLA III

Lluvia (1947 – 70) mm.

	E	F	M	A	M	J	J	A	S	O	N	D	A
Total (promedio)	64.3	66.4	77.4	70.8	87.6	119.7	141.7	109.6	308.1	205.4	160.1	102.6	1513.7
Máxima	155.0	122.2	278.0	222.4	217.8	299.0	358.0	375.5	689.3	570.0	495.5	322.8	689.3
Máxima del mes en 24 hs.	44.0	56.0	108.5	140.3	108.4	156.0	115.4	95.0	212.0	228.5	225.0	151.2	228.5
Mínima	24.6	15.5	19.3	4.7	1.4	15.0	2.9	20.5	73.5	58.9	46.2	16.5	1.4
Número de días con lluvia apreciable	12.4	11.3	10.4	7.0	6.4	8.3	11.4	9.9	13.0	10.7	10.3	11.1	122.0
Número de días con lluvia inapreciable	5.9	4.5	5.4	6.3	4.8	3.7	5.6	5.7	5.1	5.4	5.2	4.4	62.2
Número de días con granizo	0	0	0	0	0	0.04	0	0	0	0	0	0	0.04

TABLA IV

Distribución del número de días nublados

	E	F	M	A	M	J	J	A	S	O	N.	D	A
Número de días completamente nublados	19.5	15.5	16.9	14.6	12.9	14.8	17.3	13.4	15.1	13.4	13.5	16.1	15.2
Número de días medio nublados	5.4	5.5	5.4	6.5	7.9	5.1	7.8	11.9	9.0	7.4	6.3	4.8	6.9
Número de días despejados	6.1	7.0	8.7	8.9	10.2	10.1	5.9	5.7	5.9	10.2	10.2	10.1	8.9
Número de días con niebla	8.4	6.9	5.8	4.6	2.3	1.0	2.5	1.4	4.0	5.0	5.0	6.6	5.4

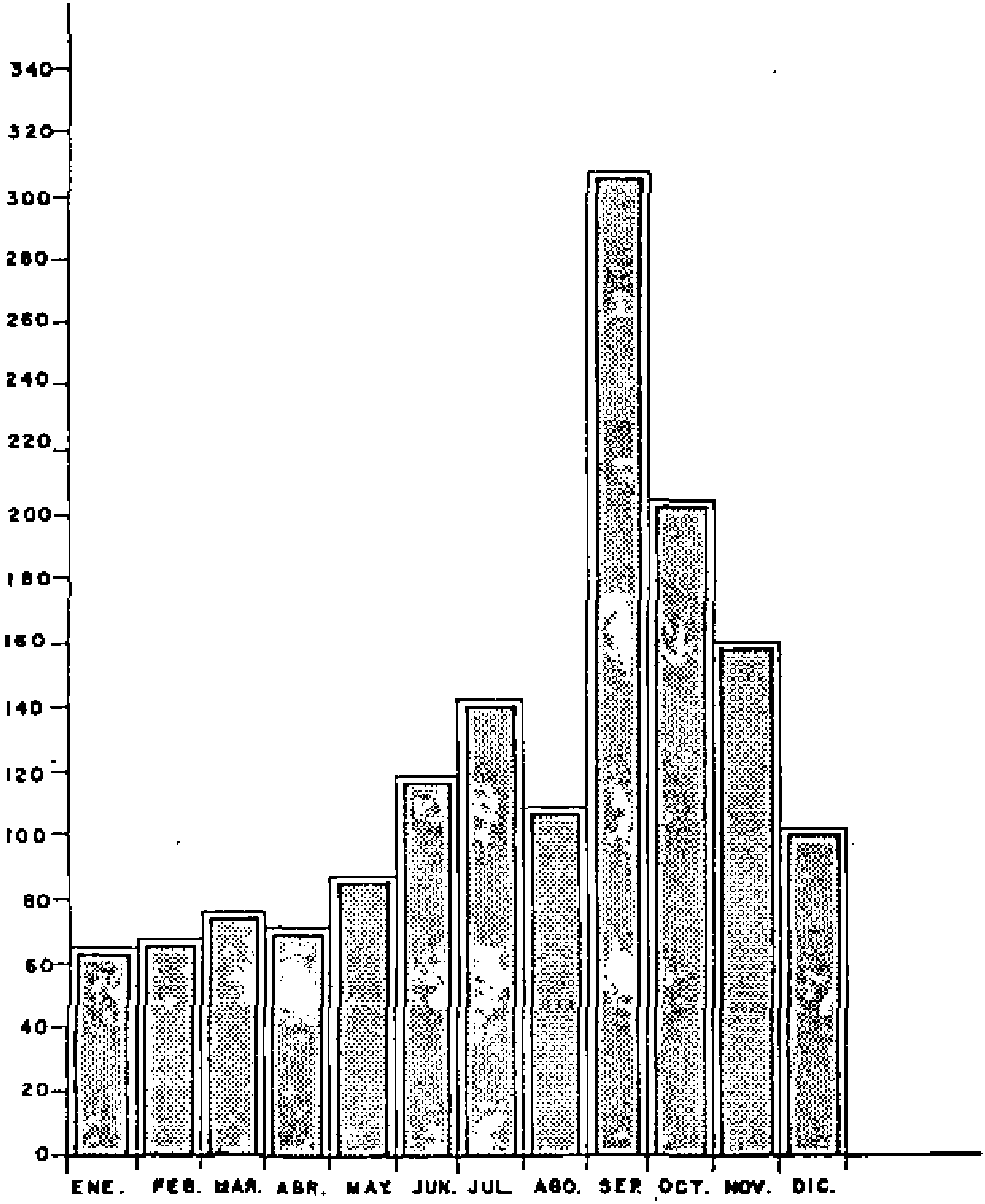


FIGURA 4

Distribución anual del total de precipitación mensual.

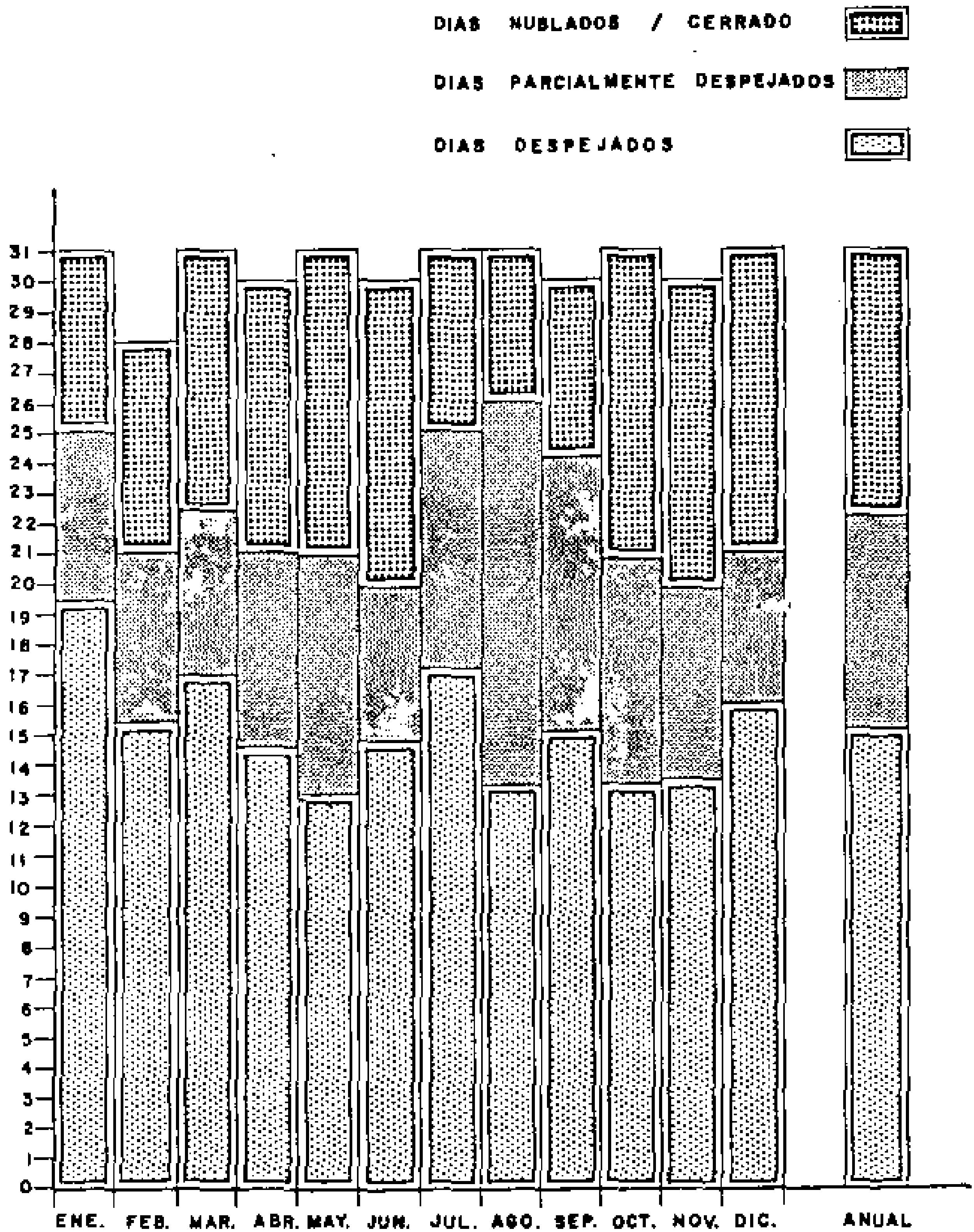
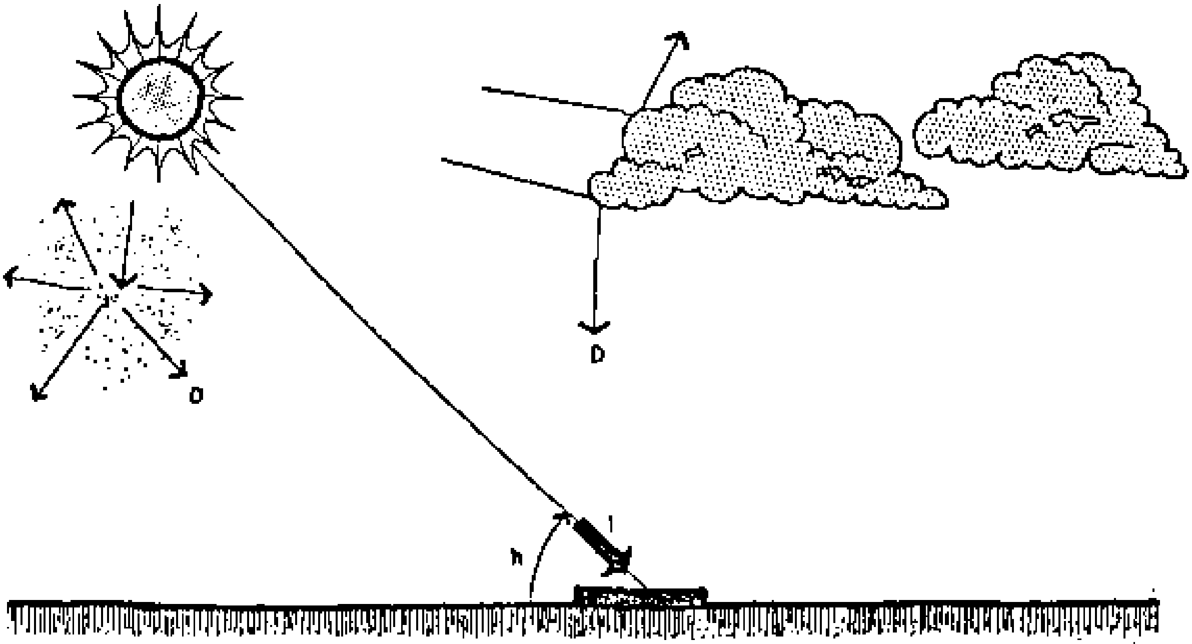


FIGURA 5

Distribución anual de la cubierta de nubes.

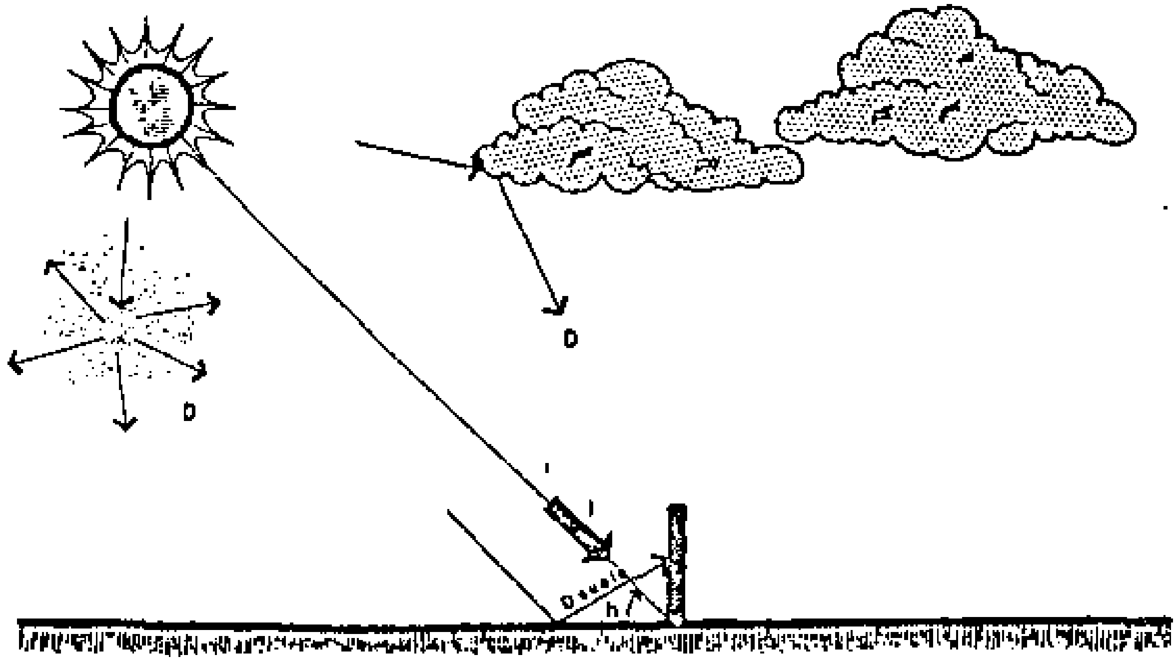


$G_H = d_H + D_H$; $d_H = I \text{ sen } h$

d_H = COMPONENTE DIRECTA $D_H = D$ = COMPONENTE DIFUSA

FIGURA 6

Radiación global sobre una superficie horizontal.



$G_V = d_V + D_V$; $d_V = I \cos h$ = COMPONENTE DIRECTA

$D_V = (D_{cielo} + D_{suelo}) / 2$ = COMPONENTE DIFUSA

FIGURA 7

Radiación global sobre una superficie vertical.

mas no es posible el paso de las radiaciones de longitud de onda más larga provenientes del suelo, cuerpos o gases calientes. Así, mediante este efecto que se incrementa por la presencia de nubes de gran espesor, se evita el enfriamiento nocturno de la superficie terrestre, permaneciendo la temperatura ambiental a un nivel elevado. Las zonas ecuatoriales y subtropicales presentan en consecuencia una débil oscilación de temperaturas diarias y estacionales. En Martínez de la Torre, esta oscilación sólo alcanza un máximo de 11.4°C. En regiones desérticas con cielos despejados, esta oscilación puede ser de 45°C en un solo día.

La Tabla V muestra la distribución anual de la radiación solar en Kwh/m^2—día.

Debido a la importancia que en helio-arquitectura tienen los asoleamientos sobre fachadas verticales, la Fig. 9 muestra la distribución anual de la insolación directa sobre el plano horizontal y sobre las fachadas este-oeste, norte y sur para condiciones de cielo despejado y a la latitud de 20°. Las abscisas representan los 36 periodos (3 por mes) en que fue dividido el año. Las ordenadas indican los valores de la radiación directa en Kwh/m^2—día.

Debido a que la radiación global G se define como la suma de las componentes directa y difusa, para el plano horizontal de captación (Fig. 6) se tiene que:

$$G_H = d_H + D_H$$

donde d_H = I sen h : componente directa

I : componente normal

h : altura solar sobre el horizonte

D_H : componente difusa

Análogamente para el plano vertical se tiene (Fig. 7)

$$G_V = d_V + D_V$$

donde : d_V = I cos h : componente directa

$$\text{y} \quad D_V = \frac{D_{cielo} + D_{suelo}}{2}$$

tal que

$$D_{cielo} = D_H = D_V$$

$$\text{y} \quad D_{suelo} = \alpha\, G_H \;:\; \alpha = \text{albedo del suelo}$$

para el caso de suelos cultivados α varía entre 0.07 y 0.14 y en selvas, de 0.06 a 0.25. Como podrá apreciarse α tiene valores pequeños, lo que significa una baja reflectividad del piso y una alta absortividad.

Respecto a la componente D_H o D_V, se tiene que ante una gran masa nubosa como lo puede ser un cumulus típico de regiones ecuatoriales o subtropicales donde los fenómenos de convección favorecen su formación, en algunas ocasiones G_H puede ser tan intensa que llegue a ser mayor que el valor de la radiación extraterrestre en el tope de la atmósfera.

Esto se origina cuando durante algunos minutos estas nubes además de difundir la radiación solar, la reflejan hacia abajo enfocándola a través de los espacios despejados que quedan entre ellas y de esta manera concentran la radiación solar global. Los elevados valores de G_H debido al fenómeno anterior contrastan con los bajos que se registran cuando las nubes llegan a ocultar al sol, (Fig. 8) tal que en promedio G_H es generalmente inferior en estas latitudes respecto a la G_H que se registra en cielos despejados. No obstante, cuando por circunstancias topográficas y orográficas existen formaciones locales de cúmulus más o menos estables, G_H puede ser superior que la G_H de cielo despejado debido a la componente reflejada desde estas nubes hacia el lugar en cuestión. En tales circunstancias y durante algunos periodos del día y del año, la G_H en presencia del cumulus es superior a la G_H teórica calculada aun para condiciones de cielo despejado.

Lo anterior es muy importante en regiones ecuatoriales y subtropicales donde comúnmente se acostumbra subestimar la radiación solar global, arguyendo la presencia continua de nubes (Tabla VI).

Viento

Para ilustrar de una manera objetiva la Tabla VI que contiene las direcciones e intensidades del viento (1946-77) en la localidad seleccionada, conviene analizar las figuras 10 a y b donde se muestran las condiciones que la circulación general de la atmósfera impone en la latitud que concierne a este caso particular y, en general, a las regiones ecuatoriales y subtropicales.

La Tabla VII indica que, durante el periodo considerado, si bien existen discontinuidades en el registro de datos (1951, 52, 53, 65 y 66), la dirección que predomina, para todos los meses es la noreste. La velocidad predominante, con clave 2, corresponde a un viento moderado con variaciones entre 2.1 a 6 m/seg. (7.56 a 21.6 Km/h.). Los vientos relativamente fuertes se presentan en los meses de junio y julio, ocurriendo en tres ocasiones por mes; la clave 3 corresponde a variaciones entre 6.1 y 12.0 m/seg (21.6 a 43.2 Km/h.).

Puede apreciarse que de 1975 a 1977, la dirección predominante es la del este, con clave 1 cuya equivalencia corresponde a velocidades entre 0.6 y 2.0 m/seg (2.16 a 7.2 Km/h.) En general, los vientos dominantes son del norte y este y sus velocidades dominantes varían entre 2.1 y 6.0 m/seg. Las direcciones que se presentan en esta localidad se deben a los alisios del noreste (Fig. 9) que soplan desde el Golfo de México a la vertiente del mismo en el Estado de Veracruz y a una latitud de 20°N.

En estas regiones el viento posee velocidades relativamente bajas, sobre todo en la zona de calmas ecuatoriales donde la advección es poco importante en comparación con los movimientos convectivos del cinturón ecuatorial de bajas presiones (Figs. 10 a y b). Respecto a las direcciones predominantes, normalmente existen dos, como sucede en este caso.

Características del suelo

Durante todo el año permanece cubierto de una vegetación generalmente densa que crece notablemente en los meses de mayor precipitación. Es debido a la vegetación que el albedo es muy pequeño, aun en áreas desforestadas, ya que el suelo, por su elevada humedad, absorbe bastante radiación solar. En épocas de lluvias intensas suelen ocurrir inundaciones que producen variaciones del albedo.

3. CONFORT TERMICO

En términos psicométricos de temperatura y humedad ambiental existen parejas de valores temperatura-humedad relati-

TABLA V DISTRIBUCION ANUAL DE LA DURACION E INTENSIDAD DE LA INSOLACION

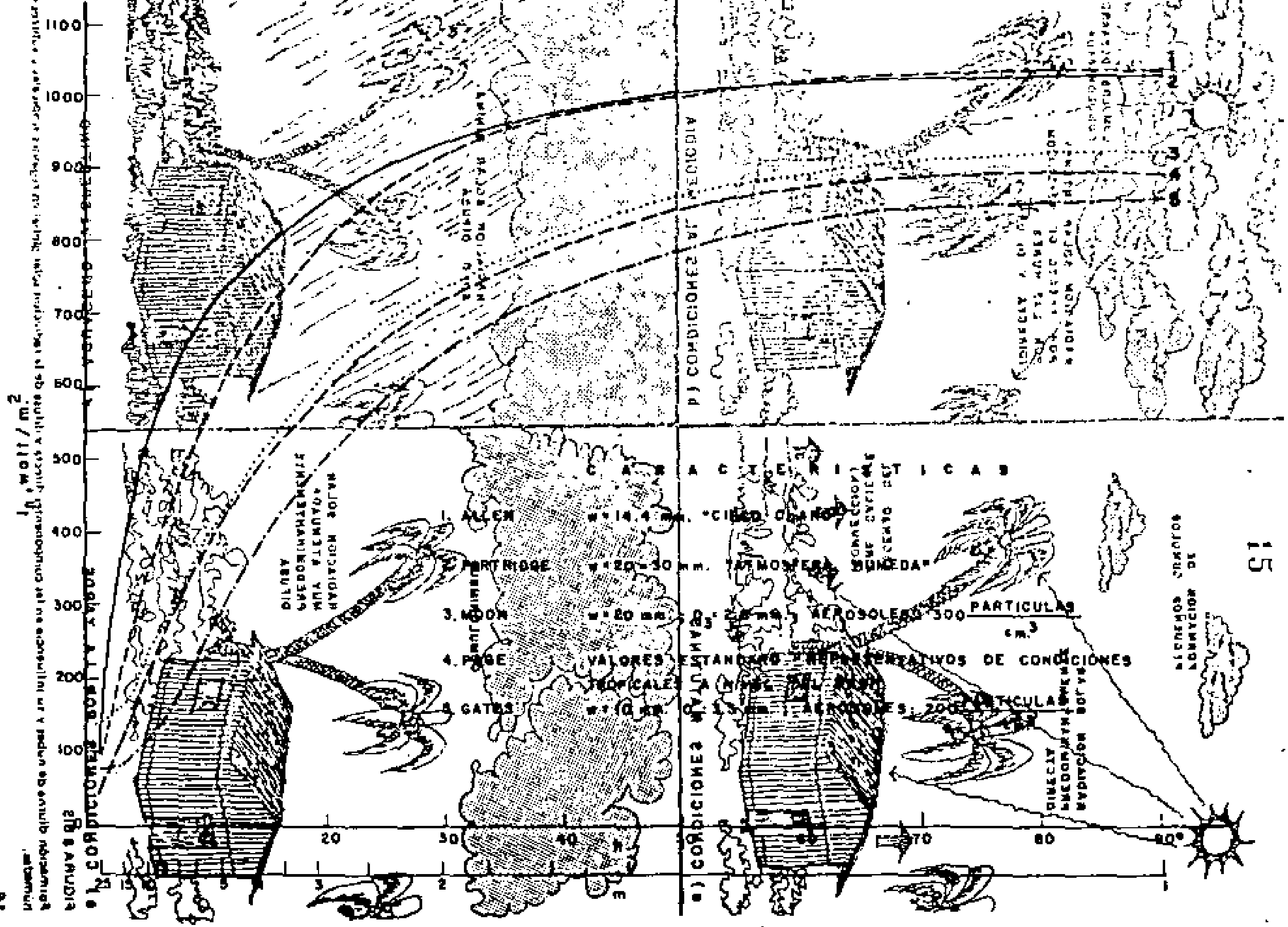
	Radiación global (kwh/m²-día)	Duración relativa de la insolación (real/máx) %	Intensidad relativa de la insolación (real/máx.) %	Radiación global máxima (días despejados Kwh/m²-día)	Radiación directa máxima (días despejados Kwh/m²-día)
Enero	3.8	59	56	5.9	4.2
Febrero	4.4	58	56	6.8	5.0
Marzo	4.4	43	47	7.7	5.8
Abril	5.5	56	56	8.4	6.5
Mayo	6.1	68	62	8.7	6.6
Junio	5.5	47	50	8.8	6.7
Julio	5.5	53	53	8.7	6.7
Agosto	4.9	49	50	8.5	6.5
Septiembre	4.4	39	44	7.9	6.2
Octubre	3.8	48	50	7.1	5.3
Noviembre	3.8	54	52	6.2	4.5
ciembre	3.8	59	56	5.7	4.0

TABLA VI Albedo de las nubes

Tipo	Espesor	Albedo
Stratus	100 m	0.4
"	200	0.5
"	300	0.6
"	500	0.7 a 0.75
Cumulus	variable	0.7
Tope de cumulus	–	0.83
Altostratus	variable	0.5

FIGURA 8

Variación del flujo de radiación solar a incidencia normal I_n en función de la masa del aire para diferentes tipos de atmósferas.



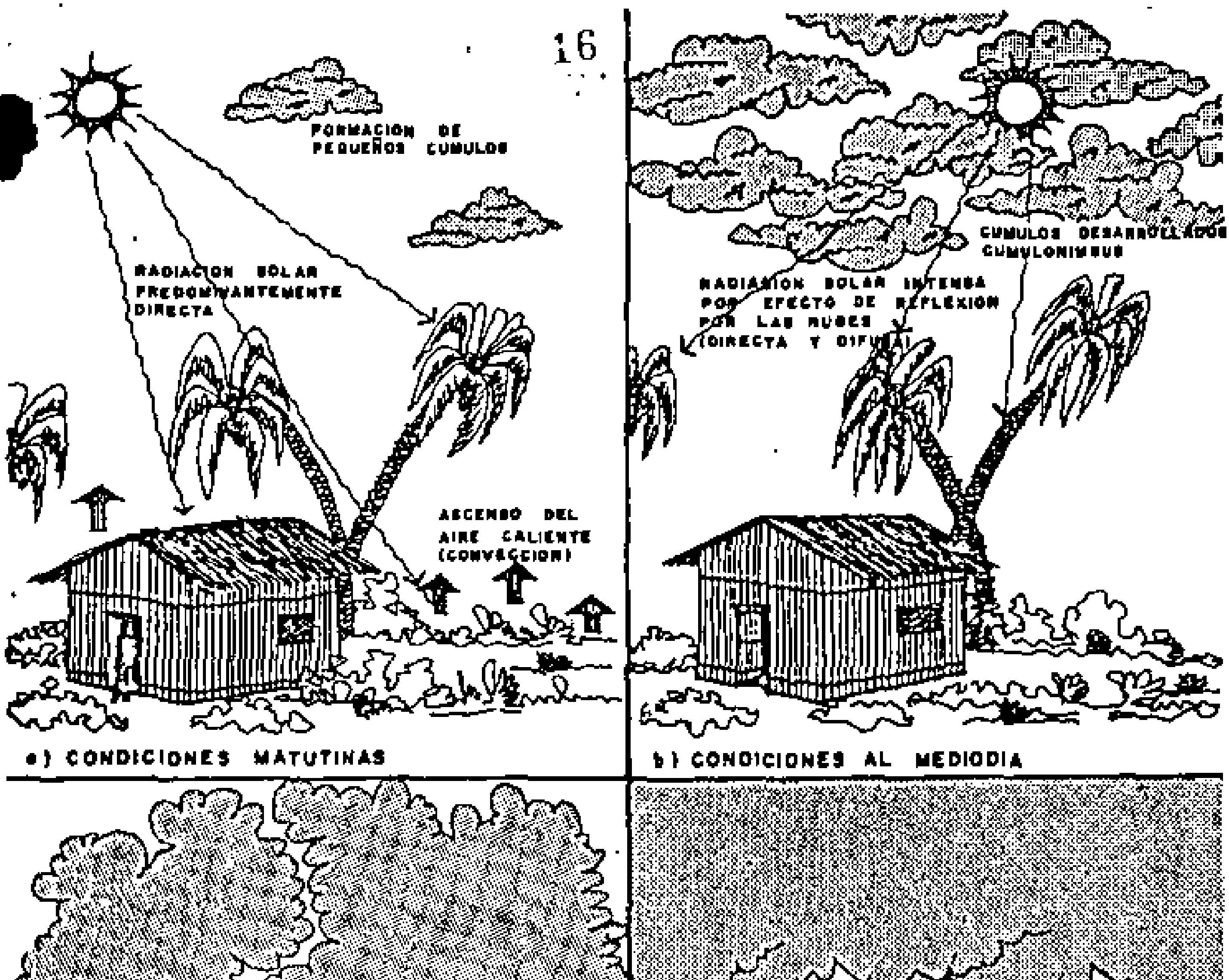


FIGURA 8 BIS

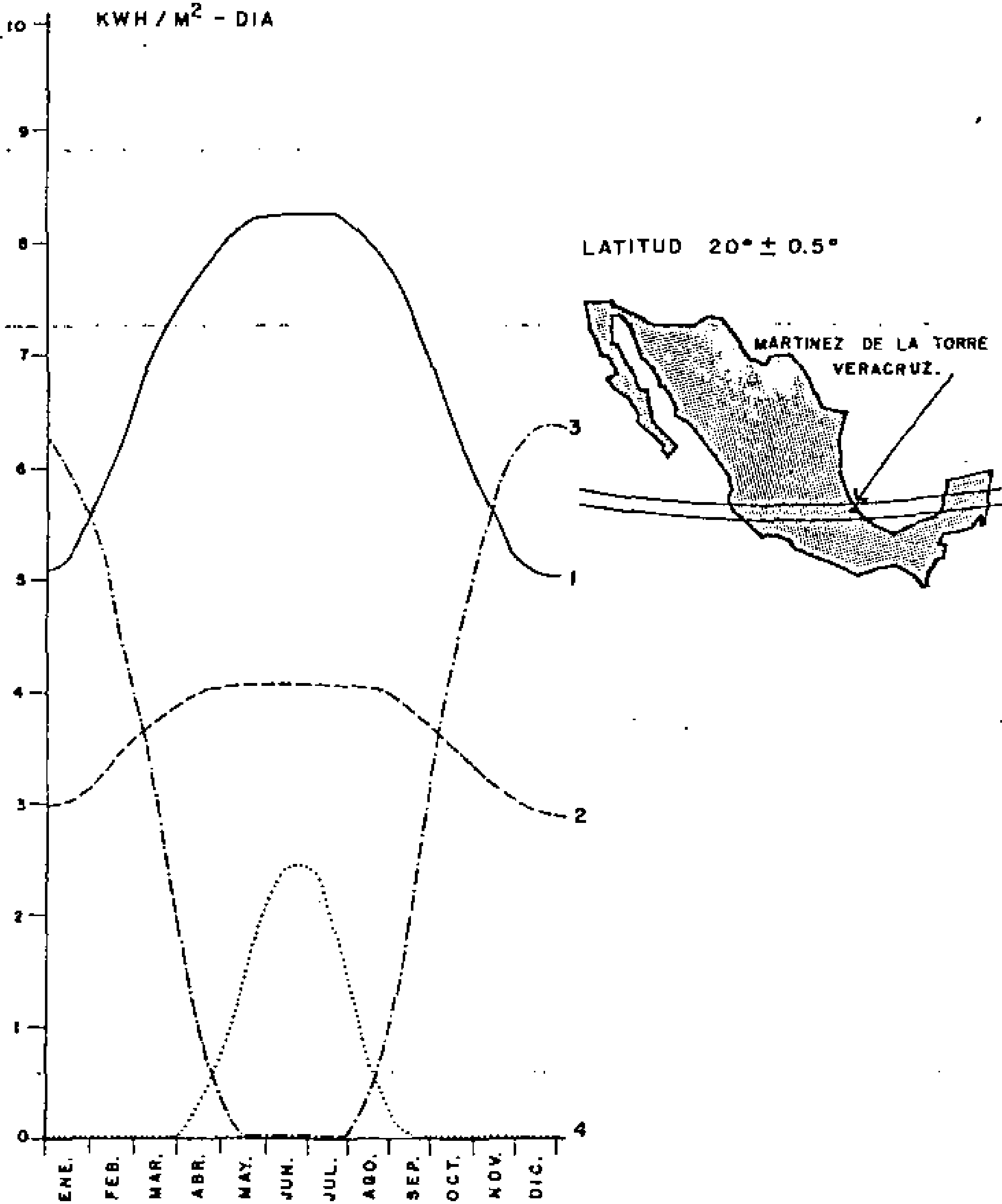
Formación diurna de nubes y su influencia en las componentes directa y difusa de la radiación solar global en regiones tropicales y subtropicales húmedas.

TABLA VII DIRECCION E INTENSIDAD DE LOS VIENTOS PREDOMINANTES

Año	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic	Anual
1946	NW^{2}	NW^{2}	NE^{2}	NE^{1}	NE^{1}	NW^{1}	NE^{3}	SE^{3}	NW^{3}	NW^{3}	NW^{3}	NW^{1}	NW^{2}
47	NW^{1}	NW^{2}	NW^{1}	NE^{2}	SE^{3}	NE^{2}	NE^{2}	NE^{2}	NW^{3}	NE^{1}	NW^{1}	NW^{2}	NW^{2}
48	E^{1}	E^{2}	E^{2}	NE^{2}	NE^{2}	SE^{3}	SE^{2}	SE^{2}	NE^{2}	NE^{2}	SE^{3}	SE^{1}	SE^{2}
49	SE^{2}	SE^{1}	SE^{3}	SE^{2}	E^{2}	E y NE^{1}	SE^{2}	SE^{2}	SW^{3}	NE^{1}			SE^{2}
50	SE^{2}	E^{2}	SE^{2}	E^{3}	SE^{3}	E^{3}	SE^{2}	SE^{3}	E^{3}	SE^{3}	E^{3}	E^{3}	SE^{2}
51	E^{2}	E^{3}	SE^{2}	E^{3}	SE^{3}	NE^{2}	E^{3}	SE^{2}					E^{3}
52													
53												SE^{2}	
54	NE^{2}	E^{3}	E^{3}	E^{3}	E^{2}	NE^{3}	E^{2}	E^{2}	SE^{3}	SE^{2}	SE^{3}	SE^{1}	E^{3}
55	NW^{3}	SW^{1}	NE^{2}	NE^{2}	NE^{1}	NE^{3}	NE^{3}	NE^{3}	NE^{2}	NE^{2}	NW^{3}	NE^{3}	NE^{2}
56	NW^{1}	NE^{2}	NE^{3}	NE^{2}	NE^{1}	NE^{3}	NE^{2}	NE^{3}	W^{2}	NE^{3}	NE^{2}	NE^{3}	NE^{2}
57	NE^{3}	NE^{3}	NE^{3}	NE^{3}	NE^{2}	NE^{3}	NE^{3}	NE^{2}	NE^{2}	NW^{2}	NE^{3}	E^{1}	NE^{3}
58	SW^{3}	NE^{3}	E^{2}	NE^{1}	NE^{2}	NE^{3}	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NW^{2}	NW^{3}	NE^{2}
59	NE^{3}	NE^{2}	NE^{3}	NE^{3}	NE^{2}	NE^{2}	NE^{2}	NW^{2}	NE^{3}	NW^{3}	NW^{2}	NW^{3}	NE^{2}
60	NE^{2}	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NE^{3}	NE^{2}	NE^{2}	NE^{2}
61	NW^{1}	NW^{1}	NE^{1}	NE^{1}	NE^{1}	NW^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{2}	NE^{1}
62	NE^{3}	NE^{1}	NE^{1}	NE^{2}	NE^{3}	NE^{2}	NE^{3}	NE^{3}	NE^{3}	NE^{3}	NE^{3}	W^{2}	NE^{2}
63	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NE^{3}	NE^{2}	NE^{3}	NE^{3}	NE^{2}	NE^{2}	NE^{3}	NE^{1}	NE^{2}
64	NE^{1}	NE^{3}	NE^{2}	NE2^{1}	NE^{3}	NE^{3}	NE^{2}	SW^{1}	NE^{3}	NE^{3}	NE^{3}	NE^{1}	NE^{2}
65	NE^{1}	NE^{2}	NE^{2}	NE^{3}	NE^{3}								NE^{2}
66						NE^{1}	NE^{3}	NE^{2}	SE^{3}	SW^{2}	NE^{2}	NE^{2}	NE^{2}
67	NE^{2}	NE^{2}	NE^{1}	NE^{1}	NE^{1}	NE^{3}	E^{3}	NE^{2}	NE^{2}	NE^{1}	NE^{2}	NE^{3}	NE^{2}
68	NE^{2}	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NE^{2}	NE^{2}	NE^{2}	NE^{2}	NE^{3}	NW^{3}	NW^{1}	NE^{2}
69	NE^{3}	NE^{2}	NE^{2}	NE^{2}	NE^{2}	NE^{2}	NE^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{1}	SW^{1}	NE^{2}
70	NE^{1}	NE^{2}	NE^{3}	NE^{1}	NE^{2}	NE^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{2}	S^{1}	NW^{2}	NE^{1}
71	NE^{1}	NE^{1}	NE^{2}	NE^{1}	NE^{1}	NE^{1}	NE^{2}	NE^{1}	E^{1}	NE^{1}	NE^{1}	NE^{1}	NE^{1}
72	NE^{1}	SW^{1}	NE^{1}	NE^{1}	NE^{3}	NE^{1}	NE^{3}	NE^{1}	N^{2}	NE^{1}	NE^{1}	NE^{1}	NE^{1}
73	NE^{1}	NE^{1}	NE^{1}	E^{3}	NE^{3}	E^{3}	NE^{3}	N^{2}	SW^{3}		SW^{1}	SW^{1}	NE^{1}
74	NW^{3}	NW^{2}	SW^{2}	SW^{1}	SW^{1}	SW^{3}	E^{1}	NE^{3}	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}
75	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}		E^{1}		NW^{2}	E^{1}	E^{1}	E^{3}	E^{1}
76	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}	W^{1}	E^{1}	E^{1}	E^{1}	W^{2}	E^{1}	E^{1}
77	NW^{1}	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}	E^{1}						

FIGURA 9

Intensidad de la insolación directa sobre el plano horizontal (1) y las fachadas este-oeste (2), sur (3), y norte (4) para 36 periodos del año (3 por mes).



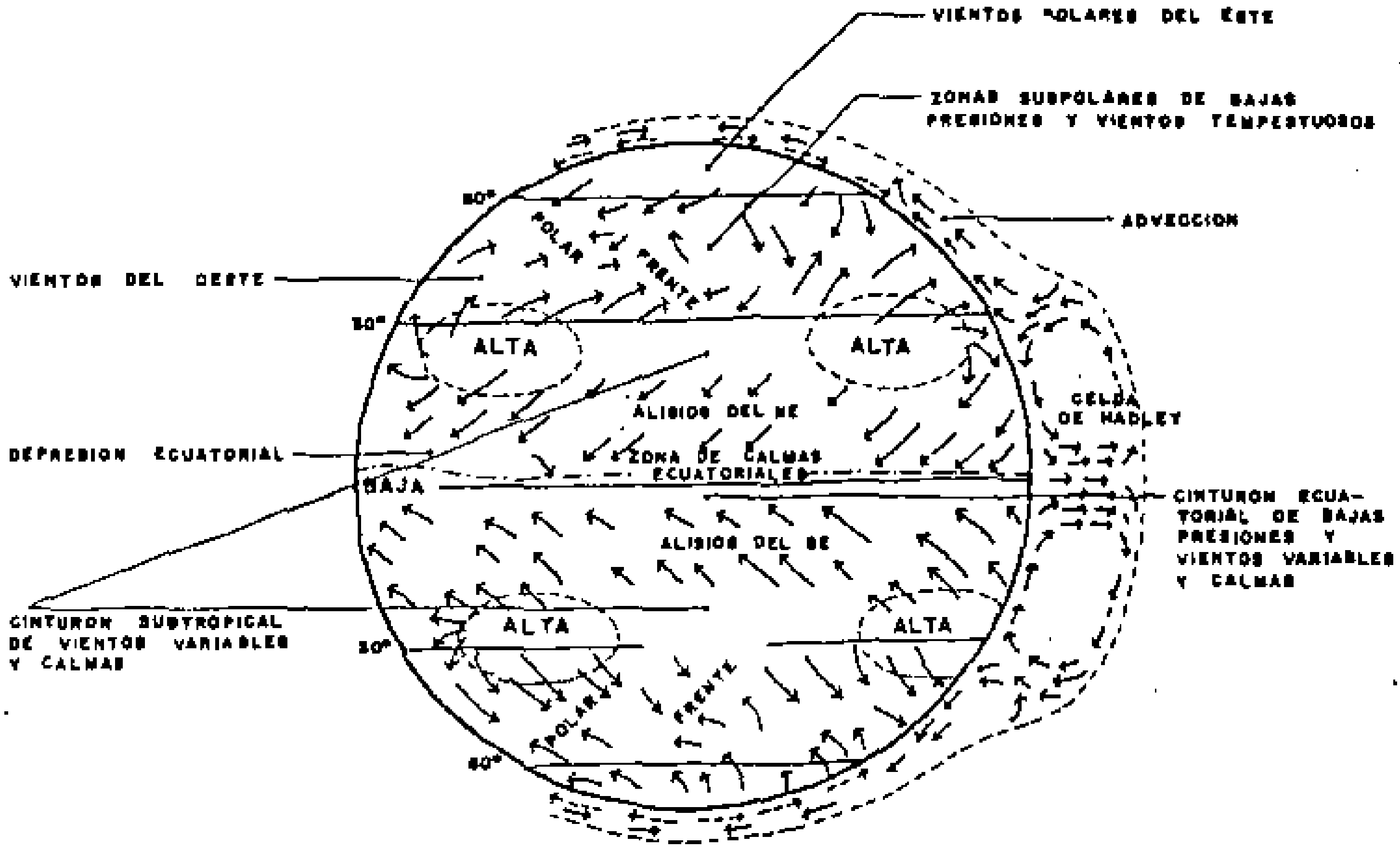
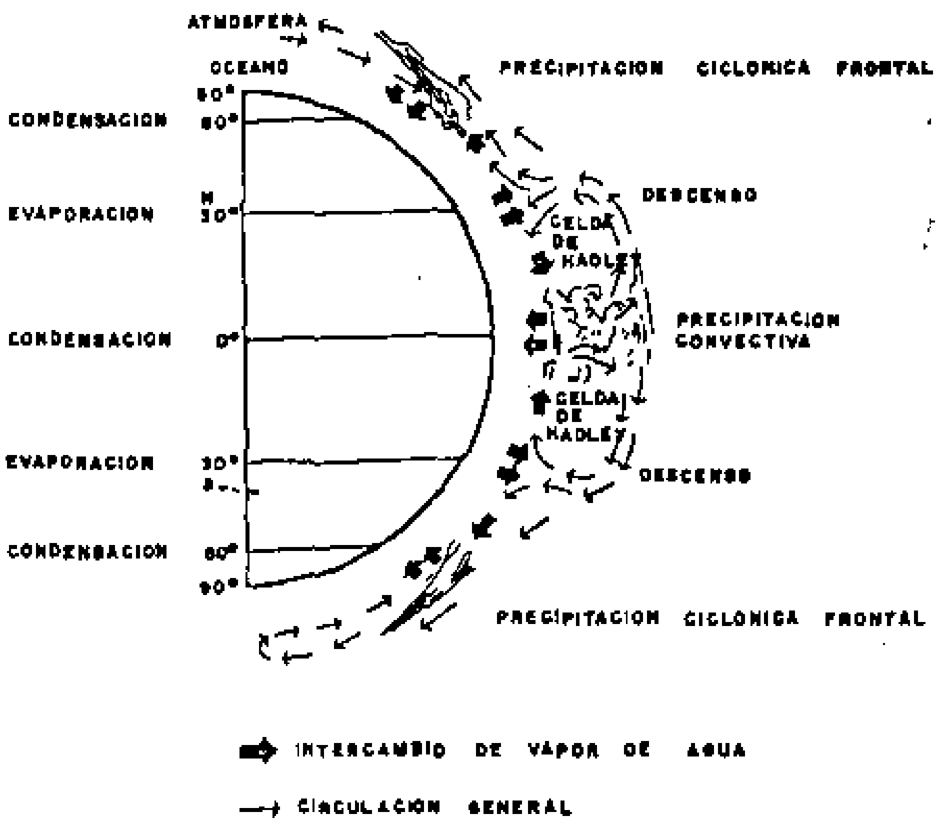


FIGURA 10 a y b

Circulación general de la atmósfera.



va que para la mayoría de la gente resultan adecuadas para el desarrollo de la vida y del trabajo. La sensación de bienestar higrotérmico, aunque depende de múltiples factores tales como: edad, sexo, vestido, forma del cuerpo, estado de salud, nivel de aclimatación, etc., generalmente se produce bajo determinados valores conjuntos de temperatura y humedad relativa.

Numerosos investigadores han realizado estudios al respecto, obteniendo diversas gráficas y diagramas donde se delimitan las condiciones higrotérmicas del confort humano.

Un concepto sumamente útil derivado de estos estudios, es el de la temperatura efectiva. Esta se define como la temperatura de la atmósfera en condiciones de saturación y de calma, que produciría la misma sensación que el aire ambiental circundante en ausencia de radiación (Fig. 11). Los índices de confort respecto a la temperatura efectiva pueden observarse en el diagrama bio-climático de la Fig. 12 donde se muestran también las líneas superiores que amplían la zona de confort al moverse el aire a distintas velocidades.

La temperatura efectiva se expresa aproximadamente como:

$$TE = 0.4\ (T_s + T_H) + 4.8 \qquad (°C)$$

donde

T_s : temperatura ambiente (bulbo seco).

T_H = temperatura de bulbo húmedo.

La TE es un índice bastante bueno de la tensión de calor a que relaciona adecuadamente las reacciones del cuerpo a la variación conjunta de la temperatura y humedad.

Más útil aún resulta el concepto de temperatura efectiva cuando se considera también el efecto de calentamiento que produce una exposición del cuerpo a la radiación, ya sea solar o proveniente de la atmósfera u otros cuerpos calientes adyacentes. A esta última se le llama temperatura efectiva corregida.

En regiones tropicales y subtropicales húmedas, la zona de confort generalmente se acepta como aquélla limitada entre las temperaturas efectivas corregidas de 22° a 27°C y entre velocidades del aire que fluctúan entre 0.15 y 1.5 m/seg.

Como la determinación de la temperatura efectiva corregida requiere un termómetro de esfera (intercambio radiativo), si no se dispone de éste y si las temperaturas de las superficies y cuerpos adyacentes son iguales a las del aire ambiente, la temperatura efectiva corregida puede considerarse la misma que la del aire (temperatura de bulbo seco). Sin embargo, si existe radiación incidente habrá que agregar 1°C por cada $90 W/m^2$ de radiación (solar o terrestre).

De acuerdo con el orden de magnitud del promedio de máximas de temperatura en Martínez de la Torre, Veracruz, representadas en el diagrama bioclimático de la Fig. 12, en las situaciones climáticas más rigurosas, se requiere mover aire a velocidades del orden de 1 m/seg. (3.6 Km/h) quedando así las condiciones ambientales de temperatura y humedad relativa comprendidas dentro de la zona amplificada de confort de las líneas superiores.

Mediante el viento que predomina en la localidad estudiada, sería posible alcanzar el nivel de confort requerido, ya que la velocidad del viento fluctúa entre 2.1 y 6 m/seg. Sin embargo, no se tiene la certeza de disponer de este viento durante las horas de calor más intenso que generalmente son las de mayor calma.

Ante este problema habrá que buscar la forma de mover aire por otro medio, o sea a través de la energía solar, y sin prescindir de la orientación adecuada de los locales que permita aprovechar el efecto benéfico del viento predominante, al menos durante algunas horas del día.

Considerando la ecuación de balance térmico que relaciona las ganancias y pérdidas de calor del ser humano:

$$\text{Balance térmico} = M \pm R \pm C \pm K - E$$

Cuando el cuerpo se encuentra en equilibrio térmico, la ecuación anterior equivale a cero.

Las ganancias y pérdidas pueden desglosarse como:

Ganancias

M: calor generado por la actividad metabólica.

R: calor ganado por radiación solar, terrestre o de cuerpos a mayor temperatura.

C: calor ganado por convección debido al aire a temperatura mayor que la de la piel.

K: calor ganado por conducción mediante el contacto con cuerpos más calientes.

Pérdidas

E: calor perdido por la evaporación de agua, por respiración o transpiración.

R: calor perdido por radiación hacia la atmósfera o hacia cuerpos más fríos.

C: pérdida de calor por convección hacia el aire a menor temperatura que la de la piel.

K: calor perdido por conducción mediante el contacto con cuerpos más fríos.

La base fisiológica del confort consiste en llegar al equilibrio térmico con el mínimo aporte de termoregulación, que consiste, en el conjunto de funciones que regulan la producción y el transporte del calor en función de las condiciones termodinámicas del medio ambiente, de tal manera que la temperatura corporal permanezca constantemente a 37°C. Analizando la Fig. 3 de la distribución anual de temperaturas de la localidad estudiada, se nota que puede ser rara la ocasión en que la temperatura del aire sobrepase la de la piel (36°C). Sin embargo, en caso de presentarse esa circunstancia debido a que la humedad relativa es elevada, la sudoración se incrementaría, pero la evaporación se obstaculizaría debido a la elevada presión del vapor de agua atmosférico. Además como el aire tendría una temperatura más elevada que la del cuerpo, en caso de que el aire se moviera, éste cedería calor al cuerpo por convección independientemente del calor que también se ganaría por radiación. En tales circunstancias, sería imposible disipar el calor corporal creándose una situación sumamente incómoda que podría llegar a ser peligrosa si continuara por un tiempo prolongado. Afortunadamente estas situaciones son muy esporádicas y el aire no se encuentra completamente saturado, por lo que existe una evaporación mínima.

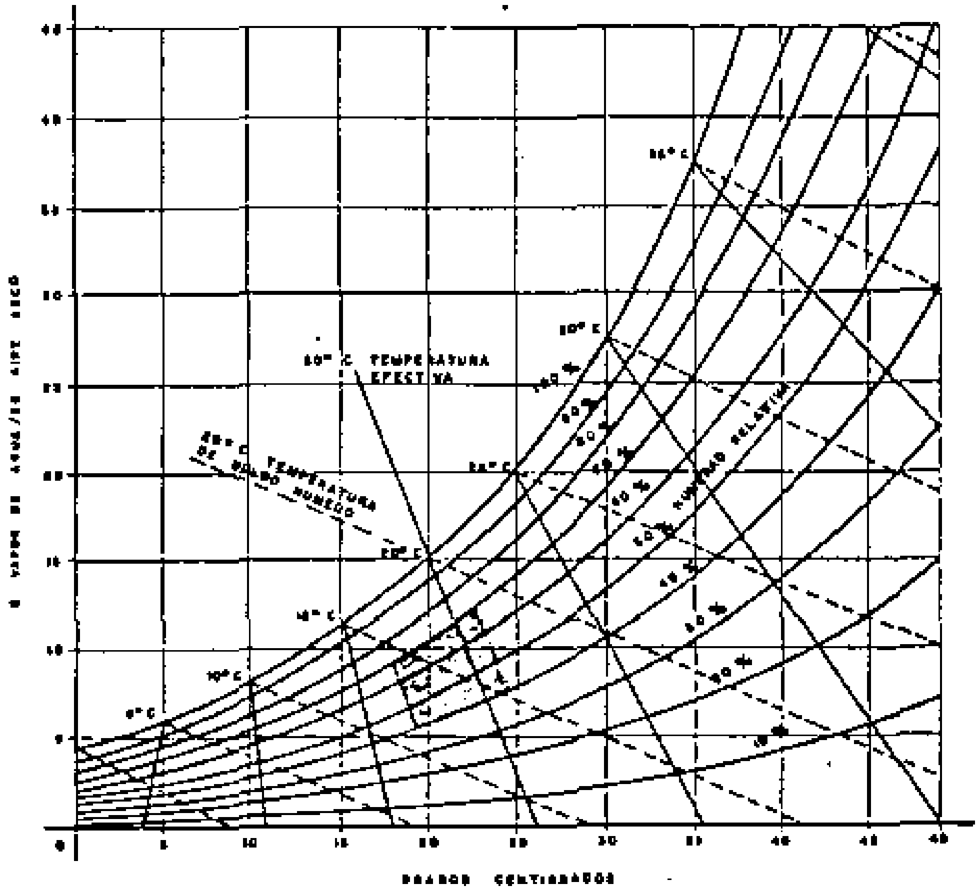


FIGURA 11

Carta de confort en función de la humedad absoluta (ordenadas), temperatura ambiente (abscisas), temperatura de bulbo húmedo (líneas interrumpidas), humedad relativa (curvas) y la temperatura efectiva (líneas inclinadas).

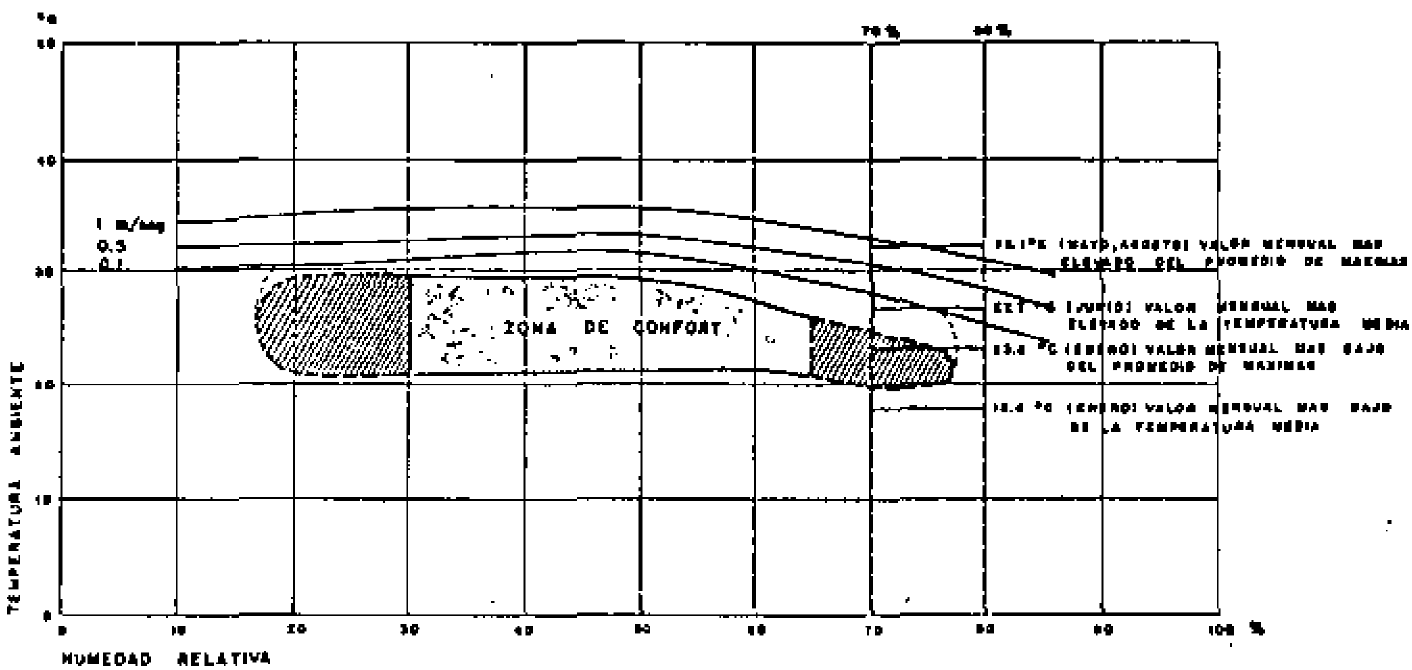


FIGURA 12

Ubicación de la zona de confort dentro de diagrama bioclimático donde se indican los valores de temperatura, media y promedio de máximas para la localidad seleccionada y dentro del rango de humedades relativas de 70 a 80% (promedio) típico de la localidad durante todos los meses del año.

En condiciones promedio, las temperaturas que se presentan en la localidad y la elevada humedad relativa impiden la disipación calorífica por convección y radiación, en consecuencia siendo éstas mínimas, la evaporación se convierte en la forma de disipación potencial de calor, sobre todo cuando hay movimientos de aire que remueven la película de aire saturado que se forma continuamente sobre la piel, a consecuencia de la evapotranspiración.

Así, la ventilación se convierte en el medio más apropiado para alcanzar la adaptación del metabolismo a las características ambientales húmedo-calientes de este tipo de climas.

Una ventilación adecuada es capaz de proporcionar una sensación de enfriamiento al incrementar la evaporación cutánea, aun cuando la temperatura del aire sea ligeramente superior a la de la piel.

4. VENTILACION EOLICA Y SOLAR

Las construcciones en las zonas cálido húmedas deben satisfacer ciertos requerimientos térmicos. Las frecuentes e intensas lluvias, la elevada humedad, la pequeña oscilación diaria y estacional de la temperatura y la intensa radiación difusa imponen condiciones de máximo abrigo a la sombra.

El techo de las construcciones es el elemento más importante y aunque no es capaz de producir enfriamiento alguno, sí evita al menos el incremento de la temperatura interior respecto a la exterior. Estos techos deben ser de materiales ligeros de muy baja capacidad calorífica para que no absorban la radiación solar. Generalmente deben escogerse materiales de color claro que aumenten la reflectividad al sol. Debido a las lluvias, deben ser impermeables y con una inclinación suficiente para el rápido desalojo del agua y preferentemente acanalados. De existir tejado y techo, debe dejarse un espacio razonable entre ambos y aberturas laterales para evitar condensaciones, favorecer la circulación del aire y desalojar el calor acumulado. Las paredes deben ser de materiales de baja capacidad calorífica y delgadas, aunque si están a la sombra de aleros durante el día, éstas pueden ser de materiales más compactos con recubrimiento (cal) o pinturas exteriores de color claro.

Debido a la intensa luminosidad (5000 a 7000 cd/m^2) que produce la radiación difusa en estas zonas, las ventanas, aunque de grandes dimensiones, deben ubicarse de tal manera que ofrezcan visibilidad externa sólo a bajas alturas cercanas al horizonte.

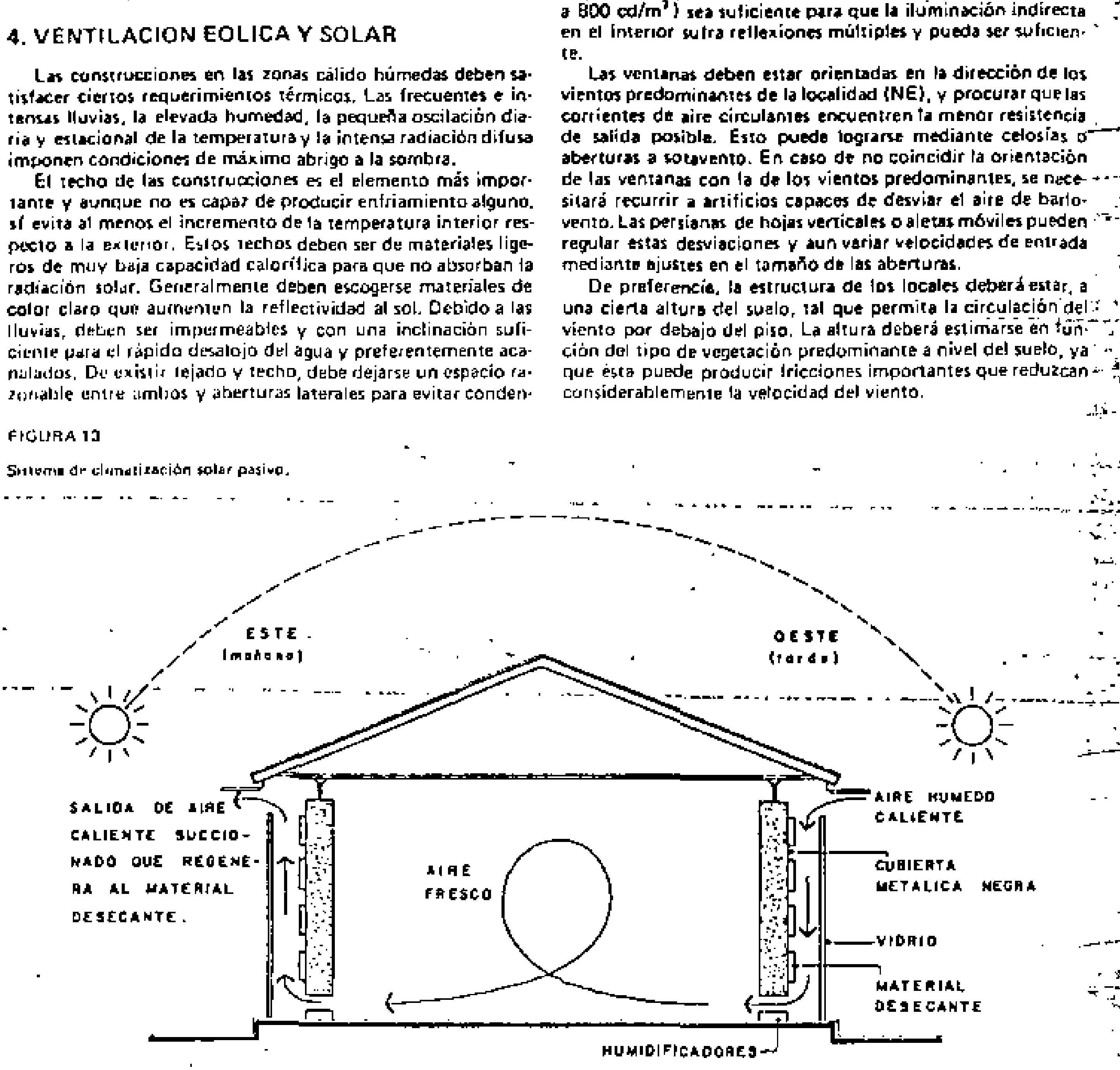
El uso de persianas o de celosías es muy recomendable, ya que producen sombras que evitan deslumbramientos. Debido a que la iluminación interior es de origen difusa, conviene pintar paredes y techo de color blanco, para que en caso de que se presenten grandes nublados, la luminosidad externa (1 200 a 800 cd/m^2) sea suficiente para que la iluminación indirecta en el interior sufra reflexiones múltiples y pueda ser suficiente.

Las ventanas deben estar orientadas en la dirección de los vientos predominantes de la localidad (NE), y procurar que las corrientes de aire circulantes encuentren la menor resistencia de salida posible. Esto puede lograrse mediante celosías o aberturas a sotavento. En caso de no coincidir la orientación de las ventanas con la de los vientos predominantes, se necesitará recurrir a artificios capaces de desviar el aire de barlovento. Las persianas de hojas verticales o aletas móviles pueden regular estas desviaciones y aun variar velocidades de entrada mediante ajustes en el tamaño de las aberturas.

De preferencia, la estructura de los locales deberá estar, a una cierta altura del suelo, tal que permita la circulación del viento por debajo del piso. La altura deberá estimarse en función del tipo de vegetación predominante a nivel del suelo, ya que ésta puede producir fricciones importantes que reduzcan considerablemente la velocidad del viento.

FIGURA 13

Sistema de climatización solar pasivo.



Como se mencionó anteriormente, en las horas de mayor asoleamiento, la velocidad del viento es mínima o francamente existen calmas. Esto implica el empleo de sistemas de ventilación que, en el caso que nos interesa, deberán operar aprovechando la energía del sol.

Un sistema muy interesante de ventilación y acondicionamiento de aire que ha sido estudiado para zonas húmedo calientes, es el de la Fig. 13. Se le considera como un sistema solar pasivo de climatización, por no incluir ningún dispositivo electromecánico. Su funcionamiento se basa en el "efecto chimenea" o de termosifón. Este consiste en la circulación por convección natural del aire, que se calienta por efecto invernadero en el espacio vertical comprendido entre la cubierta metálica ennegrecida y el vidrio. Durante la mañana penetra el aire húmedo caliente que es deshumidificado por el contacto con el material desecante (sílica-gel) y, en consecuencia, se calienta. Al circular por el humidificador inferior se enfría penetrando al interior como aire fresco. Como por la mañana el sol calienta la fachada este, seca y regenera el material desecante que quedó humedecido la tarde anterior, cuando el sol calentaba la fachada oeste y circulaba el aire en sentido inverso al matutino.

Desafortunadamente, el calentamiento de las fachadas es poco eficiente a menos que sea por captación de radiación directa, la cual no es abundante en las regiones tropicales húmedo-calientes. Aunque la radiación difusa es cuantiosa en estas zonas, su naturaleza multidireccional imposibilita su concentración hacia cualquier superficie, particularmente las verticales o inclinadas. Esto repercute en un funcionamiento deficiente del sistema al no circular efectivamente el aire que se succiona desde alguna de las fachadas. Se ha comprobado que este sistema funciona sólo cuando la radiación directa es importante y la humedad no es demasiado alta. Si esto último ocurre, el material desecante puede saturarse rápidamente.

Aunque este sistema ha sido diseñado para las zonas calientes y húmedas, se ha comprobado también que en ausencia de suficiente radiación solar para activar el fenómeno de termocirculación del aire, el efecto aislante de las paredes y la estabilidad del aire en el interior eleva la temperatura del recinto.

Podría cuestionarse entonces el porqué se ha descrito el sistema de climatización anterior, sin embargo muy poco se ha hecho hasta la fecha en este campo para zonas húmedo calientes y el ejemplo citado es uno de los más interesantes que, mediante mejoras de diseño, puede optimizarse. Aunque existen muchos diseños similares basados en la termocirculación del aire entre paredes que también producen una circulación cruzada, éstos no incluyen la deshumidificación y humidificación del aire, por lo que en mi opinión, el sistema de la Fig. 13 es el más completo al respecto y representa un ejemplo digno de mencionarse por su significación.

Basándome en los requerimientos de diseño y ventilación de la localidad seleccionada, propongo un sistema de climatización eólico-solar para ser aplicado a escuelas, y el que, como se desarrolla a continuación, está en posibilidad de crear condiciones de confort térmico para los alumnos bajo las condiciones climatológicas imperantes en la localidad.

La Fig. 14 muestra lo que podría ser una escuela de varias aulas con características tales que permitan asegurar los requerimientos de ventilación en condiciones extremas. Como se analizó anteriormente, éstas serían satisfechas con un movimiento del aire a razón de 1 m/seg. A esta velocidad y con una humedad relativa entre el 70 y 80% se puede compensar un aumento de la temperatura ambiente de 5°C por encima de la zona de confort (diagrama bioclimático).

En tales condiciones los requerimientos de ventilación pueden definirse, ya sea en función de la velocidad del aire o en función volumétrica del número de cambios de aire en cierto tiempo. El suministro de aire fresco a las aulas removerá el bióxido de carbono liberado en la respiración, disipará los malos olores de un aire viciado y oxigenará el volumen involucrado. Suponiendo que el techo y las paredes están a la temperatura ambiente y, en consecuencia, no radían en exceso, para calcular los requerimientos de ventilación en cada aula habrá que considerar fundamentalmente las siguientes fuentes de calor:

- Ganancia de flujo calorífico a través de aberturas o ventanas (Q_R)
- Flujo calorífico metabólico liberado por los alumnos (Q_M)

Suponiendo una ganancia de calor a través de las ventilas y celosías laterales de 50 W/m², el área de las fachadas laterales (2.5 m x 10 m x 2 = 50 m²) arroja una ganancia de:

$$Q_R = 50\frac{W}{m^2} \times 50\,m^2 = 2500\ W$$

Por otro lado, el calor metabólico liberado por un niño de aproximadamente 35 a 40 Kg que realiza trabajo de escritorio es de alrededor de 90 a 95 W/m². Como el área de la piel de un niño (de 35 a 40 Kg) es de aproximadamente 1 m², en un salón con 35 niños, Q_M será entonces:

$$Q_M = 35\,m^2 \times 95\frac{W}{m^2} = 3\,325\ W$$

El flujo de calor total que habrá que remover del salón de clases Q_T será de 5825 W.

Mediante la relación:

$$Q_T = C_v\, V\, N\, \Delta T$$

donde:

C_v = calor específico del aire (Vol. cte.) = 0.36 W h/m³ °C

V = Volumen del salón (125 m³)

N = número de cambios de aire necesarios por cada hora

ΔT = diferencia de temperaturas (interior-exterior).

Se tiene que el número de cambios de aire requeridos para una ΔT extrema de 10°C, es de : 12.9 cambios/hora, que para un volumen de 125 m³, representan : 1612 m³/h.

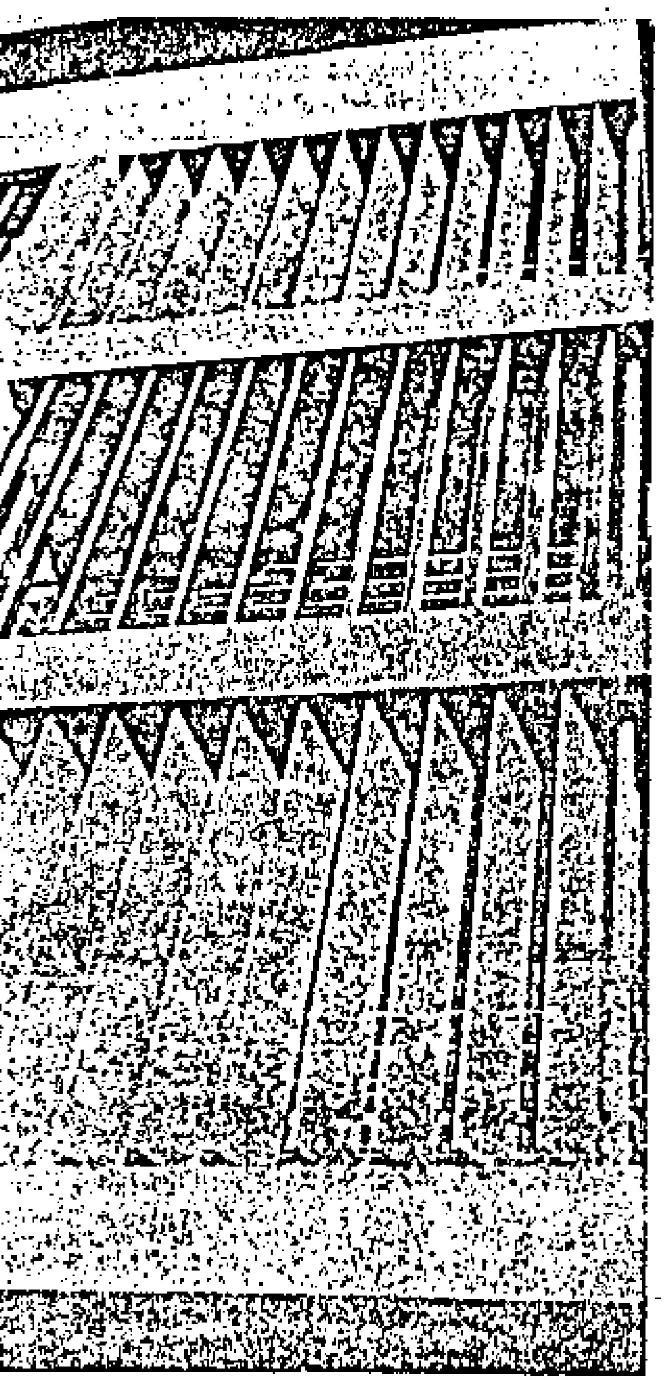
Si las dimensiones aproximadas del techo del salón, que en este caso haría las veces de un calentador solar de aire que por efecto termosifón succionaría aire del interior, fueran las que se muestran en la Fig. 14, el gasto de aire caliente a la salida de cada lado del colector sería:

$$G = vA$$

donde:

v es la velocidad de salida del aire caliente y

A es el área de la sección rectangular de salida del aire caliente



Si la velocidad del aire fuera, conservadoramente, de 0.5 m/seg., para una sección de 0.5 m^2, se tendría que G sería de 0.25 m^3/seg. o sea 900 m^3/h. En ambos lados evacuaría un volumen de aire del interior equivalente a 1 800 m^3/h, con lo cual se rebasaría el requerimiento de 1 612 m^3/h. El colector solar proporcionaría 12 cambios por hora.

Sin desear entrar en especificaciones ni cálculos detallados de diseño del colector solar, el ejemplo desarrollado tiene la intención de mostrar objetivamente la potencialidad de un sistema de ventilación que sería económicamente factible de implantar en escuelas. Los materiales empleados en el colector son fácilmente asequibles: lámina traslúcida acanalada, lámina metálica galvanizada pintada por ambos lados de negro mate, plafón de madera recubierto en su parte oculta con papel aluminio.

Para conseguir el máximo asoleamiento posible en la localidad durante el año y al mismo tiempo aprovechar los vientos predominantes, se escogió la orientación del edificio con eje mayor en la dirección este-oeste. Debido a que la dirección del viento predominante en la localidad es NE, las ventilas verticales a barlovento de la fachada norte, aparecen en la figura orientadas hacia el NE, reduciéndose así la fricción del aire y favoreciendo su paso al interior de las aulas.

Con objeto de favorecer la salida del aire a sotavento, la fachada sur consiste en celosías amplias. El alero de esta fachada evita el asoleamiento directo en los meses de enero, febrero, marzo, abril, agosto, septiembre, octubre, noviembre y diciembre. Las Figs. 9, 15 y 16 muestran las gráficas solares que sirven de base a este caso particular, en que la localidad se encuentra a 20° de latitud norte. Se ha creído conveniente anexar las tablas horarias de la altura y acimut horario de la trayectoria mensual promedio del sol sobre el horizonte a la misma latitud (Tablas VIII y IX).

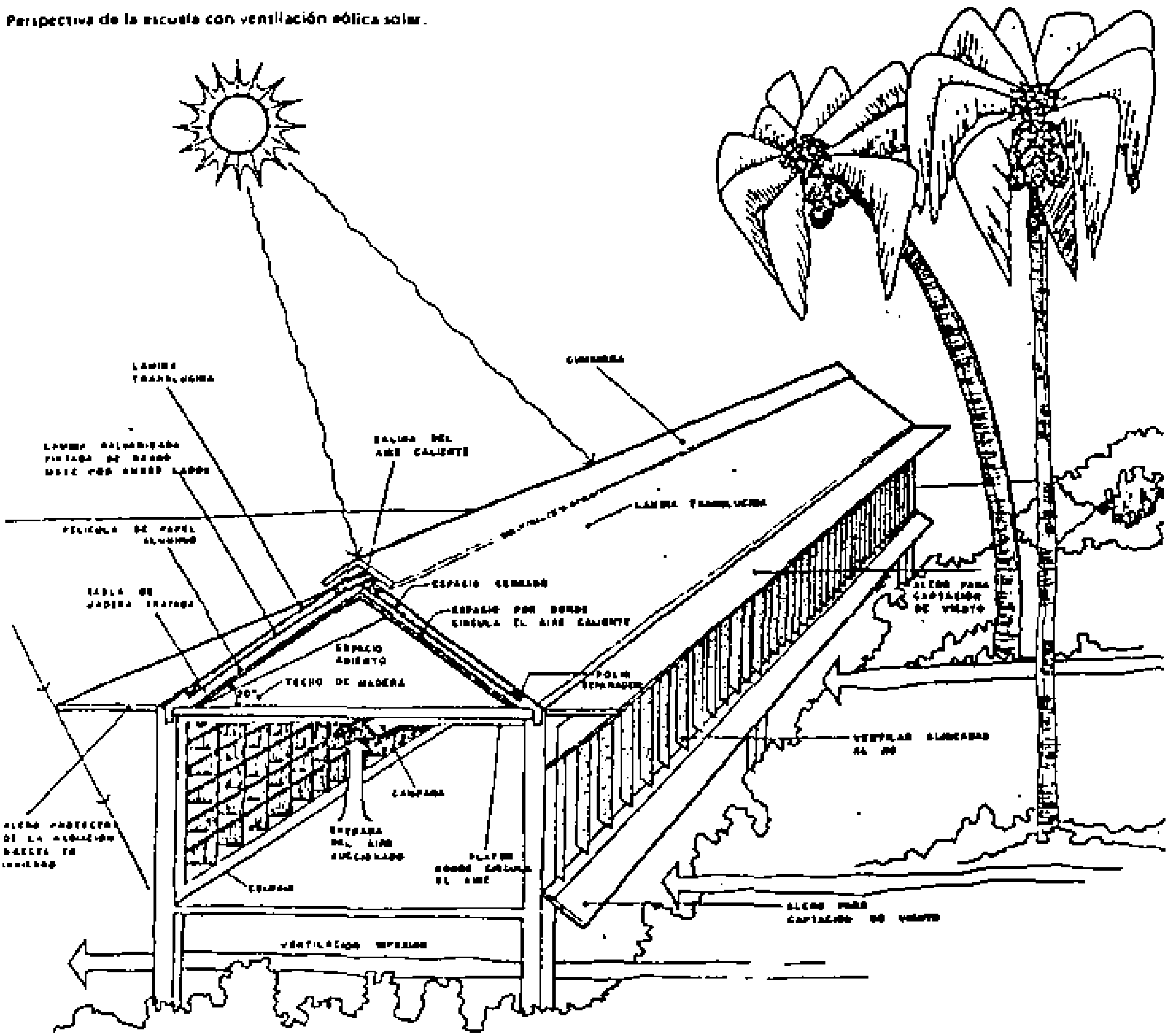
El diseño del colector, así como su orientación, inclinación y dimensiones, los he realizado en función de los datos climatológicos detallados anteriormente y sobre la base de mis experiencias personales.

CONCLUSION

Este trabajo muestra la factibilidad de implantación de sistemas pasivos de climatización eólico-solares para satisfacer requerimientos de confort térmico en zonas húmedo-tropicales. El autor agradecerá los comentarios que se deriven al respecto y plantea la posibilidad de asesoría y discusión sobre los temas tratados en este artículo a todos aquellos interesados en el aprovechamiento de la energía solar y eólica, no sólo en climas húmedo-tropicales, sino en cualquier otro característico de Latinoamérica, área del Caribe y otras zonas del mundo, cuyos climas y problemática sean similares.

FIGURA 14

Perspectiva de la escuela con ventilación eólica solar.



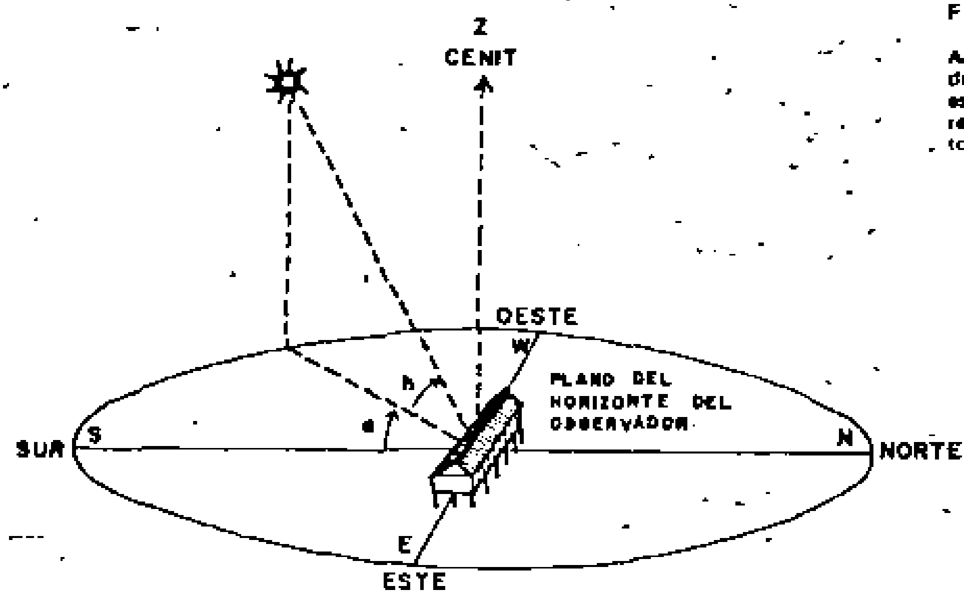
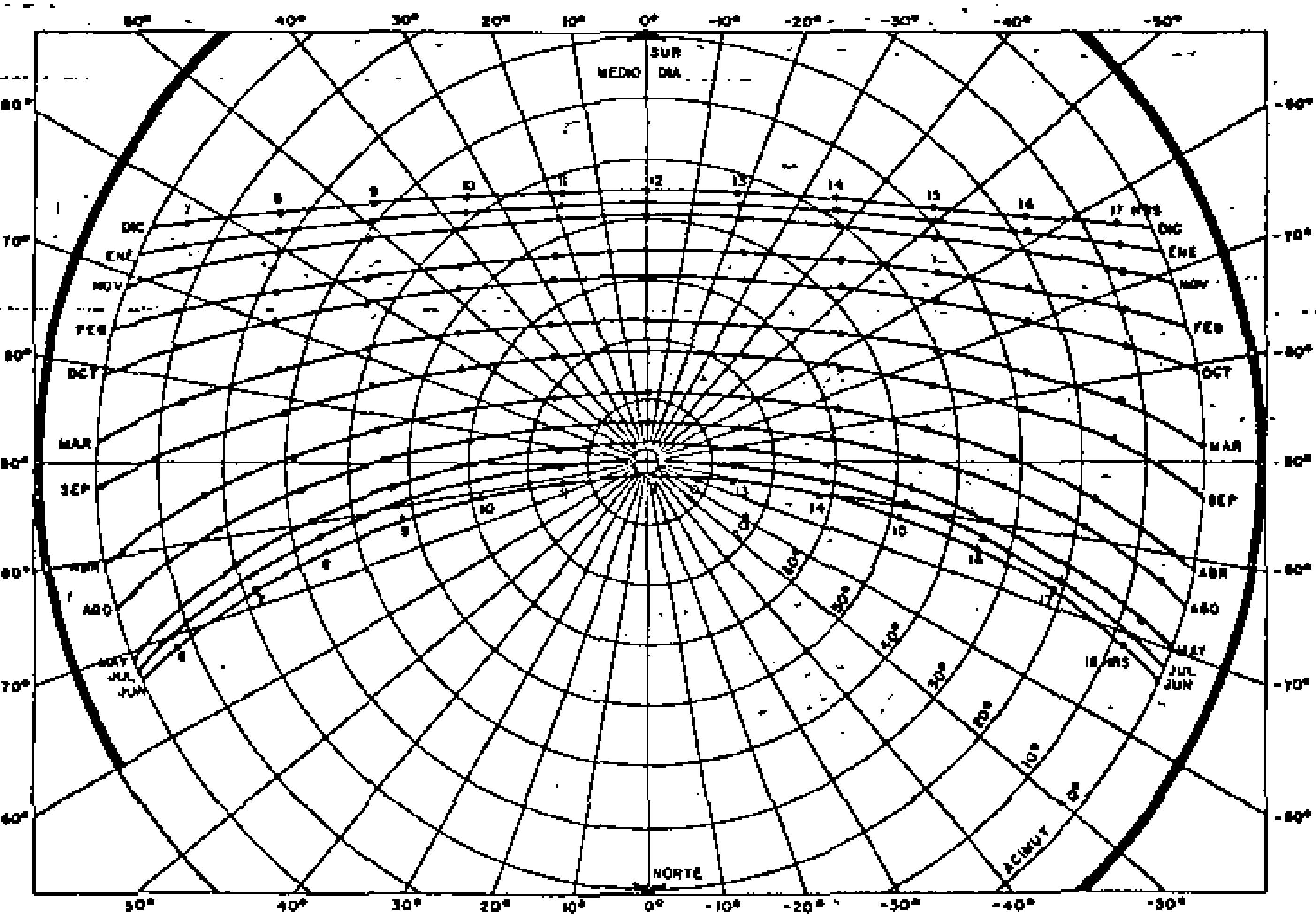


FIGURA 15

Acimut y altura solar respecto a la ubicación de la escuela con eje este-oeste para máximo asoleamiento anual sobre los colectores solares del techo y aprovechamiento de los vientos predominantes del NE.

FIGURA 16

Gráfica solar para la latitud 20°N.



Acimut horario del sol

TABLA VIII (grados) Latitud = 20°

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	******	******	64.1	57.5	48.7	36.5	20.0	0.0	-20.0	-36.5	-48.7	-57.5	-64.1	******	******
ENE.	02	******	******	65.1	55.5	49.4	37.3	20.5	0.0	-20.5	-37.3	-49.4	-55.5	-65.1	******	******
ENE.	03	******	******	64.9	60.3	51.4	38.9	21.6	0.0	-21.6	-38.9	-51.4	-60.3	-64.9	******	******
FEB.	01	******	******	69.7	63.8	54.1	41.5	23.3	0.0	-23.3	-41.5	-54.1	-63.8	-69.7	******	******
FEB.	02	******	******	72.5	65.9	57.0	44.3	25.1	0.0	-25.1	-44.3	-57.0	-65.9	-72.5	******	******
FEB.	03	******	******	74.2	69.7	61.1	48.3	28.6	0.0	-28.6	-48.3	-61.1	-69.7	-74.2	******	******
MAR.	01	******	******	79.0	72.7	64.3	51.7	31.1	0.0	-31.1	-51.7	-64.3	-72.7	-79.0	******	******
MAR.	02	******	******	82.8	76.8	68.8	56.7	35.5	0.0	-35.5	-56.7	-68.8	-76.8	-82.8	******	******
MAR.	03	******	89.1	86.7	80.9	73.5	62.2	41.0	0.0	-41.0	-62.2	-73.5	-80.9	-86.7	-89.1	******
ABR.	01	******	86.4	89.4	85.9	78.6	68.5	48.2	0.0	-48.2	-68.5	-78.6	-85.9	-89.4	-86.4	******
ABR.	02	******	80.5	85.4	89.4	83.9	75.4	57.5	0.0	-57.5	-75.4	-83.9	-89.4	-85.4	-80.5	******
ABR.	03	******	77.3	87.4	87.6	88.0	81.0	66.3	0.0	-66.3	-81.0	-88.0	-87.6	-87.4	-77.3	******
MAY.	01	******	74.9	79.4	83.5	87.4	86.9	74.6	0.0	-74.6	-86.9	-87.4	-83.5	-79.4	-74.9	******
MAY.	02	******	72.4	76.3	80.0	83.4	86.9	86.5	0.0	-86.5	-86.9	-83.4	-80.0	-76.3	-72.4	******
MAY.	03	******	70.2	74.3	77.6	80.5	82.6	83.1	0.0	-83.1	-82.6	-80.5	-77.6	-74.3	-70.2	******
JUN.	01	******	69.2	73.2	76.5	79.0	80.5	79.2	0.0	-79.2	-80.5	-79.0	-76.5	-73.2	-69.2	******
JUN.	02	******	68.1	72.2	75.4	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.4	-72.2	-68.1	******
JUN.	03	******	68.1	72.2	75.3	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.3	-72.2	-68.1	******
JUL.	01	******	68.3	72.2	75.3	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.3	-72.2	-68.3	******
JUL.	02	******	70.2	74.3	77.4	80.5	82.6	83.1	0.0	-83.1	-82.6	-80.5	-77.4	-74.3	-70.2	******
JUL.	03	******	71.1	75.3	78.8	81.9	84.6	87.4	0.0	-87.4	-84.6	-81.9	-78.8	-75.3	-71.1	******
AGO.	01	******	74.0	78.6	82.4	86.1	89.0	80.6	0.0	-80.6	-89.0	-86.1	-82.4	-78.6	-74.0	******
AGO.	02	******	76.3	81.4	85.6	87.4	82.4	69.6	0.0	-69.6	-82.4	-87.4	-85.6	-81.4	-76.3	******
AGO.	03	******	79.6	84.4	89.5	85.2	77.2	60.1	0.0	-60.1	-77.2	-85.2	-89.5	-84.4	-79.6	******
SEP.	01	******	83.1	85.6	86.3	79.9	70.1	50.1	0.0	-50.1	-70.1	-79.9	-86.3	-85.6	-83.1	******
SEP.	02	******	81.2	87.7	82.0	74.8	61.7	42.6	0.0	-42.6	-61.7	-74.8	-82.0	-87.7	-81.2	******
SEP.	03	******	******	83.8	77.6	69.4	58.0	36.7	0.0	-36.7	-58.0	-69.4	-77.6	-83.8	******	******
OCT.	01	******	******	80.0	73.7	65.4	52.4	33.1	0.0	-33.1	-52.4	-65.4	-73.7	-80.0	******	******
OCT.	02	******	******	76.2	69.7	61.1	48.3	28.6	0.0	-28.6	-48.3	-61.1	-69.7	-76.2	******	******
OCT.	03	******	******	73.4	66.4	58.0	45.2	26.0	0.0	-26.0	-45.2	-58.0	-66.4	-73.4	******	******
NOV.	01	******	******	69.7	63.0	54.1	41.3	23.3	0.0	-23.3	-41.3	-54.1	-63.0	-69.7	******	******
NOV.	02	******	******	67.5	61.4	52.1	39.7	22.2	0.0	-22.2	-39.7	-52.1	-61.4	-67.5	******	******
NOV.	03	******	******	65.1	59.5	49.6	37.5	20.5	0.0	-20.5	-37.5	-49.6	-59.5	-65.1	******	******
DIC.	01	******	******	64.6	57.5	48.7	36.5	20.0	0.0	-20.0	-36.5	-48.7	-57.5	-64.6	******	******
DIC.	02	******	******	63.2	56.7	47.6	35.7	19.5	0.0	-19.5	-35.7	-47.6	-56.7	-63.2	******	******
DIC.	03	******	******	63.2	56.7	47.6	35.7	19.5	0.0	-19.5	-35.7	-47.6	-56.7	-63.2	******	******

Altura solar horaria

TABLA IX (grados) Latitud = 20°

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	5.54	17.41	29.21	38.79	45.52	48.00	45.52	38.79	29.21	17.41	5.59	0.00	0.00
ENE.	02	0.00	0.00	6.00	18.41	29.65	39.56	46.45	49.00	46.45	39.55	29.65	18.41	6.00	0.00	0.00
ENE.	03	0.00	0.00	6.81	19.44	31.13	41.14	48.37	51.00	48.31	41.14	31.13	19.44	6.81	0.00	0.00
FEB.	01	0.00	0.00	8.02	20.94	32.99	43.47	51.10	54.00	51.10	43.47	32.99	20.94	8.02	0.00	0.00
FEB.	02	0.00	0.00	9.21	22.39	34.70	45.73	53.85	57.00	53.85	45.73	34.70	22.30	9.21	0.00	0.00
FEB.	03	0.00	0.00	10.74	24.24	37.07	48.61	57.46	61.00	57.46	48.61	37.07	24.24	10.74	0.00	0.00
MAR.	01	0.00	0.00	11.90	25.54	38.69	50.68	60.11	64.00	60.11	50.68	38.49	25.56	11.90	0.00	0.00
MAR.	02	0.00	0.01	13.36	27.23	40.70	53.26	63.53	68.00	63.53	53.76	40.73	27.21	13.38	0.88	0.00
MAR.	03	0.00	0.00	14.77	28.78	42.53	55.61	66.79	72.00	66.79	55.61	42.53	28.78	14.77	2.05	0.00
ABR.	01	0.00	2.03	16.12	30.20	44.15	57.68	69.79	76.00	69.79	57.68	44.15	30.20	16.12	3.40	0.00
ABR.	02	0.00	3.42	17.19	31.47	45.54	59.41	72.42	80.00	72.42	59.41	45.54	31.47	17.39	4.41	0.00
ABR.	03	0.00	4.41	18.30	32.13	46.42	60.44	74.02	83.00	74.02	60.44	46.42	32.33	18.30	5.41	0.00
MAY.	01	0.00	5.41	19.15	33.09	47.14	61.23	75.19	86.00	75.19	61.23	47.14	33.09	19.15	6.39	0.00
MAY.	02	0.00	6.39	19.94	33.76	47.70	61.74	75.83	89.00	75.83	61.74	47.70	33.75	19.94	7.04	0.00
MAY.	03	0.00	7.04	20.44	34.14	47.98	61.92	75.92	89.00	75.92	61.92	47.98	34.14	20.46	7.36	0.00
JUN.	01	0.00	7.35	20.71	34.14	48.09	61.97	75.84	88.00	75.84	61.97	48.09	34.37	20.71	7.68	0.00
JUN.	02	0.00	7.69	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
JUN.	03	0.00	7.68	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
JUL.	01	0.00	7.65	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.04	0.00
JUL.	02	0.00	7.04	20.46	34.14	47.98	61.92	75.92	89.00	75.92	61.92	47.98	34.14	20.46	6.72	0.00
JUL.	03	0.00	6.72	20.21	33.85	47.85	61.85	75.91	90.00	75.91	61.85	47.85	33.85	20.21	5.74	0.00
AGO.	01	0.00	5.74	19.41	33.30	47.34	61.43	75.47	87.00	75.47	61.43	47.34	33.32	19.43	4.75	0.00
AGO.	02	0.00	4.75	18.59	32.59	46.67	60.73	74.46	84.00	74.46	60.73	46.67	32.59	18.54	3.74	0.00
AGO.	03	0.00	3.74	17.74	31.77	45.85	59.78	72.99	81.00	72.99	59.78	45.85	31.77	17.70	2.39	0.00
SEP.	01	0.00	2.39	16.44	30.93	44.52	58.15	70.49	77.00	70.49	58.15	44.52	30.93	16.44	1.03	0.00
SEP.	02	0.00	1.03	15.12	29.15	42.94	56.16	67.37	73.00	67.37	56.16	42.94	29.15	15.19	0.00	0.00
SEP.	03	0.00	0.03	13.72	27.63	41.18	53.87	64.38	69.00	64.38	53.87	41.18	27.63	13.72	0.00	0.00
OCT.	01	0.00	0.00	12.27	25.99	39.21	51.36	60.98	65.00	60.98	51.36	39.21	25.99	12.27	0.00	0.00
OCT.	02	0.00	0.00	10.74	24.24	37.07	48.61	57.46	61.00	57.46	48.61	37.07	24.24	10.76	0.00	0.00
OCT.	03	0.00	0.00	9.40	22.84	35.37	46.46	54.76	58.00	54.76	46.46	35.37	22.84	9.40	0.00	0.00
NOV.	01	0.00	0.00	8.02	20.94	32.99	43.47	51.10	54.00	51.10	43.47	32.99	20.94	8.02	0.00	0.00
NOV.	02	0.00	0.00	7.22	19.95	31.75	41.91	49.25	52.00	49.25	41.91	31.75	19.95	7.22	0.00	0.00
NOV.	03	0.00	0.00	6.00	18.41	29.65	39.58	46.45	49.00	46.45	39.58	29.65	18.41	6.00	0.00	0.00
DIC.	01	0.00	0.00	5.59	17.91	29.21	38.79	45.52	48.00	45.52	38.79	29.21	17.91	5.59	0.00	0.00
DIC.	02	0.00	0.00	5.18	17.39	28.56	37.99	44.58	47.00	44.58	37.99	28.56	17.39	5.18	0.00	0.00
DIC.	03	0.00	0.00	5.18	17.39	28.56	37.99	44.58	47.00	44.58	37.99	28.56	17.39	5.18	0.00	0.00

BIBLIOGRAFIA

ANDERSON, B. "Fundamentals in building design". McGraw Hill, 1972.

GALVAN DUQUE, Héctor y Eduardo Peña Tomé. "Principios básicos de la energía solar y su aplicación en los edificios escolares". Revista CONESCAL No. 44. Julio-diciembre 1977.

HERNANDEZ, Everardo. "Las coordenadas horarias de la trayectoria diaria del sol sobre el horizonte y su representación polar en la República Mexicana". Centro de Investigación de Materiales, UNAM. 1977.

———. "Selecting optimum tilts for solar collectors as function of cloudiness". Proceedings for the ISES 1976 Sharing the sun. Orlando, Fla. 1976.

HERNANDEZ, Everardo, R. Herrera y J. Alvarez. "Anticorrective and antiradiactive systems". Proceedings of the International Solar Energy Congress. New Delhi, India. 1977.

HERNANDEZ, Everardo, R. Martínez, P. Fuentes y L. Castillo. "Factibilidad de aprovechamiento en México de la energía solar". Centro de Investigación de Materiales, UNAM. 1978.

HERNANDEZ, Everardo y R. Martínez. "La variación anual en México de la radiación solar directa sobre planos verticales orientados hacia los cuatro puntos cardinales". Centro de Investigación de Materiales, UNAM. 1977.

OLGYAY, V. "Design with climate". Princeton University Press. 1962.

TWAROWSKI, M. "Soleil et Architecture". Dunod, Zaklady ed. Paris, Varsovia. 1967.

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Business, Commercial, Poster Session, Miscellaneous

Volume 10

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The Seasonal Distribution of the Incoming Solar Radiation in Mexico

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Abstract

This paper shows the seasonal distribution of the mean daily solar global radiation in Mexico obtained by the author's results of a related paper, and compares it with the seasonal distribution of the incoming solar radiation for the northern hemisphere obtained by Lewis and London.

Excesses of global radiation were found: +29% in spring, +21% in summer, +33% in autumn, and 41% in winter, with respect to the whole hemisphere. Within the latitudinal belt in which Mexico is located, the computed latitudinal seasonal distribution of global radiation is in good agreement with the corresponding averaged measured values.

Introduction

In a related paper[1] a method for the evaluation of the regional global radiation has been proposed by the author. This method permitted to know the distribution of insolation in Mexico. The monthly and annual mean daily values have been obtained for 117 regions covering the whole country. Nevertheless, sometimes it is more suitable and significant to represent this distribution seasonally. This situation arises specially when the components of the radiative budget of the earth-atmosphere system are studied. Particularly global radiation becomes of outstanding importance for the energy-balance of the whole planet, because it represents the solar radiation reaching the earth's surface in direct or diffuse form. The first arrives along the solar beam while the latter is scattered downward by the atmospheric components or transmitted downward through the clouds.

Aside from the astronomical and geographical parameters determining the seasonal distribution of the incoming extraterrestral radiation reaching the top of the atmosphere[1] other parameters are necessary in order to know the solar radiation distribution on the surface of the earth. Under cloudless conditions, the following phenomena must be considered: scattering by dry air molecules, water vapor, and aerosols (interphase particles); absorption by atmospheric gases such as water vapor, carbon dioxide, and ozone; absorption by atmospheric aerosols with very complex absorption spectra. These phenomena concern both the direct beam and the downward scattered radiation. The global attenuation effect under clear and cloudless conditions gives generally the following percentages of extraterrestral radiation: combined reflection and absorption reach 20% (6% of scattered and diffused reflection + 14% of absorption by molecules, dust and aerosols).

In this case approximately 80% reaches the ground. Under cloudless con ditions the attenuation resulting from scattering, absorption and reflection by water droplets, and eventually by ice crystals, must be added.

This cloud reflection can account for a direct reflection into space of about 30 to 60% of the incoming radiation, with maximum values of the order of 73% for Nimbostratus clouds, as Haurwitz' remarks; the cloud absorption percentage ranges between 2% to 20% depending on the density and depth of the cloud. The combined effect could produce a depletion of about 30 to 80% and in the worst cloudy conditions it is possible that only less than 5% reaches the earth's surface.

A study of the radiative heat budget on the northern hemisphere carried out by J. London shows the general distribution of the incoming radiation in cal cm day , shown in Table I.

Values in Table I were computed following the customary climatological criteria that consist of dividing each season of the year in a three-month period, as follows:

Spring: March-April-May
Summer: June-July-August
Autumn: September-October-November
Winter: December-January-February

Under the same criteria, the seasonal mean daily global radiation values were computed by using the data obtained by the author in ref. 1. The results are shown in Figs. 1, 2, 3 and 4.

An examination of the maps shows that the highest mean daily values occur during the summer, followed by those that occur during spring, autumn, and winter.

Table I

Incoming radiation cal. cm^{-2} day $^{-1}$	Spring	Summer	Autumn	Winter	Annual
Insolation at top of atmosphere	835	929	611	501	720
Absorption in the atmosphere					
By ozone	23	27	14	16	20
By water vapor and dust	96	132	82	63	94
By clouds	14	16	10	7	12
Total absorption	134	176	107	86	125
Reflection and scattering back to space by atmosphere	53	69	[illegible]	33	49
By clouds	203	233	[illegible]	112	174
Total reflection before reaching the earth's surface	256	302	1[illegible]	145	223
Total reaching the earth's surface	445	451	316	270	372

Table II

	Maximum cal. $cm^{-2}day^{-1}$	Region	Minimum cal. $cm^{-2}day^{-1}$	Region
Spring	662	San Luis de la Loma, Gro. 17°10'N, 100°54'W	421	O.[illegible]ama, Ver 21[illegible]'N, 97°51'W
Summer	684	San Javier, B.C.S. 25°51'N, 111°35'W.	351	T[illegible]uix[illegible]lán, Oax. 1[illegible]24'N, [illegible]5°36'W.
Autumn	503	Cerro Giganta, B.C.S. 26°10'N, 111°35'W	269	C[illegible]amaloa[illegible], Ver. 1[illegible]22'N, 95[illegible]W
Winter	511	San Luis de la Loma, Gro. 17°10'N, 100°54'W	262	[illegible]amoros, Tam. [illegible]°52'N, 97°31'W

The variation range of the computed values can be observed on Table II.

Although the highest regional values were found during the summer, the overall country maximum mean daily values computed for each season can be seen from Table III in cal. cm^{-2} day^{-1}.

Table III

Spring	Summer	Autumn	Winter
575	545	420	380

The ratios of the above results to the corresponding seasonal values of the whole hemisphere (Table I) gives the following values. Spring: 1.29, Summer: 1.21, Autumn: 1.33, Winter 1.41, annual 1.31

Conclusions

The annual average of the global radiation incident over Mexico is 31 percent greater than that of the whole hemisphere. From Table III it can be seen that the magnitudes of the overall country mean daily values, follow the same sequence as the seasons of the year. This can be explained considering the hemispherical cloud cover distribution which indirectly enters in the latitudinal and seasonal distribution of atmospheric transmission given by Lewis[4] and extended by J. London[5] Fig. (5)

Although Fig. (5) represents a longitudinal average of the seasonal latitudinal distribution of global radiation, the order of magnitude of the seasonal values within the belt in which Mexico lies 14° 30'N. to 32° 42'N. follows the same seasonal sequence as Table III. Figure 5 also shows a maximum transmissivity in the subtropical belt. This maximum shifts northward during summer and southward during winter. This is why during summer the north of Mexico lying on the subtropical zone shows the maximum seasonal values, and the southern part of Mexico shows its minimum seasonal values during this season when the cloudiness reaches in this zone its annual maximum.

Finally it can be said that the 31% excess of global radiation in Mexico with respect to the whole hemisphere is a direct consequence of its latitudinal location, in which almost the whole year the sun's elevations remains high above 52°.

Acknowledgement

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REFERENCES

1 Hernandez, H.E., 1975 " On the Numerical Computation of Solar Radiation Parameters from Satellite Cloud Data" M.S. thesis, Facultad de Ciencias,, Universidad Nacional Autonoma de Mexico.

2 Milankovitch, M. 1920, Theorie Mathematique des Phenomenes Thermiques Produits par la Radiation Solaire. Gauthier-Villard et Cie. Editeurs, Paris.

3 Haurwitz B., 1948, "Insolation in Relation to Cloud Type" Journal of Meteorology, Vol. 5, p.p.110-113.

4 Lewis, B. M., 1955, "The Distribution of effective Solar Radiation in the Northern Hemisphere." M.S. thesis, College of Engineering, New York University.

5 London J., 1957, "A Study of the Atmospheric Heat Balance.", Final Report, Research Division College of Engineering, New York University.

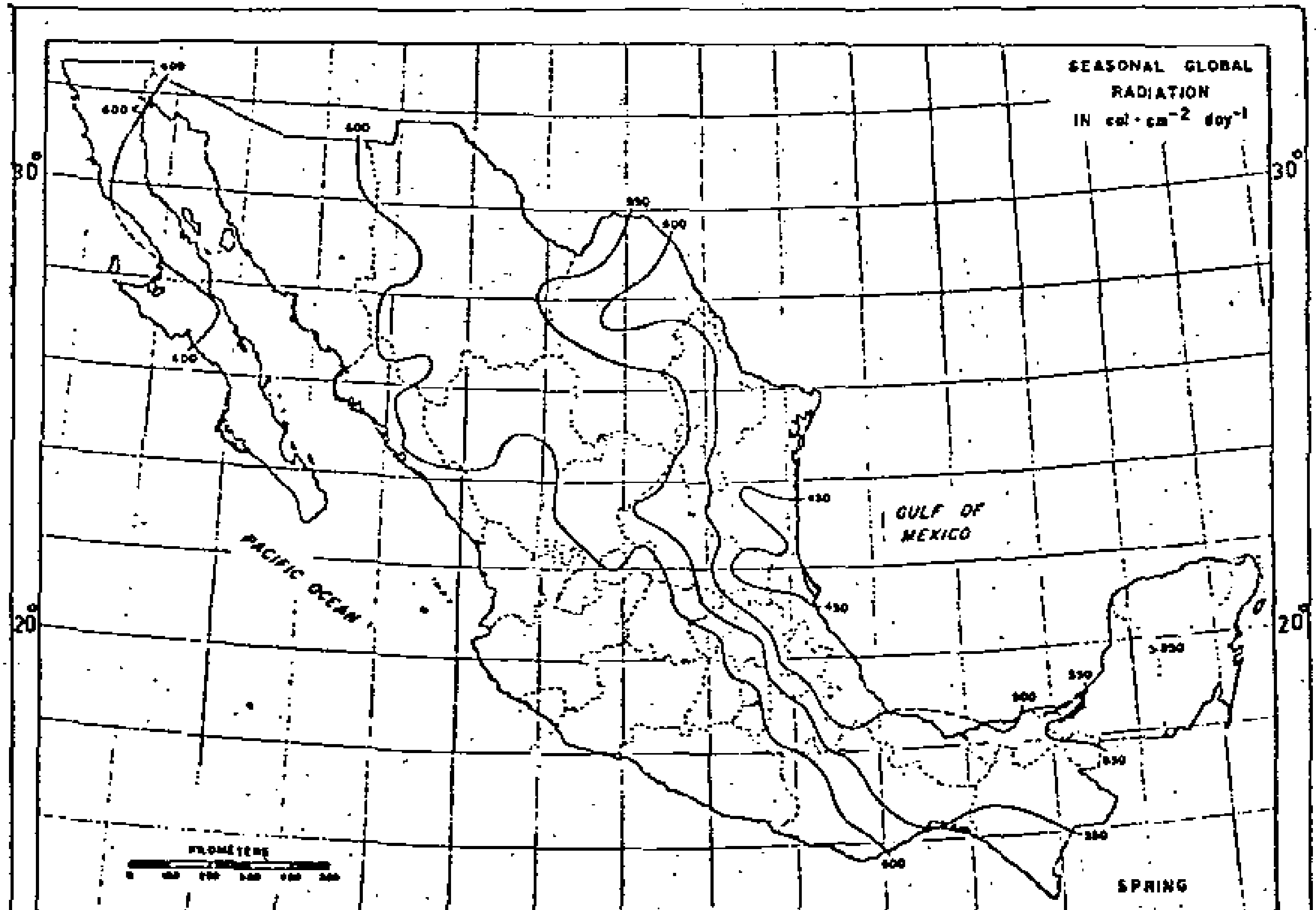

SEASONAL GLOBAL
RADIATION
IN cal·cm⁻² day⁻¹
30°
20°
GULF OF
MEXICO
PACIFIC OCEAN
SPRING
KILOMETERS

FIG. 1

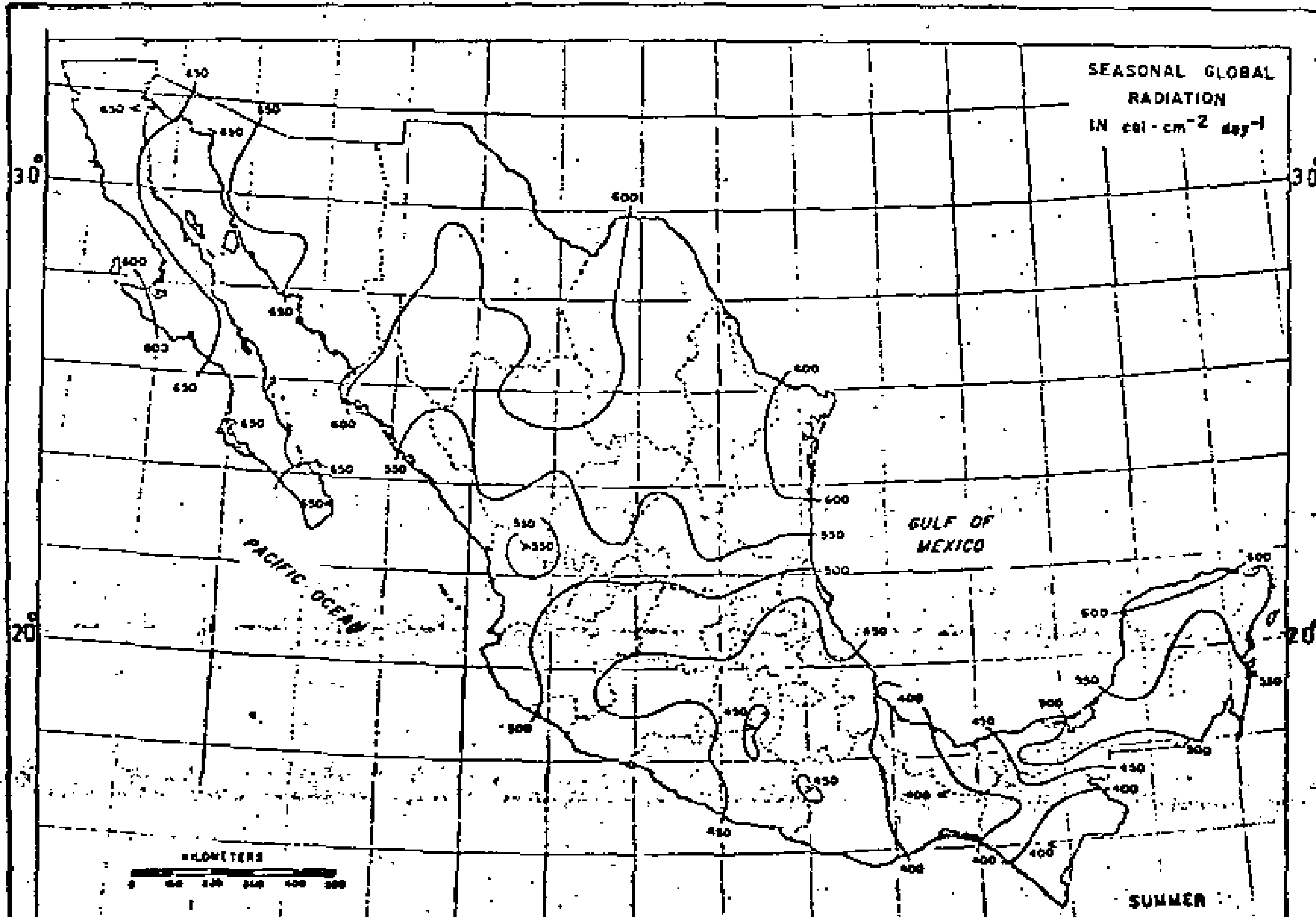

SEASONAL GLOBAL RADIATION
IN cal · cm^{-2} day^{-1}
GULF OF MEXICO
PACIFIC OCEAN
SUMMER
KILOMETERS

FIG. 2

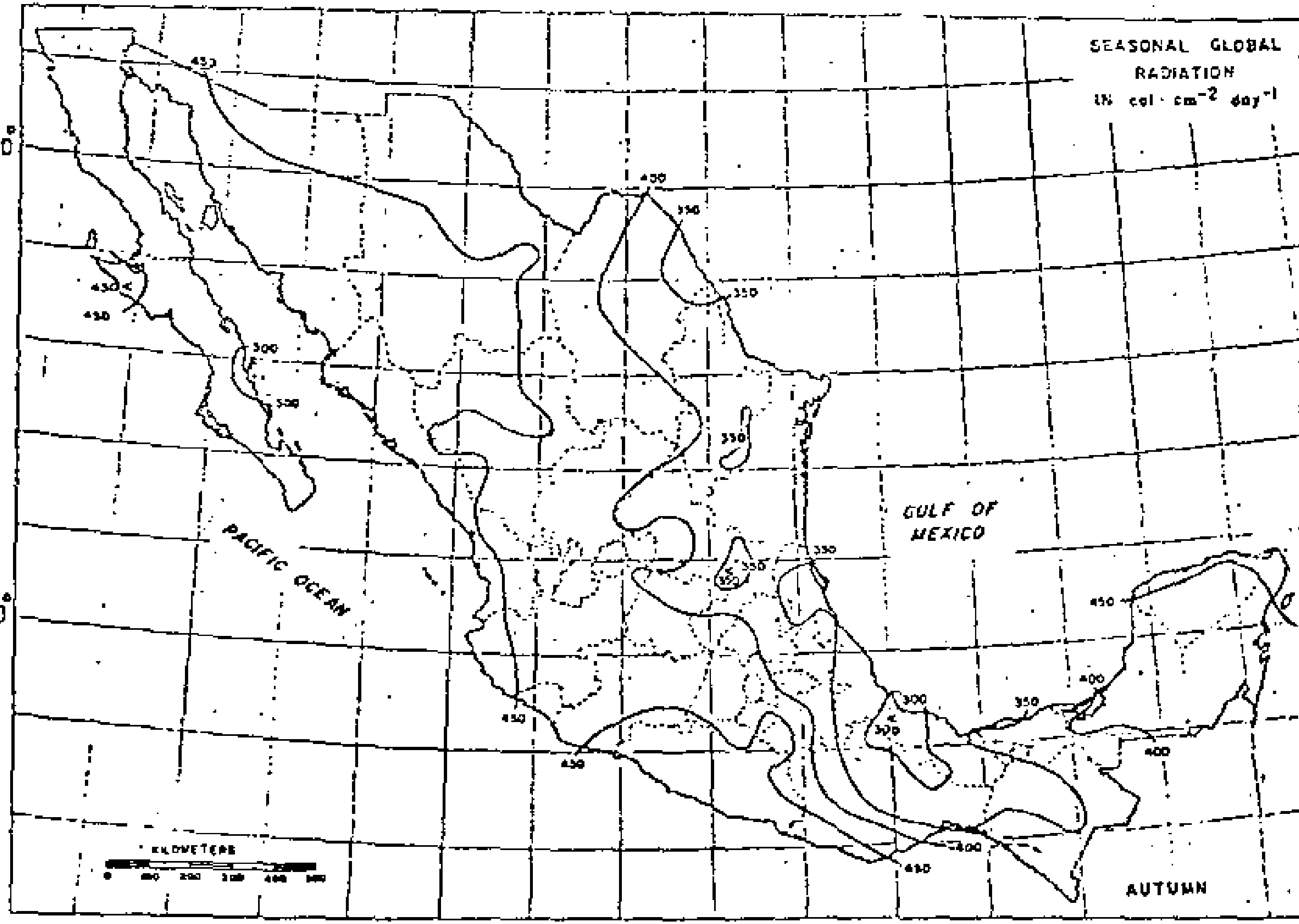

SEASONAL GLOBAL RADIATION
(IN cal · cm⁻² day⁻¹)
30°
20°
PACIFIC OCEAN
GULF OF MEXICO
450
400
350
300
KILOMETERS
0 100 200 300 400 500
AUTUMN

FIG. 3

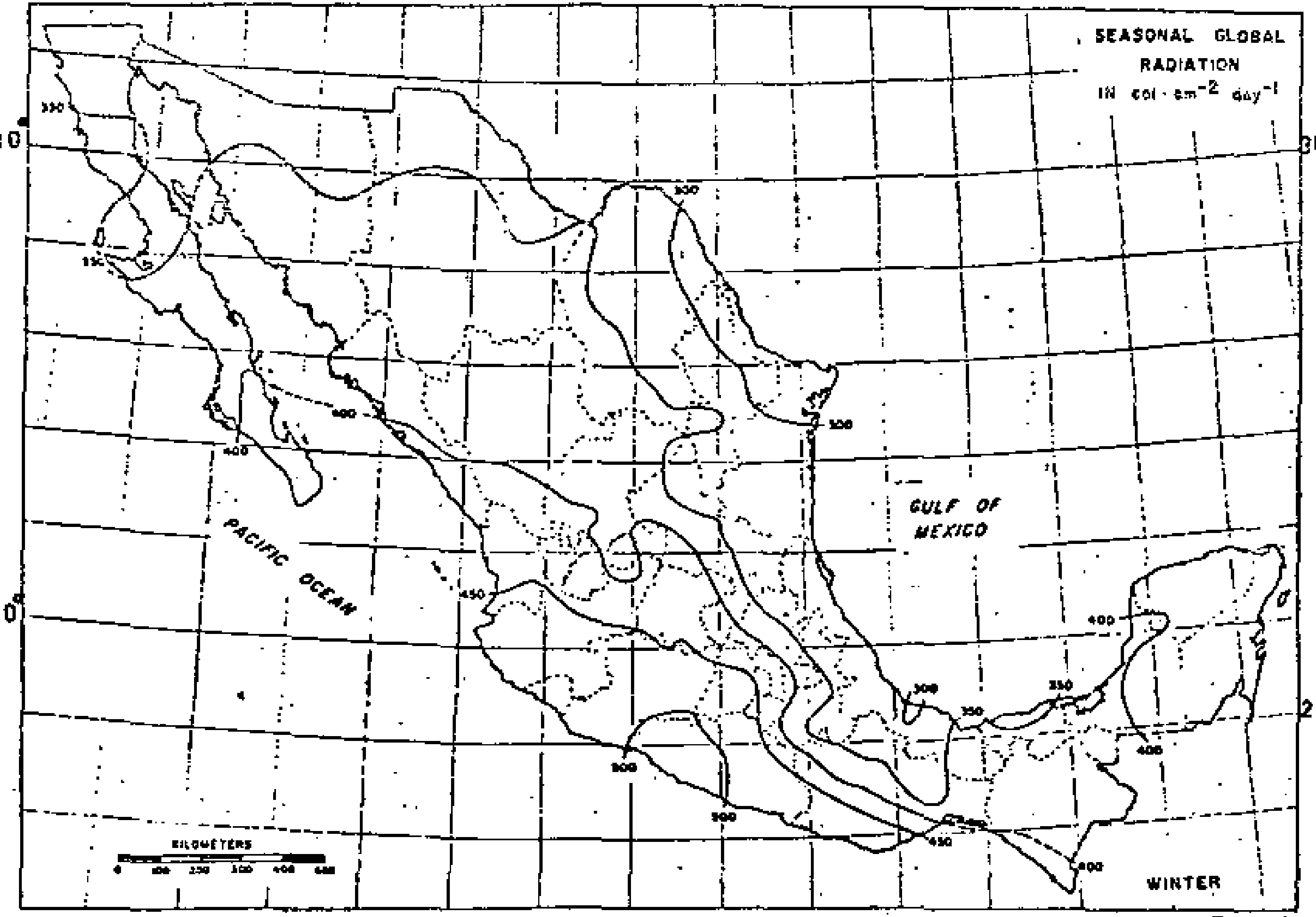
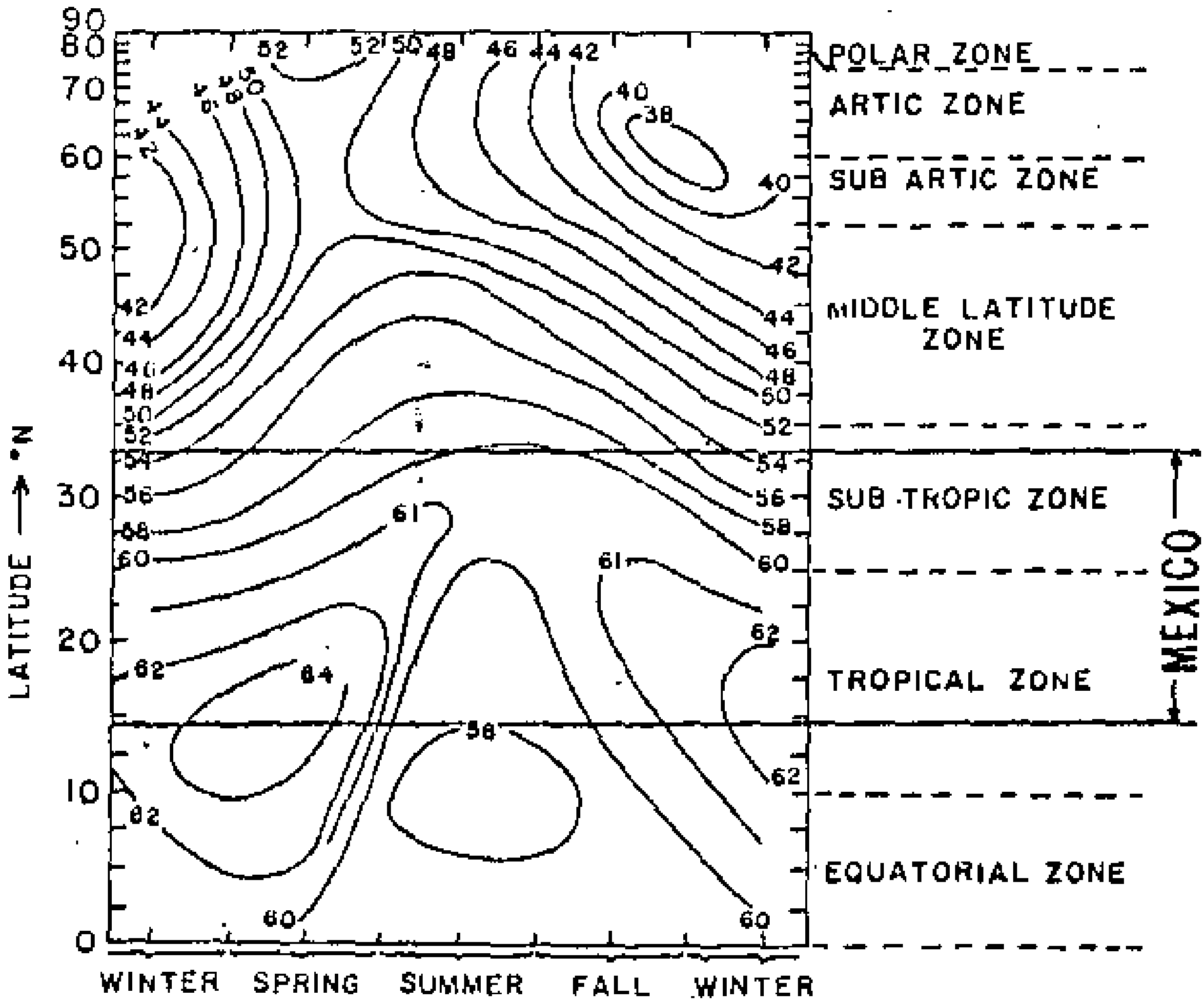

SEASONAL GLOBAL RADIATION
IN cal · cm^{-2} day^{-1}
30°
20°
PACIFIC OCEAN
GULF OF MEXICO
KILOMETERS
0 100 200 300 400 500
300
350
400
450
500
WINTER

FIG. 4



Insolation received at the ground, observed in percent of the extraterrestral radiation (adapted after J. London)

Figure 5

2º CONGRESSO LATINO-AMERICANO DE ENERGIA SOLAR

PROMOÇÃO DA
ASOCIACIÓN LATINOAMERICANA DE ENERGIA SOLAR E
UNIVERSIDADE FEDERAL DA PARAÍBA

JOÃO PESSOA - PARAIBA - BRASIL
13 a 18 de fevereiro de 1978

ANALISIS DE VARIOS METODOS PARA LA EVALUACION DE LA RADIACION SOLAR GLOBAL

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Cuantificación de la Radiación Global en función de datos meteorológicos.

El aprovechamiento racional de la radiación solar, precisa de un conocimiento previo de la intensidad de la radiación incidente en la localidad en cuestión.

La forma más precisa de cuantificar la radiación solar es indiscutiblemente la piranométrica. Sin embargo, ante la escasez de este tipo de datos, se hace indispensable recurrir a formulaciones teóricas, que ante la aleatoreidad de los parámetros involucrados, no representan sino meras aproximaciones. No obstante, algunas de estas formulaciones resultan bastante precisas, sobre todo cuando en ellas intervienen parámetros cuyas mediciones han sido confiables, continuas y extensas

Entre las diversas formulaciones existentes destacan las de Ångström, Kondratyev, Savinov y recientemente las de Reddy y Sabbagh, Sayigh y El Salam.

Los tres últimos autores, han desarrollado un método empírico de tipo exponencial que correlaciona la intensidad de radiación solar, horas de brillo solar (duración de la insolación), humedad relativa, temperatura máxima, latitud y altitud del lugar. Según los autores de esta fórmula, la radiación solar anual puede estimarse con una aproximación del $\pm$ 5% sobre datos registrados por aparatos de medición (1) Ante la precisión de este método, resulta interesante aplicarlo a ciertas localidades del país cuyas características climatológicas son semejantes a las estudiadas por ellos, ésto es, en zonas subtropicales.

Los parámetros involucrados en la fórmula pueden ser calculados técnicamente lo cual implica un cierto grado de incertidumbre en los resultados, debido a la alcatoreidad de los componentes atmosféricos que intervienen en el modelo. Preferentemente estos parámetros deben ser tomados de registros continuos, tomados durante prolongados períodos lo cual permite utilizarlos para estudios estadísticos.

Mientras que para algunos investigadores como Ångström, Black, Glover & McCullock, Sabbagh-Sayigh y El-Salam utilizan las horas de insolación para estimar la radiación solar media; Lui & Jordan, Bennet, Mateer, Krith, Sharma & Pal y Whillier utilizan otros parámetros meteorológicos; Reddy y otros autores obtienen la fórmula correspondiente utilizando horas de insolación, humedad relativa y temperatura media. Reddy sugiere utilizar en otra formulación número de días con lluvia, horas de insolación y un factor que depende de la latitud y la altitud. Swartman y Ogunlade por su parte utilizan la humedad relativa y las horas de insolación.

Para establecer una fórmula empírica que estime la radiación solar incidente sobre la superficie terrestre, es necesario considerar los factores que afectan esta radiación desde su llegada a la parte superior de la atmósfera hasta que incide sobre la superficie de la tierra. Un factor que no es frecuentemente analizado es el correspondiente a la temperatura del aire. Las variaciones de la temperatura del aire no están directamente relacionadas con la predicción de la radiación solar, pero como se puede observar en las Figuras (1) y (2), su patrón de distribución es similar al de la radiación global siendo al mismo tiempo antisimétrica al patrón de la humedad relativa. La temperatura del aire es un factor importante en la cantidad de vapor de agua y agua existente en la atmósfera, los cuales son importantes elementos atenuadores de la radiación solar.

<u>Ensayo de formulaciones empíricas que incluyen factores meteorológicos.</u>

Entre las ecuaciones empíricas propuestas por diferentes autores y que relacionan parámetros meteorológicos con la radiación solar incidente en la superficie terrestre, se escogió la de Sabbag-Sayigh y El-Salam(1) la cual se expresa como sigue.

$$Q = \alpha \, k e^{a_1 L^a} \, (b_1 D^b + C_1 R^c + d_1 t^d) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

donde: a, a_1, b_1, c_1 y d_1 son coeficientes,
y a, b, c y d son factores.

L es el ángulo de latitud en radianes.
D es la insolación efectiva
R es la humedad relativa.
t es la temperatura máxima del aire.
k es un factor de latitud y altitud.

El método que sugieren los autores -apoyado en un programa de computadora- consistió en ajustar la fórmula (1) con los datos meteorológicos disponibles en cada estación estudiada.

Los valores reportados de los coeficientes y de los factores se enlistan en la Tabla I.

TABLA I

Factores o coeficientes	a	b	c	d	a_1	b_1	c_1	d_1	α
Valores	1	1	1/3	-1	1	1	-1	-1	1.530

El valor de α fué también obtenido con un programa de computadora para cada estación.

El promedio de los valores de α calculado de los valores obtenidos en trece localidades de la Península Arábiga resultó ser de 1.530 y los autores sugieren aplicarlo indistintamente en cualquier localidad.

Sustituyendo los valores obtenidos de los coeficientes y de los factores en la fórmula (1) se obtiene que:

$$Q = 1.530\ k e^{L\ (D - s/\bar{R}\ -\ 1/T)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Para analizar el grado de aproximación de esta fórmula, es necesario contar con suficientes datos de los parámetros que intervienen en ella. Los lugares escogidos en México para los que se encontraron datos suficientes son Chihuahua y México, D. F.

El primer problema que se presentó en el estudio de la fórmula (2) fué el cálculo del factor k. Sabbagh, Sayigh y El-Salam sugieren utilizar una relación propuesta por S. Jeevananda Reddy(2) y que puede expresarse de la siguiente manera:

$$k = (\lambda N + \psi_{ij} \cos \phi)\ 10^2 \text{ cal cm.}^{-2} \text{ día.}$$

donde:

ϕ es la latitud del lugar (en grados).

λ 0.2/1 + 0.1 0 (factor de latitud).

N duración astronómica de la insolación.

ψ_{ij} factor estacional (i=1,2 tal que i=1, se utiliza para estaciones continentales localizadas lejos de la costa. e i=2 se utiliza para estaciones costeras. j varía de 1 a 12 donde j representa el mes del año. La ψ_{ij} se utiliza de acuerdo a los datos dados en la Tabla II.

TABLA II
Factor de variación estacional para el Hemisferio Norte

	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov.	Dic
ψ_1:	1,28	1,38	1.54	1.77	2.05	2.30	2.48	2.41	2.36	1.73	1,38	1.17
ψ_2:	1,46	1,77	2.05	2.15	2.05	2.06	2.10	2.17	2.14	1.96	1.60	1.43

El valor de N fué tomado de la serie de datos previamente calculado por E. Hernández(3).

Debido a que al aplicar la fórmula (2) con los valores obtenidos de k, se obtuvieron valores de radiación global muy diferentes a los registrados con piranómetros, la k tuvo que ser evaluada mediante otro método. Este método consiste en despejar la k de la fórmula (2) aprovechando que para los años 1967-1972 (Chihuahua y 1927-1937 (México, D.F.) existen todos los parámetros que intervienen en esta fórmula. La expresión que se obtiene es la siguiente:

$$k = \frac{Q}{1.530\ e^{L(D - \sqrt{R} - 1/t}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Los valores de Q, para Chihuahua, fueron tomados de los datos reportados por el Instituto de Geofísica de la U.N.A.M.(4)

Los valores de S, para Chihuahua, fueron tomados de los datos reportados por el Instituto de Geofísica de la U.N.A.M.(5)

Los valores de los parámetros restantes fueron tomados de los datos reportados por el Servicio Meteorológico Mexicano.

Los valores obtenidos del factor k para la localidad de Chihuahua se muestran en la Tabla III y para México, D.F. en la Tabla IV.

Haciendo una comparación de los valores de k obtenidos por medio de la expresión de Reddy y por medio de la fórmula (3), se observa que existe mucha diferencia entre ellos. Por consiguiente se efectuó el cociente k_1/k_2 (k_1: Reddy, K_2: fórmula (3) con el fin de analizar la existencia de alguna dependencia entre ambas constantes).

Los resultados del cociente k_1/k_2 se muestran en las mismas Tablas III y IV. En las Figuras (1) y (2), pueden observarse los contornos de los patrones de distribución del promedio de radiación mensual real (Q); del promedio de humedad relativa (R); promedio mensual de la temperatura máxima extrema (t); y del promedio mensual de las horas de insolación (relativas a 12 horas) (D).

Ensayo de las formulaciones de Ångström.

Escencialmente el método de Ångström(6) consiste en emplear la fórmula empírica:

$$\overline{Q} = \overline{Q}_o \left(a + b \frac{\overline{S}}{\overline{S}_o} \right) \qquad (4)$$

donde:

$\overline{Q}$ es el promedio de la radiación global real (la que llega a la superficie de la tierra considerando los efectos de nubosidad, turbidez, etc.)

$\overline{Q}_o$ es la radiación global máxima (la que llega a la superficie terrestre en un día completamente despejado y limpio)

$\overline{S}$ es la duración de la insolación real (el tiempo en el cual el sol ilumina directamente tomando en cuenta las disminuciones en tiempo que pudieran ocurrir por la presencia de nubes y efectos topográficos).

$\overline{S}_o$ es la duración de la insolación máxima (la que puede esperarse en un día completamente despejado y limpio).

a y b son constantes que se determinan de acuerdo al siguiente criterio:

1) Si $\overline{S} = 0$, entonces: $\overline{Q} = a\ \overline{Q}_o$; tal que al efectuarse el cociente de Q (cielo completamente cubierto) y Q_o (cielo completamente despejado) se obtiene el valor de a.

2) Para $\overline{S} = \overline{S}_o$, entonces: $\overline{Q} = \overline{Q}_o$; por lo que en éste caso se tiene: a + b = 1. Los valores de a y de b se determinan experimentalmente y dependen de los períodos en los cuales $\overline{Q}$ y $\overline{S}$ fueron determinados. Es decir, a y b varían con la época del año y con la localidad.

P. de Brichambaut y G. Lamboley(7) al analizar en múltiples casos la radiación global media ($\overline{Q}$) en función de la fracción de la insolación media encontraron que la expresión de Ångström (4) no es del todo lineal y sugieren reemplazar la expresión anterior por los valores de la curva que se muestra en la Figura (3), indicando además que la presición que puede ser obtenida es del 8% o aún mayor (dependiendo de la continuidad y extensión del acopio de datos y registros de que se disponga).

Entre las dificultades que se encuentran al utilizar la expresión de Ångström destacan las dos siguientes:

a) La definición de insolación es ambigua. Algunos autores consideran a S_o como la duración astronómica de la insolación, esto es, el tiempo transcurrido entre la salida y puesta del sol; otros la toman como el tiempo transcurrido entre la salida y puesta del sol, tomando en cuenta los factores topográficos de la localidad en cuestión; finalmente, otros autores aceptan el valor de S_o como el tiempo máximo de insolación registrado por algún heliógrafo en un día perfectamente despejado y limpio. La última definición depende del umbral de sensibilidad del instrumento. Es por ésto que algunos autores sugieren hacer correcciones aditivas a los registros de horas de insolación partiendo del hecho que los heliógrafos no registran señal alguna cuando la intensidad de la radiación solar es menor que cierto valor crítico.

b) El valor preciso de Q_o no puede ser determinado en lugares donde no existen mediciones pirheliométricas. Algunos investigadores recomiendan que en los lugares donde se dispongan de datos de radiación, se tome el valor de Q_o como el promedio (mensual durante varios años) de la radiación máxima registrada (piranométricamente). Otros autores sugieren para simplificar el problema, tomar directamente el valor de la radiación solar extraterrestre, aunque esto modifica sensiblemente los valores de las constantes a y b, Si S = 0, al efectuar el cociente: a= Q/Q_o, a tendrá un valor mayor cuando Q_o represente la radiación máxima en un día despejado.

No obstante las dos dificultades antes citadas, tanto la ecuación original de Ångström como algunas otras que se derivan de ella y que contienen ligeras variantes que dependen de la disponibilidad de los datos necesarios para emplearla, han resultado ser en general bastante aceptables para el cálculo de la radiación global Q. Se ha encontrado también a lo largo de múltiples estudios efectuados por un sinmémero de inves tigadores, que los resultados de Q_o obtenidos mediante ecuaciones del tipo Ångström son las que más se aproximan a los datos piranométricos, aunque como ha podido constatarse en incontables ocasiones, no se conoce con certeza la precisión misma de estos datos ya que ha sucedido que al hacer mediciones simultáneas de Q con instrumento de diferente marca, los valores obtenidos difieren entre sí hasta en un 15 o 20% aún en los casos en que dichos instrumentos hayan sido recientemente calibrados. Esta diferencia de resultados es la que originó la suspensión del funcionamiento de docenas de piranómetros de la red que operaba en los Estados Unidos de Norteamérica hasta hace apenas unos cuantos años.

Un método que permite evaluar a Q con bastante aproximación y que también se basa en la ecuación de Ångström, es el desarrollo por E. Hernández(3) el cual en sustitución de los datos de insolación de superficie, utiliza la duración de la insolación obtenida a partir del análisis de la distribución de la nubosidad observada por satélites meteorológicos. La descripción completa del método puede observarse del diagrama de la Figura (4).

Los resultados obtenidos al aplicar este método mostraron una diferencia del 6% anual con respecto a la serie casi completa de datos piranométricos del período 1969-71, medidos en la Ciudad Universitaria de México, D. F. y reportados en la Referencia (4). En otras localidades colindantes con los Estados Unidos de Norteamérica, donde no se contó con series completas de datos piranométricos, los resultados de Q fueron comparados con los valores reportados por Bennett (8). La diferencia encontrada entre Brownsville, Tex. (E.U.) y Matamoros, Tam. (Méx.) fué de sólo 1.5% sobre el valor medio anual de Q. Para las localidades de Yuma, Ariz. (E.U.) y Mexicali, B.C.N. (Méx.) la diferencia fué de sólo 2.5% aunque estas localidades se encuentran un poco mas separadas.

Conclusiones.

De los dos métodos estudiados para determinar la radiación global, el de Ångström presenta la ventaja de incluir a la duración real de la insolación la cual puede ser fácilmente registrada heliográficamente. Por su parte la formulación de Sabbagh, Sayigh y El-Salam aunque contiene parámetros meteorológicos de fácil medición, presenta el inconveniente mismo del número de datos que es preciso considerar. Mientras que en el primer caso sólo es necesario controlar el registro de la duración de la insolación, en el segundo el problema se complica, ya que es necesario controlar con la presición requerida un número mayor de parámetros que aunque son datos de fácil adquisición, introducen una mayor incertidumbre, sobre todo si no son datos suficientemente confiables, ya que en este caso, los datos meteorológicos involucrados en lugar de representar una ventaja, se convierten en una desventaja.

En México se cuenta con la información casi continua de muchos de los principales elementos meteorológicos sobre una red que puede considerarse extensa.

Los datos heliográficos aunque escasos, resultaron, sin lugar a dudas, ser más convenientes para los propósitos requeridos en un estudio de este tipo, ya que aunque solamente se dispuso de unas cuantas estaciones, su continuidad, volumen, así como el mantenimiento suministrado a los heliógrafos en los períodos comprendidos, permiten asignarles una mayor confiabilidad.

Sin embargo, es necesario hacer notar que algunos métodos de evaluación de la radiación solar global que incluyen fundamentalmente datos meteorológicos han mostrado tener bastante aproximación, por lo que si en el país en cuestión se dispone del acopio suficiente de datos meteorológicos con la calidad requerida, estas formulaciones seguramente reportarían resultados importantes.

De los resultados obtenidos en éste trabajo se aconseja que en ausencia de datos de insolación se recurra a las aproximaciones basadas en la fotointerpretación de la nubosidad registrada y transmitida por satélites meteorológicos, que aunque pudieran cubrir un período muy corto de tiempo, son datos continuos y su distribución regular (sobre una gran extensión territorial) es importante puesto que permite localizar de manera precisa la posición de las isolíneas de radiación global.

Referencias.

(1) Sabbagh, J. A., Sayigh, A. A.M., El-Salam, E. M., "Estimation of the total solar Radiation from Meteorological Data". Proceedings ISES 75, Los Angeles, Calif. (1975).

2 Reddy, S. J. "An Empirical Method for the Estimation of the total Solar Radiation". Solar Energy 13, 289-290 (1971).

3 Hernández, E. "La Distribución de la Radiación Global en México Evaluada Mediante la Fotointerpretación de la Nubosidad Observada por Satélites Meteorológicos". Tesis Maestría en Ciencias. Facultad de Ciencias UNAM (1976).

4 Solar Radiation and Radiation Balance Data (The World Network). USSR Chief Administration of the Hydrometeorological Service. Leningrad. (1969-71).

5 Galindo, I., Leyva, A., Muhlia, A., Valderrama, V., Galindo, L., Alvarez, A., Ramírez, I., Datos Geofísicos, Serie B, Meteorología 1. Instituto de Geofísica, U.N.A.M., México(1974,)

6 Ångström, A., "On Computation of Global Radiation from the Records of Sunshine". Arkiv for Geofysica Stockholm, Vol. 2, No.22, 1956.

7 Pernin de Brichambaut, Ch., "Rayonnement Solaire et Echanges Radiatifs Naturels". Gauthier Villard. Paris (1963).

8 Bennett, I. "Monthly Maps of Mean Daily Insolation for the United States". Solar Energy Vol. 9, No. 3,(1965).

EH/mjss,

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EH/mjss.

TABLA III

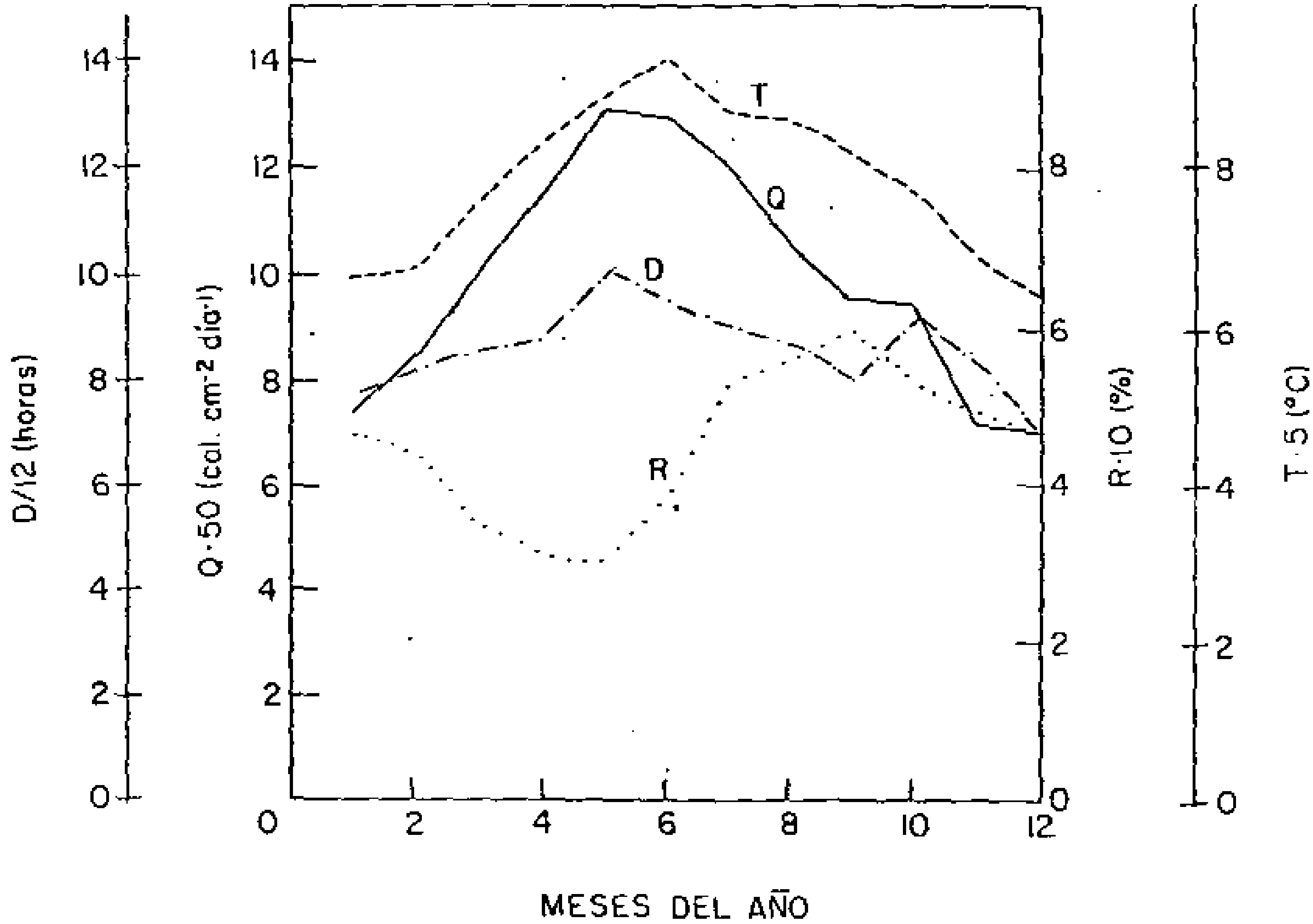
Valores de k para Chihuahua

Mes	k_1	k_2	k_2/k_1
Enero	165	266.50	1.62
Febrero	177	288.92	1.63
Marzo	195	333.14	1.70
Abril	219	369.26	1.69
Mayo	247	398.90	1.62
Junio	271	416.26	1.54
Julio	286	412.67	1.44
Agosto	277	368.95	1.33
Septiembre	269	344.84	1.28
Octubre	209	322.67	1.54
Noviembre	174	250.66	1.44
Diciembre	154	256.43	1.66

TABLA IV

Valores de k para México, D. F.

Mes	k_1	k_2	k_2/k_1
Enero	193	260.44	1.35
Febrero	206	332.55	1.61
Marzo	226	358.13	1.58
Abril	253	366.34	1.45
Mayo	283	353.66	1.25
Junio	309	360.81	1.16
Julio	325	313.77	0.99
Agosto	316	326.50	1.04
Septiembre	306	285.50	0.93
Octubre	205	289.31	1.41
Noviembre	204	275.03	1.35
Diciembre	1?	[illegible]	[illegible]



EST. CHIHUAHUA

FIGURA 1

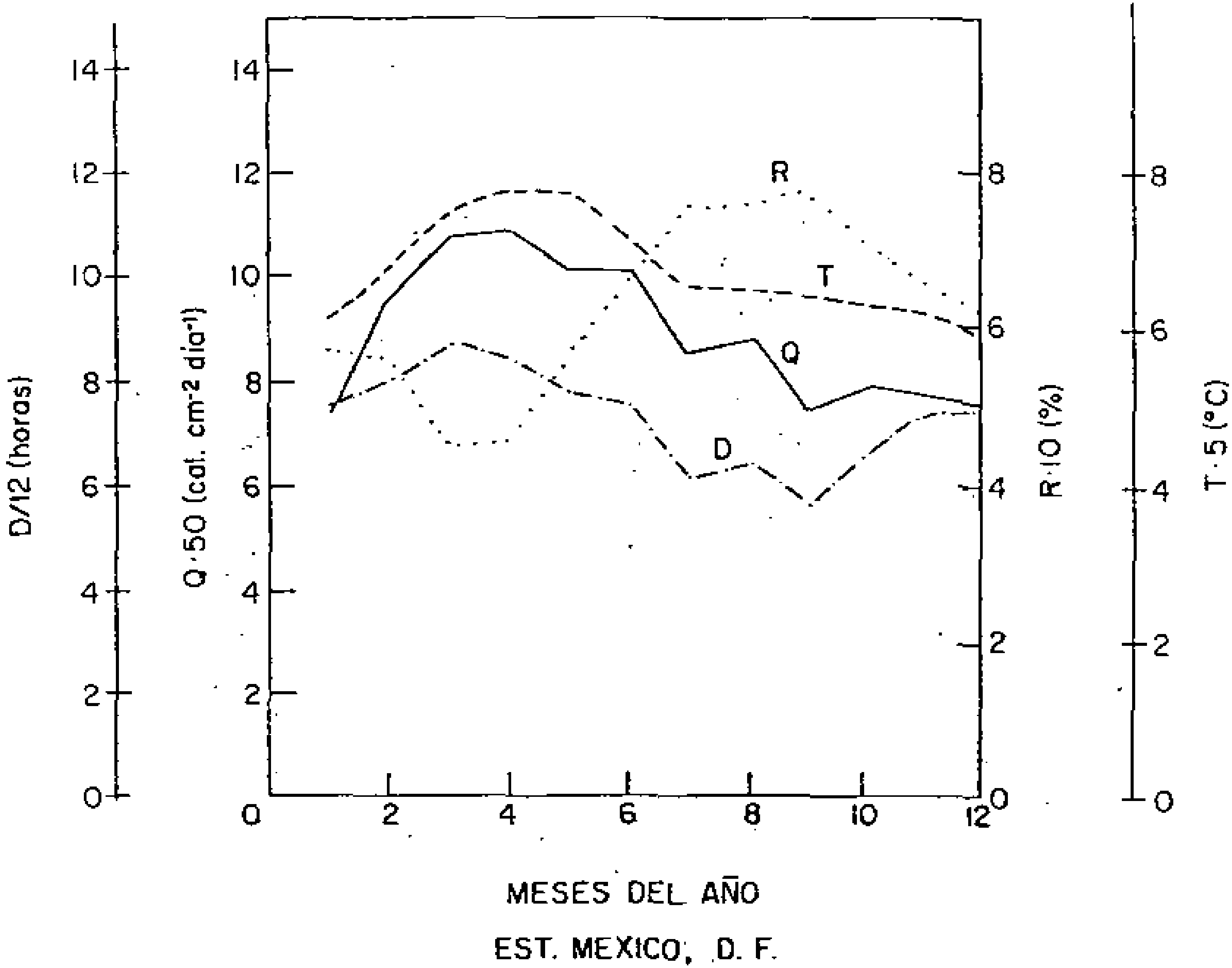

D/12 (horas)
Q·50 (cal. cm-2 dia-1)
R·10 (%)
T·5 (°C)
R
T
Q
D
MESES DEL AÑO
EST. MEXICO, D. F.

FIGURA 2

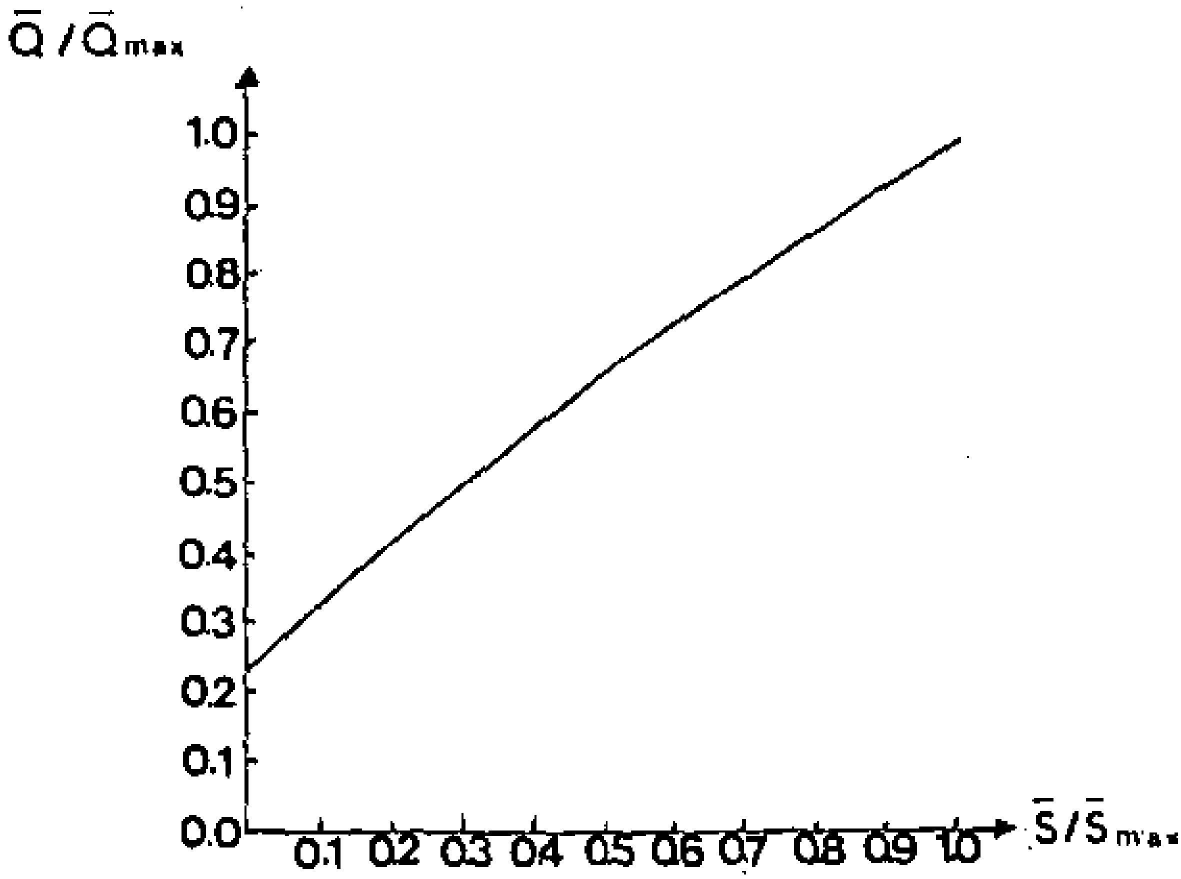


FIGURA 3. RELACION ENTRE LA DURACION DE LA INSOLACION Y LA RADIACION GLOBAL.

DATOS INICIALES:
PORCENTAJES MENSUALES DE LA NUBOSIDAD REGIONAL OBTENIDA DE LOS SATELITES NIMBUS III Y ESSA (APT) CUBRIENDO LA TOTALIDAD DE MEXICO DIVIDIDO EN UNA RED DE 117 CUADROS DE APROXIMADAMENTE 130 Km POR LADO

FOTOINTERPRETACION

CIELO DESPEJADO 0 % NUBOSIDAD

CIELO NUBLADO 100 % NUBOSIDAD

CIELO PARCIALMENTE NUBLADO 0 % < NUBOSIDAD < %

APROXIMACION DEL MODELO

CUBIERTA FRACCIONAL DE NUBES ϵ

DIAS DESPEJADOS $\epsilon = 0.0$

PARCIALMENTE DESP. $\epsilon = 0.5$

NUBLADOS $\epsilon = 1.0$

DURACION ASTRONOMICA DE LA INSOLACION EN UN LUGAR DE LATITUD ϕ

$S = \cos^{-1}(-\tan\phi \tan\delta)$

d = DECLINACION SOLAR

VALORES MEDIOS DEL TOTAL MENSUAL DE HORAS DE INSOLACION ASTRONOMICA

$$\overline{S}_{d_0} = 1/n \sum_{i=1}^{n} Hi \quad \text{(MEDIO DIARIO)}$$

VALOR MEDIO DEL TOTAL MENSUAL DE HORAS DE INSOLACION ASTRONOMICA

$$\overline{S}_0 = \sum_{i=1}^{n} Hi$$

Hi ES TOTAL DE HORA DE INSOLACION ASTRONOMICA DEL DIA i EN LA LATITUD ϕ

η = NUMERO DE DIAS EN EL MES

η_1 = NUMERO DE DIAS NUBLADOS EN EL MES

η_2 = NUMERO DE DIAS PARCIALMENTE NUBLADOS EN EL MES

DE LA APROXIMACION DE FRITZ LA RADIACION GLOBAL INSTANTANEA Q_{max} EN UN DIA DESPEJADO ES:

$Q_{max} = 1.76 \operatorname{sen} h - 0.07$; $h > 8°$

$Q_{max} = 1.20 \operatorname{sen} h$; $h < 8°$

h = ALTURA SOLAR

$$Q_m = \int_{t_0}^{-8°} Q'_{max}dt + \int_{-8°}^{+8°} Q_{max}dt + \int_{+8°} Q'_{max}dt$$

+ t_0 INSTANTES CUANDO $h = 0°$

COMO PRIMERA APROXIMACION:
EL VALOR MEDIO DEL TOTAL MENSUAL DE HORAS DE INSOLACION MAXIMA ES:

$$\overline{S}_{max} = \overline{S}_0$$

VALOR MEDIO DEL NUMERO MENSUAL DE HORAS CON CIELO DESPEJADO

$$\overline{S}_m = \eta_1 \overline{S}_{d_0}$$

VALOR MEDIO DEL NUMERO MENSUAL DE HORAS CON CIELO PARCIALMENTE CUBIERTO

$$\overline{S}'_m = \eta_2 \overline{S}_{d_0} \overline{\epsilon}$$

VALOR MEDIO MENSUAL DEL TOTAL DE HORAS DE INSOLACION REAL

$$\overline{S} = \overline{S}_m + \overline{S}'_m$$

VALOR MEDIO MENSUAL DE LA RADIACION GLOBAL MAXIMA

$$\overline{Q}_{max}$$

ECUACION DE ANGSTROM REVISADA

$$\frac{\overline{Q}}{\overline{Q}_{max}} = a + b \frac{\overline{S}}{\overline{S}_{max}}$$

a, b: CONSTANTES

LOS VALORES MEDIOS MENSUALES DE LA RADIACION GLOBAL REAL $\overline{Q}$, SE INTERPOLAN DE LA CURVA OBTENIDA AL USAR LA APROXIMACION SUGERIDA POR P. DE BRICHAMBAUT Y G. LAMBOLEY RELACIONANDO A:

$\overline{Q}/\overline{Q}_{max}$ y $\overline{S}/\overline{S}_{max}$

FIG. 4 METODO DE OBTENCION DE Q BASADO EN FOTOINTERPRETACION

hc

SUN

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Pergamon

Volume One

ON THE DETERMINATION OF THE OPTIMUM SITE IN MEXICO FOR AN INTERNATIONAL SOLAR ENERGY EXPERIMENTAL CENTER

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ABSTRACT

Due to the necessity of selecting the optimum location for the Mexican Solar Energy Experimental Center, studies were made on various possible sites. These studies were directed towards factors such as: insolation and climatic characteristics, living conditions, technical and scientific infrastructure, accesibility and local socioeconomic conditions. The short and long term objectives of this Center are also summarized. After a close examination of global information, seven places were selected. These are: La Paz, B.C.S; Ciudad Juárez, Chih.; Progreso, Yuc.; Hermosillo, Son.; Puerto Vallarta, Jal.; Acapulco, Gro.; and Durango, Dgo. The city of La Paz, B.C.S. being the best place for the Solar Research Center which will soon be established there. (1)

INTRODUCTION

Solar research and development in Mexico is carried out at present at several academic institutions, among which the most important are (2):

The National University of Mexico (UNAM)
- Materials Research Center (C.I.M.)
- Engineering Institute (I.I.)
- Atmospheric Sciences Center (CCA)

The Metropolitan University (U.A.M.)
The Electrical Research Institute (I.I.E.)
The Center for Research and Advanced Studies of the National Politechnical Institute (C.I.E.A.)
The Technological Institute of Monterrey (ITESM).

The Solar Energy research areas covered by these institutions are the following:

- Water heaters (domestic and industrial)
- Air heaters (drying)
- Water -energy- food relationships
- Solar Architecture
- Refrigeration
- Air conditioning
- Selective surfaces
- CdS and Si cells
- Solar flux and cloudiness data treatment
- Solar Instrumentation development
- Water pumping

Most of the experimental work has, up to now, been carried out in the area of Mexico City where due to atmospheric pollution, the climatic and insolation conditions are by no means the best as they were before. In order to guarantee either work continuity or offer better operation conditions in the country, it was therefore considered necessary to establish a Solar Research Center in a location which would provide the best working conditions.

This paper deals with some of the aspects studied for various locations in Mexico which resulted in the city of La Paz (Baja California) being chosen as the site for the Solar Research Center which will soon be established there.

OBJECTIVES OF THE SOLAR RESEARCH CENTER

Table I summarizes the short and long term objectives of the Solar Research Center. As can be seen, the Center will coordinate research activities and will carry out specific work as well as supporting activities at other institutions. It will also serve as an experimental station for long term testing of new developments and will establish research agreements with national and international institutions.

CRITERIA FOR THE SELECTION OF THE SITE

The main criteria used in order to select the optimum site for the Solar Research Center were the following:

- Insolation and climatic characteristics
- Living conditions
- Technical and scientific infrastructure
- Accesibility
- Local socioeconomic factors

INSOLATION AND CLIMATIC CHARACTERISTICS

Since the best insolated areas of the world are those located between the latitudinal belts of 15°-35°N. and 15°-35°S., this means that the geographical situation of

Mexico becomes excellent. The annual distribution of insolation in Mexico can be synthesized from reports published by Hernandez (3), (4). An examination of Figure 1 showing the annual distribution of global radiation in Mexico will explain why Mexico has been called for so long time Country of the Sun. It can be easily distinguished that although the entire country has favourable insolation conditions, there are several regions especially suitable for solar energy technological research. These regions are those with values higher than 500 cal. cm^{-2} day^{-1}. It is a well known fact that the zones of highest annual insolation are also those where the great desert zones of the earth are found. The corresponding arid zones of Mexico can be seen from Figure 2. Both arid and semi-arid zones make up about 41% of the entire national territory.

From Figure 3, it can be observed that the maximum mean daily summer values of global radiation occur in the Peninsula of Baja California and in the northwest of Mexico, especially the states of Sonora, Durango, Chihuahua, Coahuila, Sinaloa, and north of Yucatán Peninsula. During this season more than the half of the country has insolation values above 500 cal. cm^{-2} day^{-1}.

After a close examination of the above information, seven sites were selected as the best possible sites for the Solar Research Center. These are: La Paz, Baja California Sur; Ciudad Juárez, Chihuahua; Progreso, Yucatán; Hermosillo, Sonora; Puerto Vallarta, Jalisco; Acapulco, Guerrero; and Durango, Durango.

Figures 4 and 5 show respectively the climatic and cloudiness conditions of the seven selected places. The annual mean values of their main climatic and insolation factors are described in Tables II and III, and also in Figures 6 to 12.

As far as global radiation is concerned, the three best localities are: La Paz, B. C.S.; Hermosillo, Son.; and Ciudad Juárez, Chih. These three also have high relative duration of insolation and low index of cloudiness during the year. Relative humidity is lower in Ciudad Juárez, while in La Paz and Hermosillo it is about 10 to 20% higher. One important characteristic favourable for La Paz is that although relative humidity is higher than at Ciudad Juárez, annual rainfall and cloudiness are lower. On the other hand, considering ambient temperatures, the annual warmest place is Hermosillo, followed by La Paz and Ciudad Juárez. However, if we consider that the maximum temperatures at each one of the places are respectively: 32.6°C (Jul.), 29.6°C (Aug.) and 27.6°C (Aug.); and their corresponding minimum temperatures are: 17.2°C (Jan.), 18°C (Jan.) and 6.2°C (Jan.), we can observe that a smaller temperature oscillation during the year occurs at La Paz; hence it offers more temperature stability which may represent better weather operating facilities and living conditions. Thus from the insolation and climatic point of view, La Paz, B.C.S., seems to offer the best possible conditions in the country. In order to reach a final decision for the location of the Research Center it was necessary to consider other criteria, as previously mentioned.

LIVING CONDITIONS

It is a fact that most of the research personnel who will colaborate and work with the Research Center, will be people who have probably lived most of their lives in major cities and used to following a comfortable life style. It is therefore of great importance to be able to offer to these people a range of services and conditions similar to those of their present environment. Some of the main services which have to be offered are: Municipal services (electricity, water, telephones); Schooling facilities (Primary to University); and Medical services.

The city of La Paz not only offers all these services, but is recognized as a place which has a high level of urbanization, preserving its Colonial architecture. Schooling includes up to university level which comprises a newly formed University and a Technological Institute. Medical services are very adequately covered by both state and private facilities.

As far as other commodities are concerned such as shops, cinemas, theatres and outdoor activities like sports, La Paz is the main cultural and shopping center for the entire population of the state of Baja California Sur. The range of sport activities which can be carried out in La Paz are obvious due to its geographical position and its climatic conditions throughout the year. Regarding housing, La Paz offers a variety of possibilities and the Research Center will have certain accomodation facilities.

ACCESIBILITY

Figure 13 shows the distances from La Paz to the places with which it will have the most contact (Mexico City, Guadalajara, Los Angeles, Hermosillo). La Paz can be reached by road from the north; by sea from the Pacific Coast (there are several year-round ferry services from several Pacific ports); or by air. There are two national airlines and one U.S.A. airline which fly to La Paz with national and international connections. There are also local air services connecting La Paz with major cities across the Gulf of California and on the peninsula itself.

TECHNICAL AND SCIENTIFIC INFRASTRUCTURE

The aspects which were analyzed in these areas were mainly the following: workshops, libraries, scientific equipment agencies and scientific information services. It is a fact that this type of infrastructure is only found in large Mexican cities which do not fullfil the first selection criteria (insolation and climatic conditions). It is therefore in these service areas where it is most important to concentrate the first efforts of the Center, and its first activities will be directed towards establishing and promoting the necessary local infrastructure.

LOCAL SOCIO-ECONOMIC FACTORS

It is interesting to analyze the socio-economic development of the Peninsula of Baja California in general. Specifically its southern portion which constitutes the state of Baja California Sur and which until 1973 was not properly communicated by road. In that year the transpeninsular highway was concluded opening La Paz to the north. Since 1968 there has been a regular ferry boat service from the Pacific coast ports of Mazatlán, Guaymas, Manzanillo, Acapulco and Salina Cruz (and touristic routes from Los Angeles, Calif.) Although badly communicated in the past, a constant flow of colonizers existed for many years, mainly attracted by the growing mining and by the cotton and fishing industries. It is interesting to note that since the XVII century several mining settlements have been in operation. Nowadays, the state of Baja California Sur is one of the fastest growing areas of the country, and a great impulse to its economy have been the tourist and cotton industries. In order to mantain its growth and converts it into a balanced-economy state, it is necessary to promote a local medium weight industry. It is considered that the establishing of the solar Research Center in La Paz will promote a local solar industry with the benefits sought. It is also necessary to promote the water-energy- food chain so necessary in arid and semi-arid regions. The Center will help to prepare specialists who will be capable of promoting new technologies and agricultural techniques around the La Paz area.

CONCLUSIONS

Based on its insolation and climatic conditions, the city of La Paz (Baja California Sur) has been selected as the best place to establish the Mexican Solar Research Center.

Analyzing other selection criteria, such as local living conditions, accesibility, technical and scientific infrastructure and local socio-economic factors, the city of La Paz is considered, not only to comply with the necessities established, but is considered as an optimum place for national and international solar research development and industrialization.

REFERENCES

(1 Best B., G.; Mayer B., E.; Hernández, E. (1977) "Algunas ideas sobre los objetivos de un Centro de Energía Solar" Internal Report of the Solar Energy Section CIM-UNAM.

(2) Mayer B., E. (1976) "Present State and Perspective of Solar Energy Applications in Mexico". Proceeding of the "Sharing the Sun - 1976". Solar Energy Joint Conference of the American Section of the International Solar Energy Society, Winnipeg, Canada; Vol. I. p.p. 37-57.

(3) Hernández H., E. (1976) "On the Numerical Computation of Solar Radiation Parameters from Satellite Cloud Data" Proceedings UNESCO-WMO Solar Energy Symposium, Geneva, Swiss.

(4) Hernández H., E. (1976) "The Seasonal Distribution of the Incoming Solar Radiation in Mexico", Proceedings of the "Sharing the Sun-1976" Solar Energy Joint Conference of the American Section of ISES. Winnipeg, Canada, Vol. 10, pp 259-258.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Organization of American States in this work. Thanks also to Mr. H. Cortés for inking the figures and to Miss M. Spíndola for transcription of the manuscript.

T A B L E I

OBJECTIVES OF THE SOLAR RESEARCH CENTER

Short Term (1 Year)	Medium Term (3 Years)	Long Term (6 years)
Establish research programs based on the National Solar Energy Program.	Initiate its own research projects.	Promotion of the National Solar Industry.
Create the Physical facilities needed (buildings, installations, services, etc.) to initiate work.	Sponsor projects at other institutions.	Organize specialized courses.
Initiate buying of equipment according to research program needs	Accept research contracts with industry (national & international)	Organize Congresses.
Establish a solar collector normalization and certification system.	Coordination of the National Radiometric Stations.	Test pilot plants.
Promote demonstration projects.	Prepare solar technology specialists.	Technological transfer with industry.
Establish National & International agreements.		
Promote local technological infrastructure.		

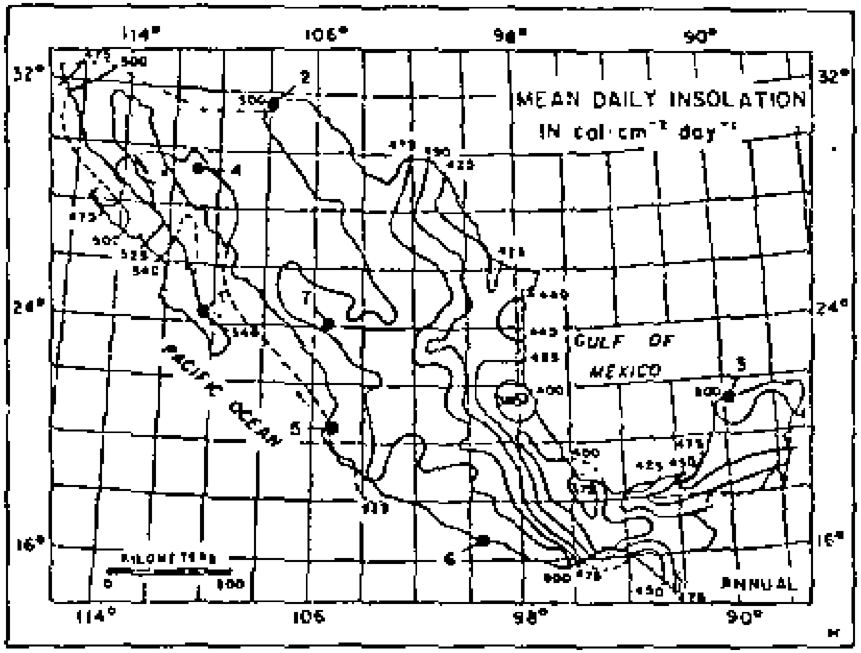


FIGURE 1

Mean Daily Values of the Annual Global Radiation in Mexico

T A B L A 2.

Distribution of Insolation		
Characteristics	Percentage of total surface	Surface
Areas receiving more than 500 cal. cm.$^{-2}$ day^{-1}	38	749,570 Km^2
Areas receiving between 400 and 500 cal. cm^{-2} day^{-1}	57	1,124,150 Km^2
Areas receiving less than 400 cal. cm^{-2} day^{-1}	5	98,827 Km^2

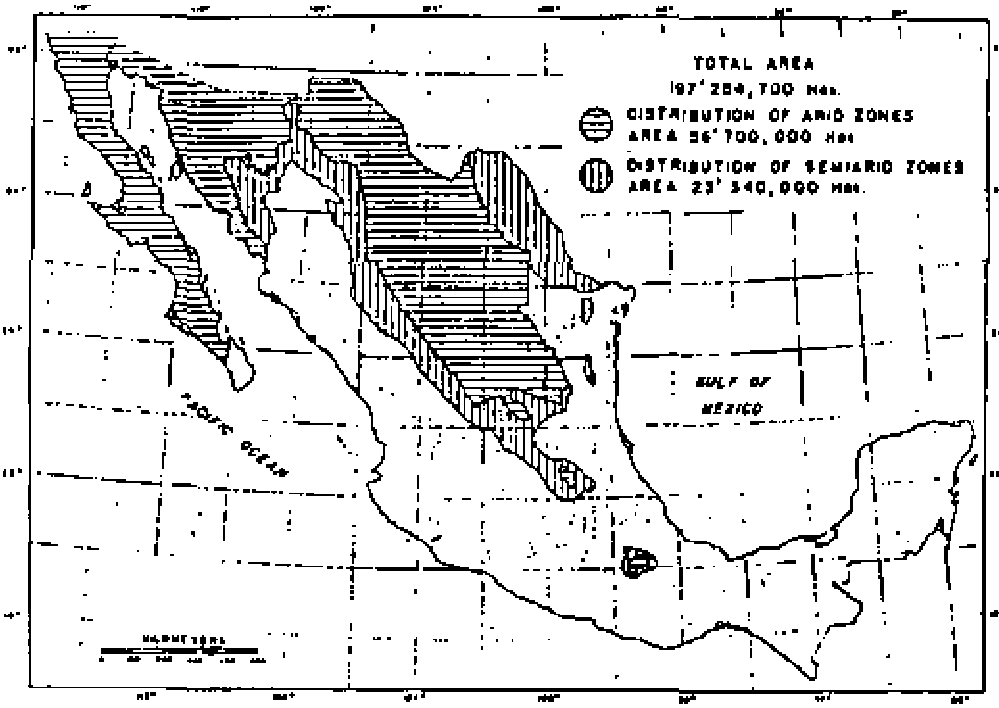


FIGURE 2

Arid and Semi Arid Zones

INSOLATION CLIMATIC CHARACTERISTICS
AT THE SEVEN SELECTED PLACES

TABLA 3.

Place	Latitude	Longitude	Altitude m.	Annual Mean Daily Values					
				Global Radiation Cal. cm^{-2} day^{-1}	Relative Duration of Insolation (%)	Cloudiness %	Temperature °C	Humidity %	Rainfall mm.
La Paz, B.C.S.	24° 09'	110° 20'	6	540	85	15-20	24	60-70	204
Ciudad Juárez, Chihuahua.	31° 44'	106° 40'	1133	530	79	20-25	17.2	40-60	234
Progreso, Yucatán.	21° 17'	89° 40'	3	515	75	20-25	25.4	80-90	469
Hermosillo, Sonora.	29° 05'	110° 57'	237	535	85	15-20	25.2	60-70	244
Puerto Vallarta, Jalisco	20° 45'	105° 16'	2	515	75	25-30	26.2	70-80	1403
Acapulco, Guerrero.	16° 50'	99° 56'	3	515	68	25-30	27.5	70-80	1412
Durango, Dgo.	24° 01'	104° 40'	1889	500	75	26-30	17.5	50-60	441

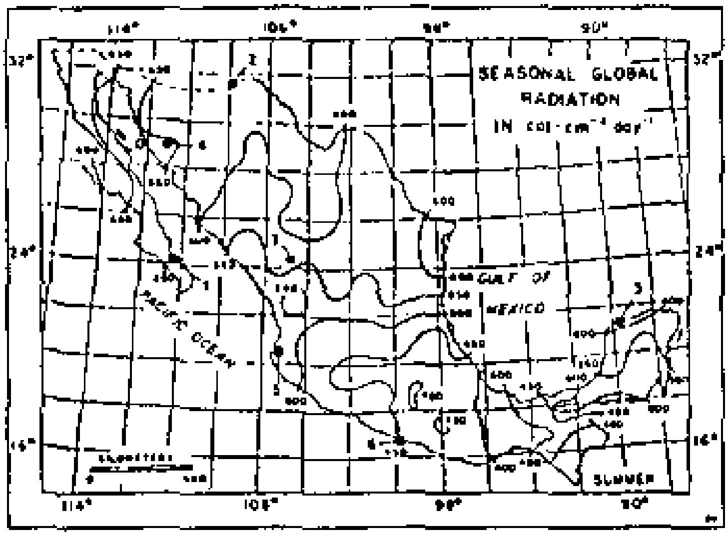
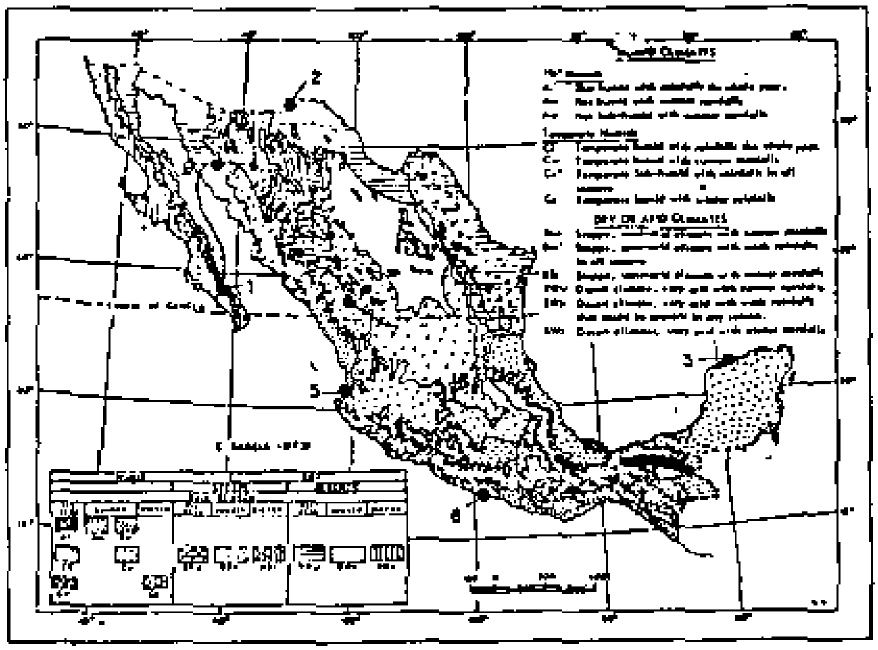


FIGURE 3

Global Radiation During Summer

FIGURE 4

Climate of Mexico



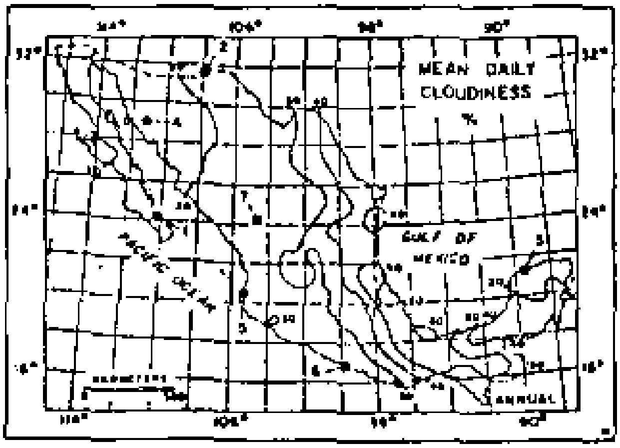


FIGURE 5

Cloudiness in Mexico

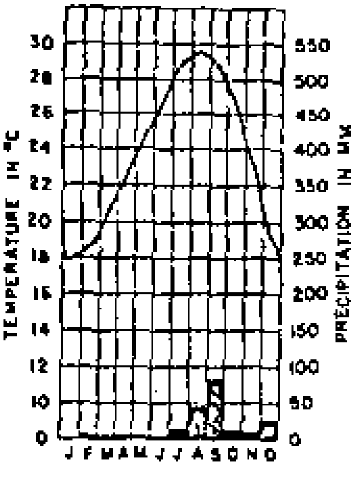


FIG. 6

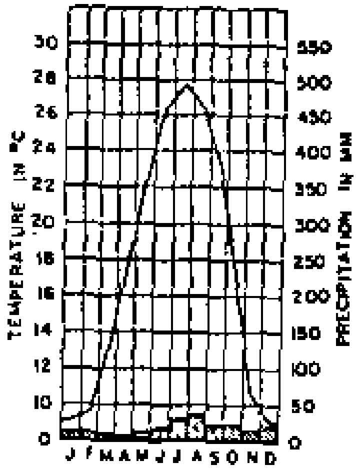


FIG. 7

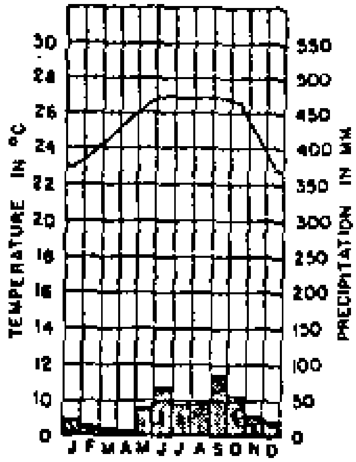


FIG. 8

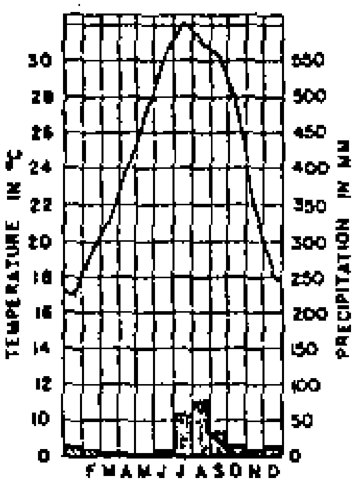


FIG. 9

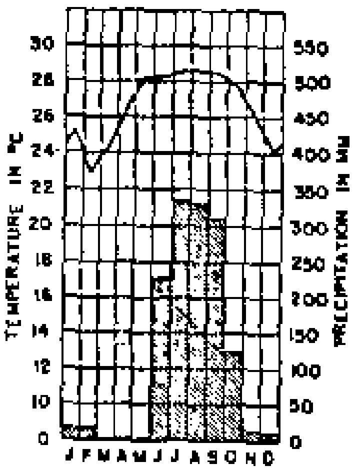


FIG. 10

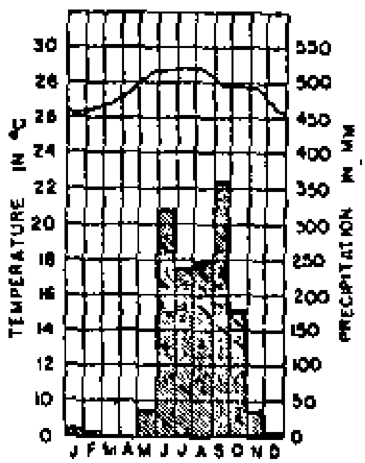


FIG. 11

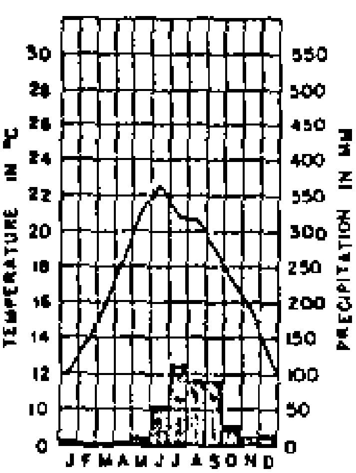


FIG. 12

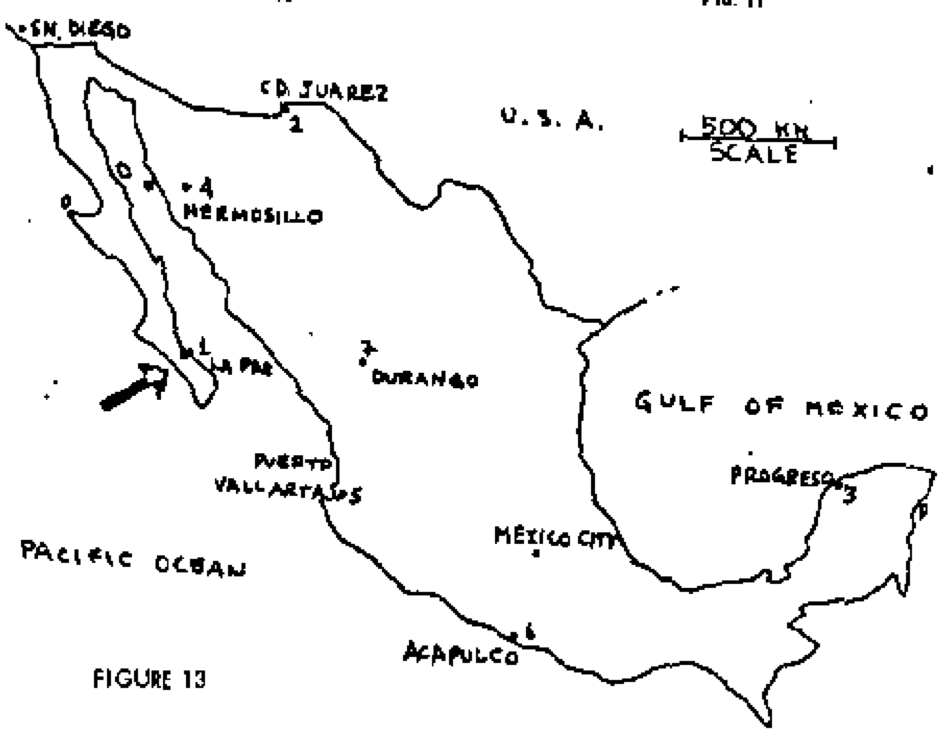


FIGURE 13

SUN

Mankind's Future Source of Energy

Proceedings of the International Solar Energy Society Congress
New Delhi, India—January 1978

Edited by Francis de Winter and Michael Cox

Pergamon

Volume Two

ANTICONVECTIVE ANTIRADIATIVE SYSTEMS

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ABSTRACT

The development of solar collectors has become of great interest. The efficiency and cost have been reported. At the same time, with the widespread use of computers new methods to improve design characteristics have been used. In this paper, a computer model of a flat plate collector with or without anticonvective-antiradiative system (honeycomb) is presented. The model can simulate a flat plate collector with one or more covers and with or without selective surfaces. The test simulated is that proposed by the National Bureau of Standards (U.S.A.) (2), where collector efficiency is plotted as a function of $(T_P-T_A)/I$ (°C m²/w), where, T_P, T_A are the absorber plate and ambient temperatures respectively a I is the incident radiation. It is also possible to simulate a working day for the collector, however, in this case some experimental data is needed as input data for the model.

INTRODUCTION

In the last few years, the development of solar collectors has become of great interest to researchers; new systems to improve collector efficiency have been tested and a good deal of information has been published. In this paper, the results from a mathematical model of a collector with an anticonvective-antiradiative system (honeycomb) are analyzed and compared with the corresponding ones for a normal collector (without honeycomb).

It is planned to build a flat plate collector with a honeycomb system operating with good efficiency within the range of 80 to 100°C.

Optimization of the collectors performance can be obtained through the mathematical model presented in this paper. This model takes into account factors such as: the use of selective surfaces, the use of one or more covers (up to three). The absorption by the medium between the covers and the characteristic of the honeycomb system. A detailed description of the model is given in (1).

A simplified flow diagram of the computer program is given in Figure 1. An iterative process to determine the absorber plate and cover temperatures was followed; an energy balance at the absorber plate and cover (or covers) is performed to determine the steady state.

In order to evaluate the honeycomb performance, collector efficiency is calculated and compared with the calculated value for a collector without honeycomb. The model computes the absorber plate and cover (or covers) temperatures and the heat transfer within the system by considering different heat transfer mechanisms. For the collector with honeycomb, it is possible to obtain information for different L/D (length/diameter) ratios of the honeycomb cells, provided the transmisitivity for a given L/D is known.

The collector simulated by the model without honeycomb has the following design characteristics: A flat plate with high thermal conductivity. Under this plate, there are welded a number of parallel pipes through which the working fluid circulates carrying away the energy collected by the absorber plate. The absorber plate and pipes are back covered by a thick layer of insulating material. On top of the absorber plate, there is, at least, one cover made of transparent material to the visible wavelength and at the same time, opaque to the infrared (i.e. glass). The collector with the honeycomb, has the same design characteristics as the one previously described, with the exception that a honeycomb is installed between the absorber plate and the first cover.

In order to evaluate collectors performance, a standard test proposed by the National Bureau of Standards (U.S.A.) (2) was simulated. The simulated test has as input data: (besides the design characteristics given in Figure 2), radiation intensity, flow rate, ambient temperature and wind speed. During the test these quantities remain constant.

The inlet fluid temperature is given, but varies during the test from a value close to ambient temperature up to a value where collector efficiency is neglegible. For the computer run the variation is linear, however this does not impose any restriction. This data is represented by an efficiency vs $(T_p-T_a)/I$ plot where T_p, T_a are the absorber plate and ambient temperatures respectively and I is the radiation intensity reaching the collector surface.

The following computer runs were done for the NBS test:

1. A collector with one cover (cover thickness = 0.3 cm), with non-selective surface (ε=0.9) with or without honeycomb (L/D=5).
2. A collector with one cover (cover thickness=0.3 cm) with selective surface (ε=0.1) with or without honeycomb (L/D=5).
3. A collector with two covers (both cover thicknesses = 0.3 cm), with non-selective surface (ε=0.9), with or without honeycomb (L/D=5).
4. A collector with two covers (both covers thicknesses = 0.3 cm), with selective surface (ε=0.1) with or without honeycomb (L/D=0.5).

A similar set of runs was made for a cover 0.6 cm. thick and this was compared with the first set of runs.

Figures 3 and 4 show the efficiency vs $(T_p-T_A)/I$ for the set of runs with covers' thickness of 0.3 cm. From the plots, the effect of the following factors: number of covers, selective surface and honeycomb over the efficiency can be seen. The absorber plate temperatures shown in the figures are the points where two collectors have the same efficiency. From these plo plots, information about the collector characteristic can be obtain, depending in the temperature range where the collector is going to operate. It is clear from these plots, that the honeycomb system is quite effective in reducing the heat losses, and also it can be seen how the two covers system works to reduce heat losses at certain temperature levels.

Another type of information provided by the model is shown in Figure 5. The total heat losses for the collectors represented in Figure 3 (i.e. collector without selective surface) are plotted as a function of the absorber plate temperature; the same trend shown in Figure 3 is shown here.

For a cover thickness of 0.6 cm., the efficiency vs $(T_p-T_a)/I$ plots show similar behavior, Figure 6. The efficiency curves for cover thicknesses of 0.3 cm. and 0.6 cm are shown, only to give an idea how much an increase in thickness decreases collector efficiency.

A run was made to simulate the performance of the collector during a normal working day, assuming inlet fluid temperature, flow rate and radiation intensity distributions for the day. Figure 7 shows the efficiency vs time plot for a collector without honeycomb compared with experimental data. The difference between these curves shows, to some extent, the limitations of the model.

The efficiency curve for a collector with honeycomb is also shown in Figure 7, the curve has to be interpreted with some reservations, because due to the lack of experimental data, some of the input data used, was taken from the collector without honeycomb, however it seems that the general trend of the results agrees with the expected results.

CONCLUSIONS

With the model it is possible to simulate the performance of a flat plate solar collector with or without an anticonvective-antiradiative system (honeycomb), with or without selective surface and with one or more covers.

For the design of a flat plate collector several runs could be made to study the influence of the geometry and the material properties in the collectors performance taking into account the working temperature range. The NBS test can be taken as a standard to compare the results of the different designs.

Due to the lack of experimental data available for the anticonvective-antiradiative systems, this model can be used to simulate those systems. The advantages of the use of these systems are clear from the efficiency vs $(T_p-T_a)/I$ plots presented here.

The model can also simulate a working day for the collector, however, for this case some experimental data is needed as input data.

REFERENCES

1. R. Herrera, Thesis, National University of Mexico (UNAM) "Simulación Digital de un Sistema Anticonvectivo Antiradiativo en Colectores Solares Planos", 1977.

7. N.B.S. Technical Note 899. "Development of Proposed Standars for Testing Solar Collectors and Thermal Storage Devices." U. S. Department of Commerce (National Bureau of Standars), February 1976.

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FIGURE 1

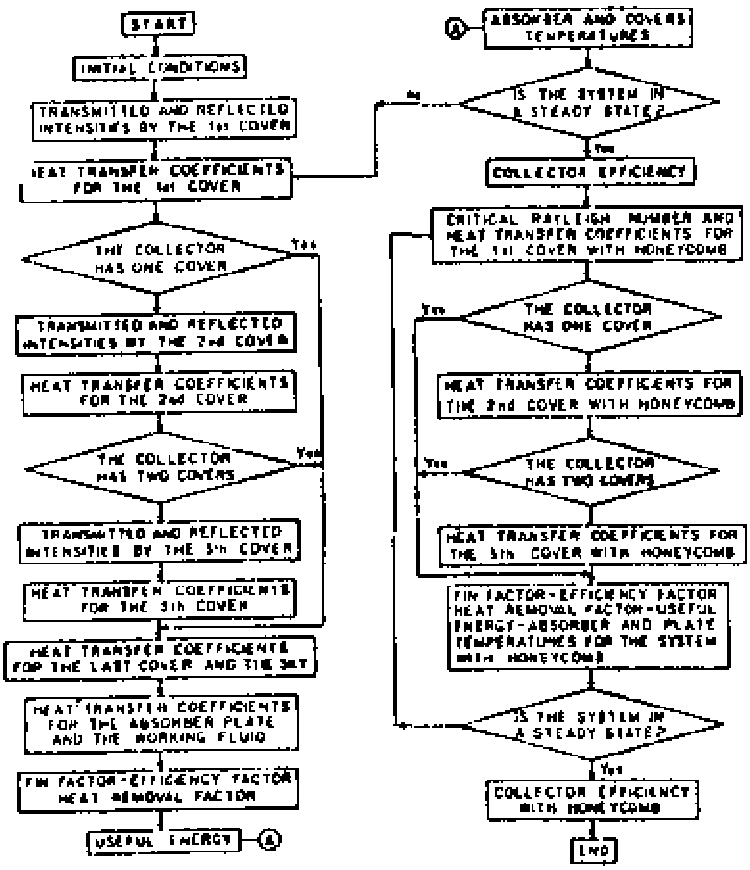


FIGURE 2

Collector Surface = $0.69 m^2$

Number of Pipes = 28

Pipe Length = $0.78 m^2$

Pipe Cross Section = 0.03 m x 0.015 m

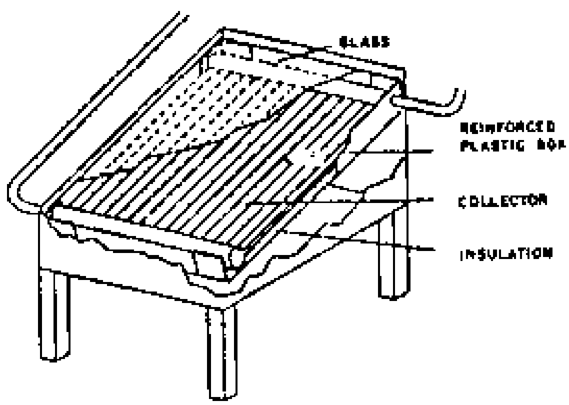
Pipe thickness = 0.1 m

Insulation Thermal Conductivity = 0.036 w/m°C

Cover Thickness = 0.003 m

Cover Index of Refraction = 1.53

Cover Extinsion Coefficient = $0.0165 m^{-1}$



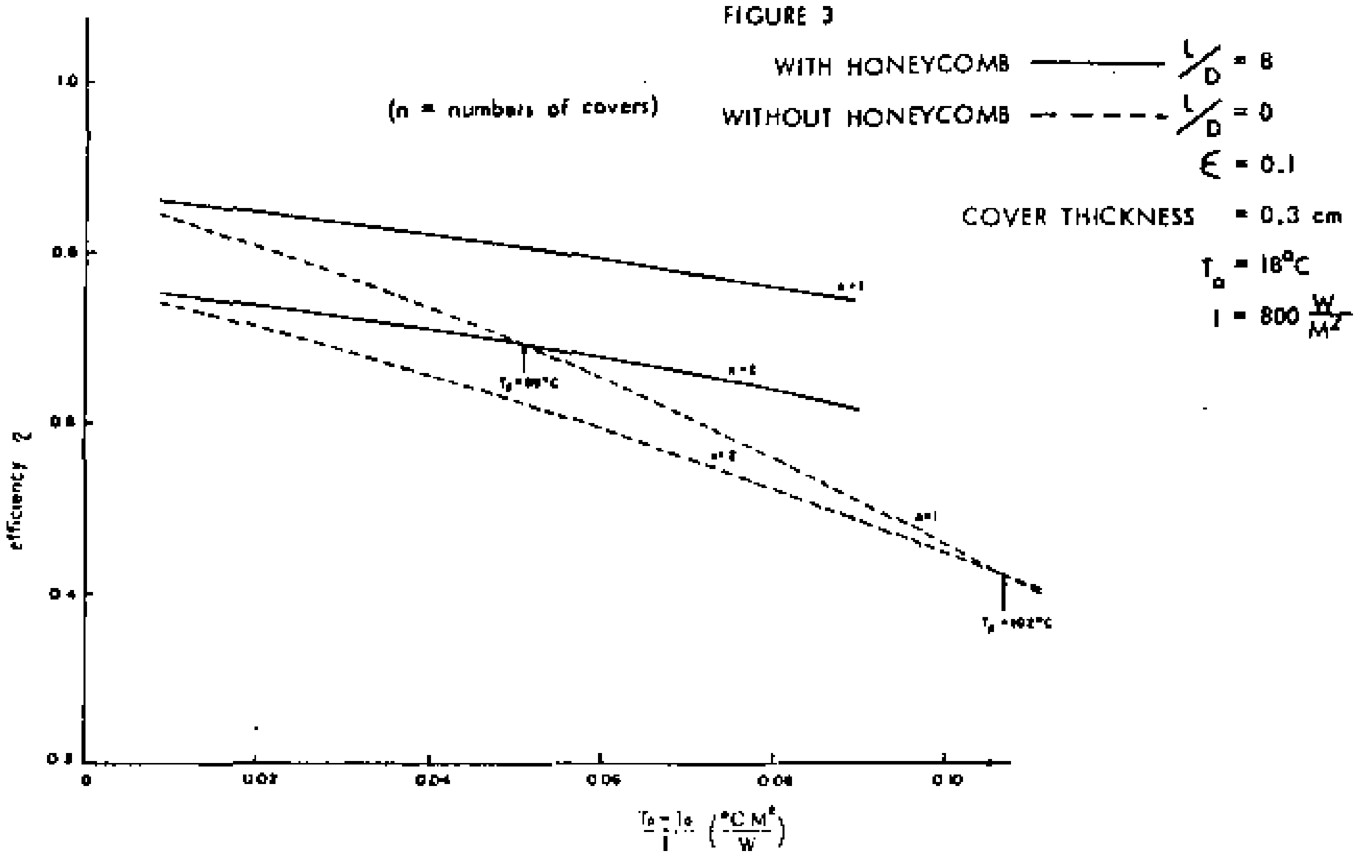
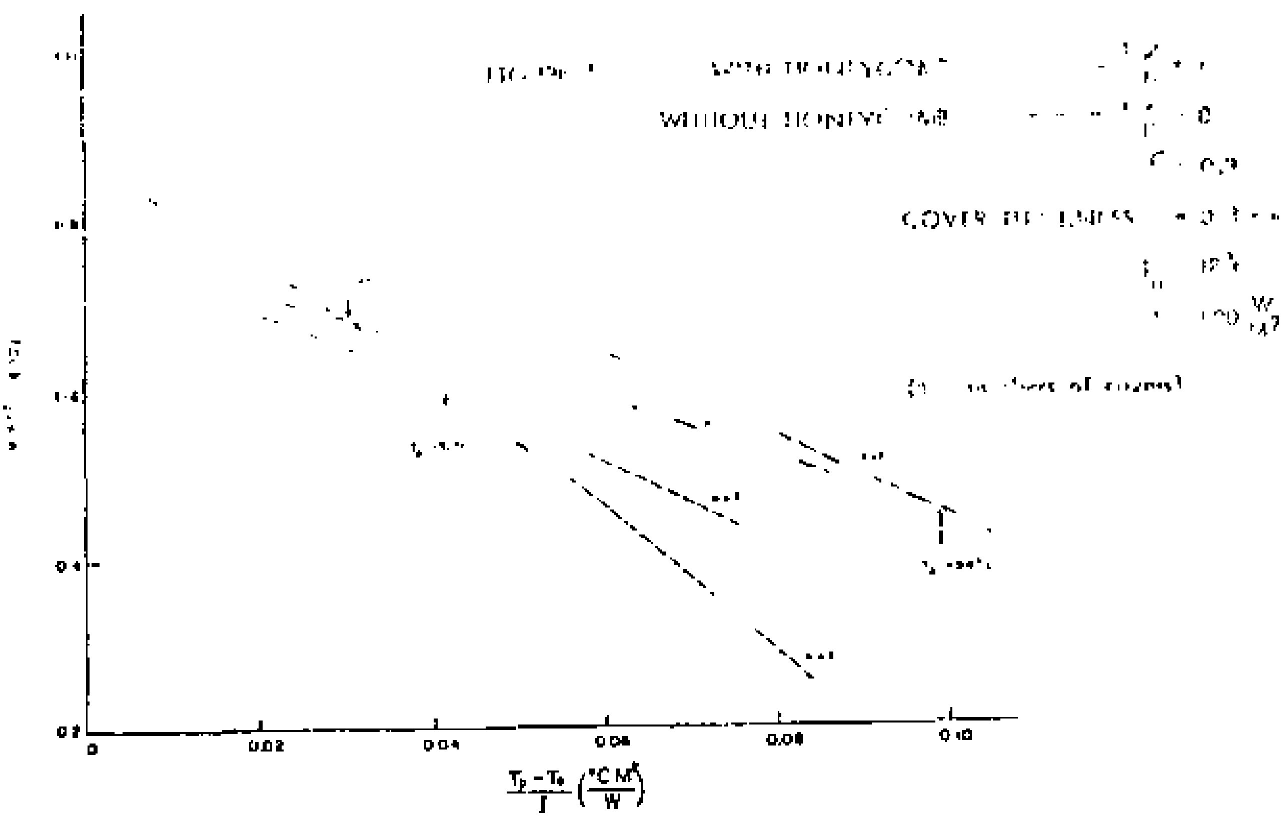


FIGURE 3
WITH HONEYCOMB L/D = 8
WITHOUT HONEYCOMB L/D = 0
ε = 0.1
COVER THICKNESS = 0.3 cm
T_a = 18°C
I = 800 W/M²
(n = numbers of covers)
efficiency η
0
0.02
0.04
0.06
0.08
0.10
1.0
0.8
0.6
0.4


WITHOUT HONEYCOMB
COVER
0
0.02
0.04
0.06
0.08
0.10

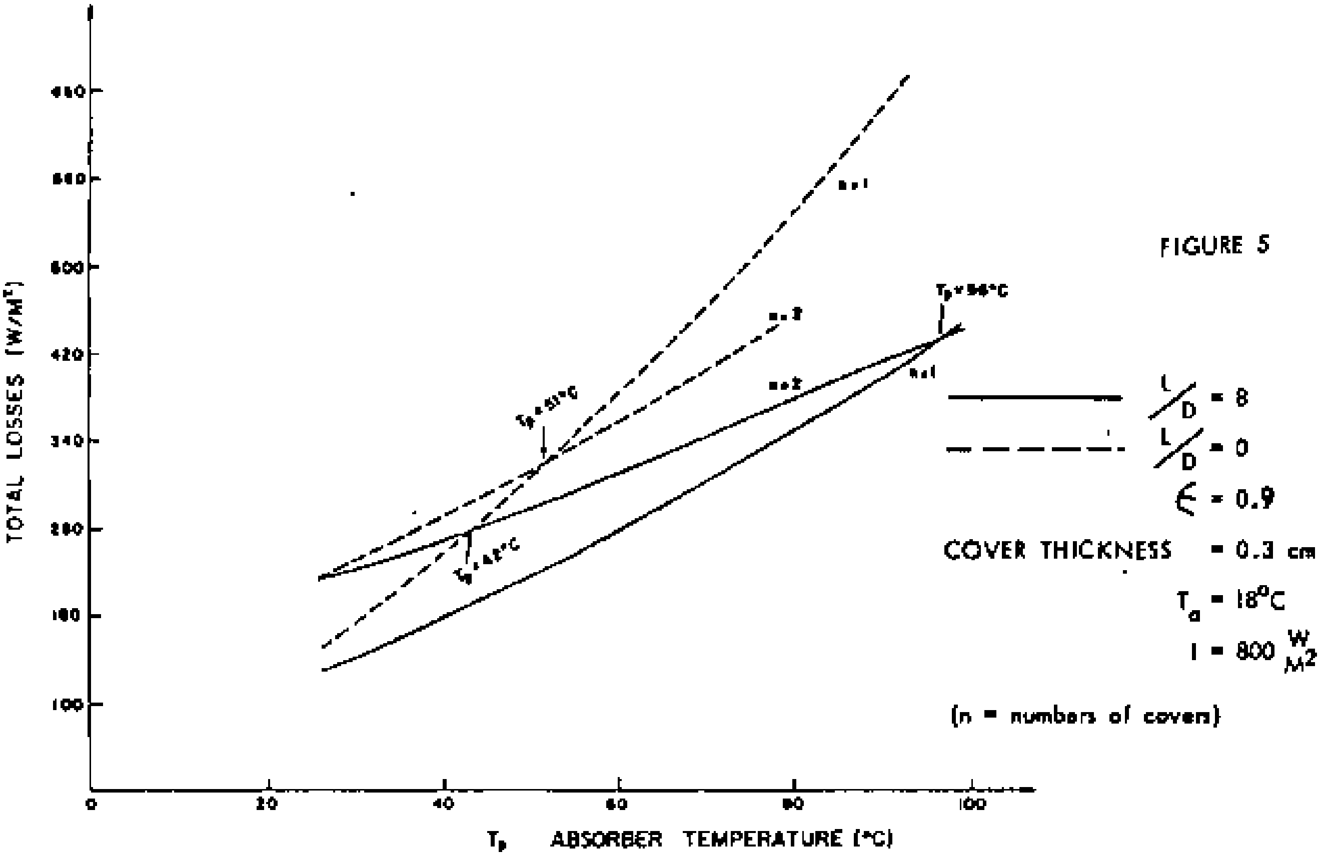


FIGURE 5

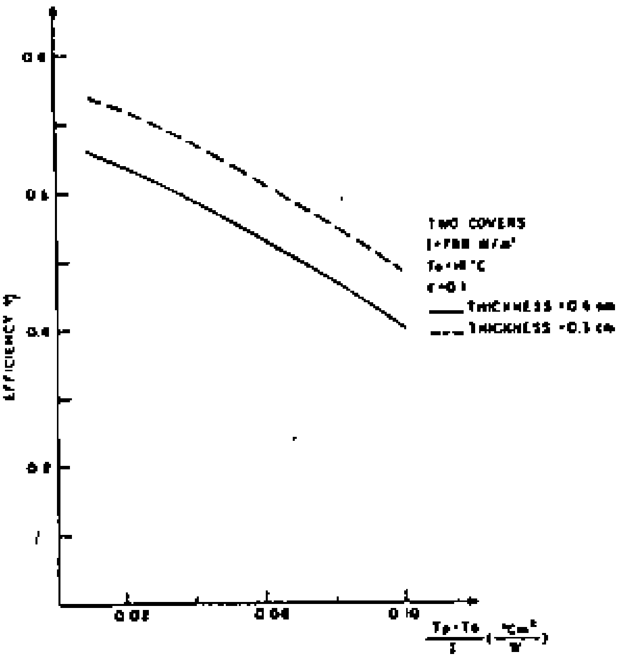


FIGURE 6

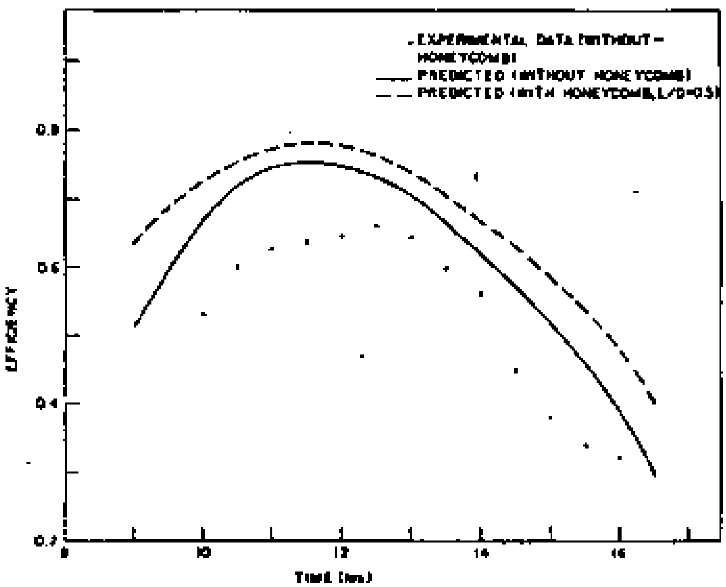


FIGURE 7

WORLD METEOROLOGICAL ORGANIZATION

UNESCO/WORL METEOROLOGICAL ORGANIZATION INTERNATIONAL

SOLAR ENERGY SYMPOSIUM

GENEVA SWITZERLAND

SEPTEMBER 1976

ON THE NUMERICAL COMPUTATION OF SOLAR RADIATION PARAMETERS FROM SATELLITE CLOUD DATA

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ABSTRACT

Three years of satellite cloud cover data, have been used to estimate the monthly and annual mean values of the duration and intensity of insolation at 117 regions of Mexico. With only the knowledge of the monthly and annual regional percentages of cloudless and partially cloudy days, an approximation was done of the monthly and annual mean values of the relative duration of insolation. The Fritz formulae have been used to obtain the maximum global radiation that can be expected in cloudless days. Both, the relative duration of insolation, and the maximum global radiation values, were related to interpolated values of the quasi-linear approximation of Ångström's equation, as suggested by P. de Brichambaut and G. Lamboley. The obtained monthly and annual mean values of the real global radiation were mapped. The corresponding isoradiation lines show countours that have a remarkable continuity with those found by Bennett for the United States of America. The results obtained enable a study of the best place-time areas for the future development of solar energy applications and pretend to be a contribution to the knowledge of the solar climatology of the country.

Introduction.

Whereas the irregular world distribution of oilfields and waterfalls have allowed only a few countries to reach a high rate of development, the world distribution of solar energy on the earth's surface is fortunatelly more uniform. Moreover, if we consider that the best insolated areas correspond to the less developed countries, for which the scarce energy resources represents at present their main limiting factor of development, harnessing solar energy in these undeveloped countries represents a feasible solution to their energy shortage problem. Nevertheless, design of solar energy equipment involves a through knowledge of insolation characteristics which unfortunately is very often limited.

The quantitative determination of global radiation, i.e. The incoming solar short wave ($2 \div 3\mu$) radiation (in direct and diffuse form) over an horizontal plane at the earth's surface level, can be done with the aid of intensity, or at least, with duration of insolation records. These must be systematically taken over a long period of time and with enough accuracy. Considering that even the micro-climate of a place, which generally does not exceed extensions of more than one square kilometer, could be completely different from that of the surrounding meso-climate, or regional climate, therefore the solar climate of a place may be different from another not very distant, even more, if orographic irregularities exist. Regionally speaking, a solar climatological study depends on a well distributed network of stations continously collecting the required insolation data. The dimensions of the network depends directly on the size of the region under study but due to the high cost of the pyrheliometric instrumentation this size must be restricted.

Global Radiation Obtention.

After A. Ångström[1,2] (1924), several investigators have developed empirical formulae to evaluate global radiation. Parametrization of duration of insolation and cloudiness are commonly carried out. As was previously mentioned, evaluation of global radiation necessitates at least of insolation records. In this paper, replacement of these data have been achieved by means of data on cloudy and partially cloudy days. In a recent paper by E. Mendoza, J. Luna, and T. Gómez,[3] the monthly and annual percentages of regional cloudiness in Mexico were reported. These values were obtained by interpreting three years (1969-71) of cloud cover photographs (APT) from the Nimbus III and ESSA-8 meteorological satellites. The whole country was divided in a network of 117 squares (each one of 130 Km long per side, approximately).

Inside each square a regional reference town was assigned. In order to obtain the monthly and annual mean daily values of real global radiation, the formulae summarized in the flow chart of figure 1 has been followed. The curve used to interpolate the values of $\overline{Q}$ has been adapted from the given ratios of $\overline{Q}/\overline{Q}$ max and $\overline{S}/\overline{S}$ max, suggested by P. de Brichambaut and G. Lamboley[5]. (Figure 2).

The computed monthly and annual mean daily values of real global radiation, were mapped as can be seen from figures 3 to 15. The annual distribution of insolation can be summarized as follows: 30 percent of the national extension (total area 1,972,547 Km^2) corresponds to regions with more than 500 cal. cm^{-2} day^{-1}, 57 percent correspond to regions between 500 and 400 cal. cm^{-2} day^{-1}, and 5 percent correspond to regions with less than 400 cal. cm^{-2} day^{-1}. The annually best insolated zones are: Peninsula of Baja California, the West of Chihuahua, almost all Sinaloa, Nayarit, the West of Jalisco, Michoacán (except the Northwest), almost all Guerrero, the Southwest of Oaxaca, the North of Yucatán, and the Northeast of Quintana Roo. The results obtained could only be compared with a few pyrheliometric measurements existing in Mexico and corresponding to the same 1969-71 period as the cloudiness data[6]. The annual computed value at the Mexico City region, shown only a 6 percent difference with respect to those reported by the pyrheliometric station .

When the computed values of $\overline{Q}$ at frontier Mexican regions were compared with those neighbouring localities at the United States of America[7], only small differences were found, For instance; between Brownsville, Tex. (U.S.A.) and

Matamoros, Tam. (Mex.) the difference was of 1.5 percent, between Yuma, Ariz. (U.S.A.) and Mexicali, B.C.N. (Mex.) it was of 2.5 percent . Similarly, the iso-radiation lines betwen Mexico and U.S.A., shown a good continuity. Because the cloudiness data used in this study, does not correspond to specific localities but to regions, interpretation of the computed results must be considered as mean regional values. Taking into account that 95 percent of the country extention, annualy receives more than 400 cal. cm^{-2} day^{-1}, the panorama of solar energy utilization in Mexico is excellent. Thus, this paper attempts also to enliven the attention of all those who are interested in a clean energy resource which can to improve, the now-a-days critical, world ecologic equilibrium.

Acknowledgements.

The author is endebted to Dr. E. Mayer, Dr. E. Mendoza, and Math. J. Luna of the National University of Mexico for their helpful comments. Also to Mr. H. Cortez for inking the maps and to Miss M. Spíndola for the transcription of the manuscript. All the computations were carried out at the Centro de Servicios de Computo of the National University of Mexico.

References.

1. Ångström, A., 1924. Solar and terrestial radiation, Quart. J. Roy. Meteorol. Soc., Vol. 50, P.P. 121-125.

2. Ångström, A., 1956. On the computation of global radiation from records of sunshine, Arkiv för Geopysik, band 2, Nr22, P.P. 471-479.

3. Mendoza, E.; Luna, J., and Gomez, T.; 1972, A Study of cloudiness in Mexico through meteorologicall satellites, Bol. de Obs. de Tonantzintla y Tacubaya, Num. 38, V. 6., P. P. 215-227.

4. Fritz, S., Feb. 1957. Solar energy on clear and cloudy days, The Scientific Monthly, P.P. 55-65.

5. Brichambaut, P. de; Lamboley, G., 1968. Cahiers de l'A.F.E.D.E.S., Vol. 1, Editions Europeennes. "Thermique et Industrie", Paris 13e. P.86.

6. Solar Radiation and Radiation Balance Data (The worldnetwork), USSR Chief Administration of Hydrometeorological Service, Leningrad 1969, 1970, 1971.

7. Bennett, I.; 1965, Monthly Maps of Mean Daily Insolation for the United States, Solar Energy, Vol. 9, No. 3, P.P. 145-158.

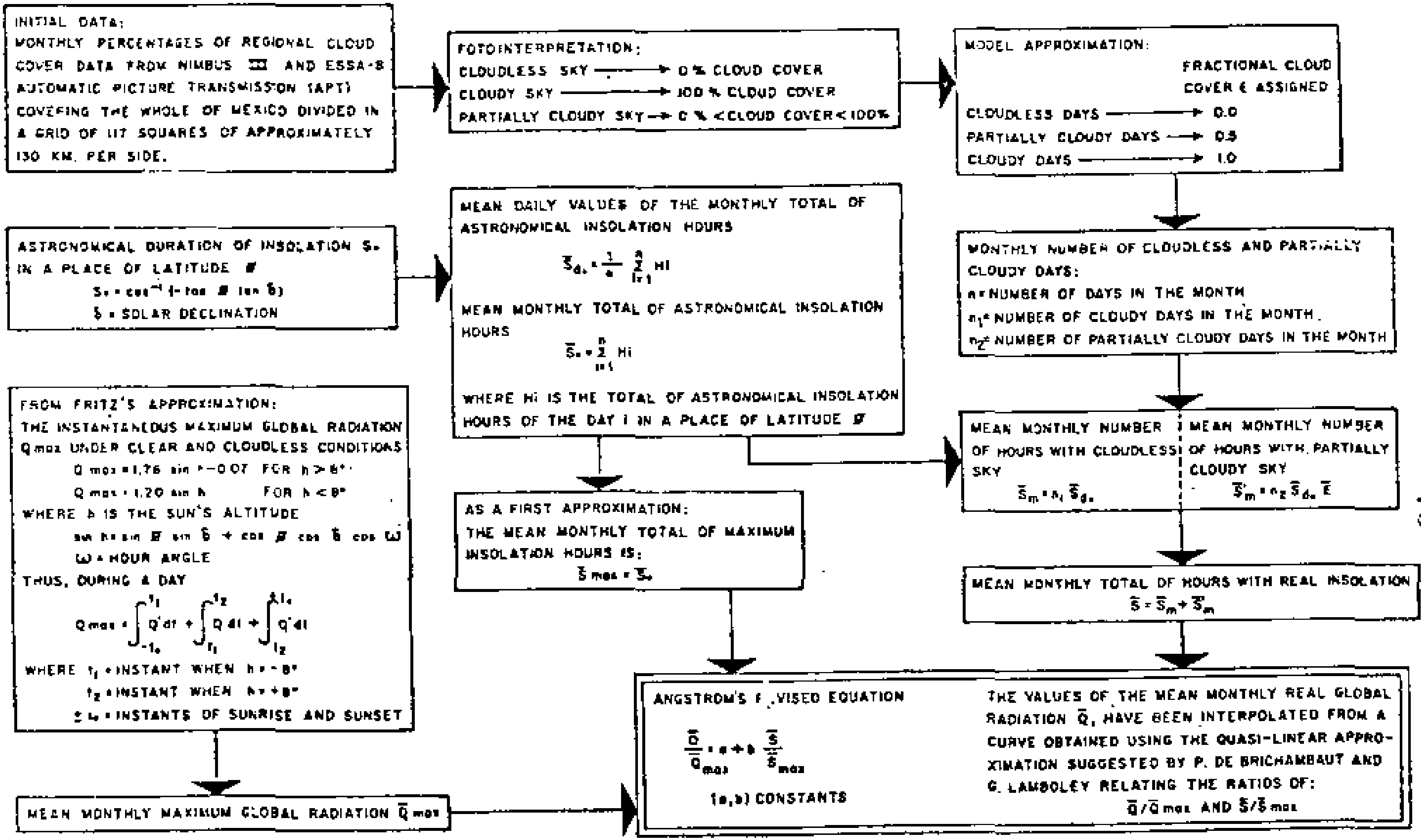
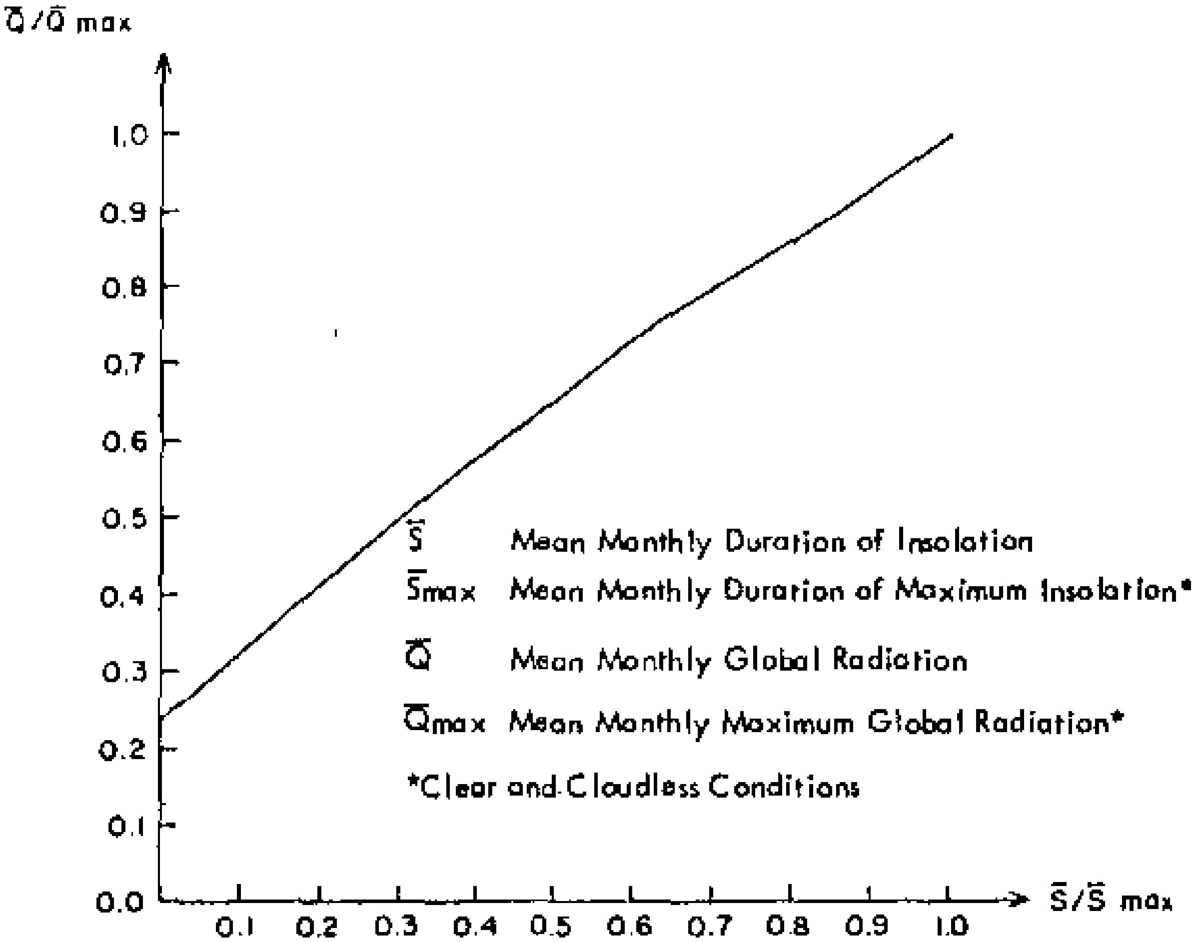
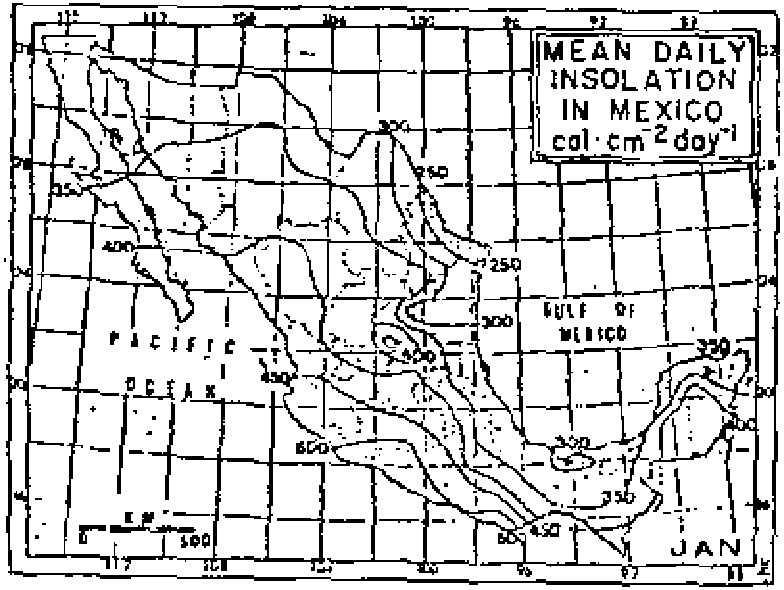


Fig. 1. Mathematical method flow chart

Fig. 2. Relationship between relative global radiation and relative duration of insolation (curve adapted after P. de Brichambaut and G. Lamboley).




MEAN DAILY INSOLATION IN MEXICO
$cal \cdot cm^{-2} day^{-1}$
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PACIFIC OCEAN
KM
0 500
300
250
300
350
400
450
500
JAN


MEAN DAILY INSOLATION IN MEXICO
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PACIFIC OCEAN
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0 500
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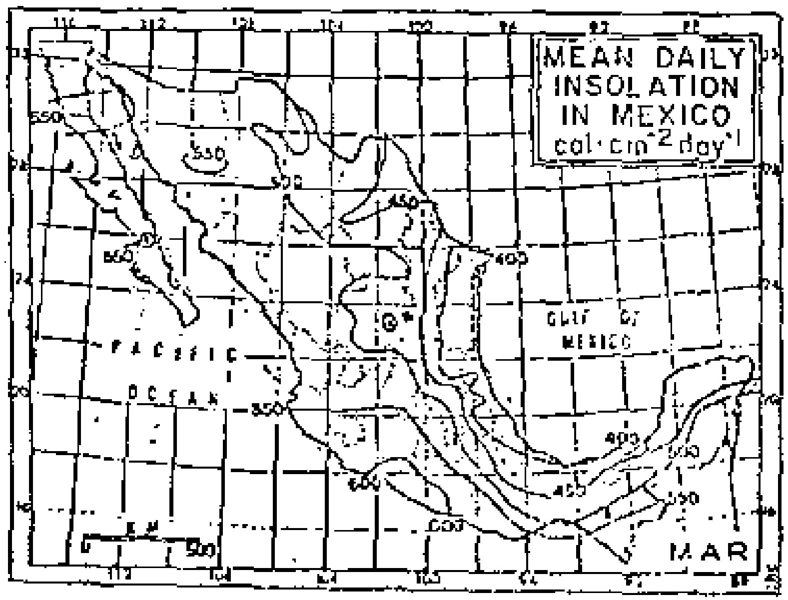
500
FEB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400
MAR


MEAN DAILY INSOLATION IN MEXICO
$cal \cdot cm^{-2} day^{-1}$
GULF OF MEXICO
PACIFIC OCEAN
KM
0 500
600
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MEAN DAILY INSOLATION IN MEXICO cal·cm^{-2}day^{-1}
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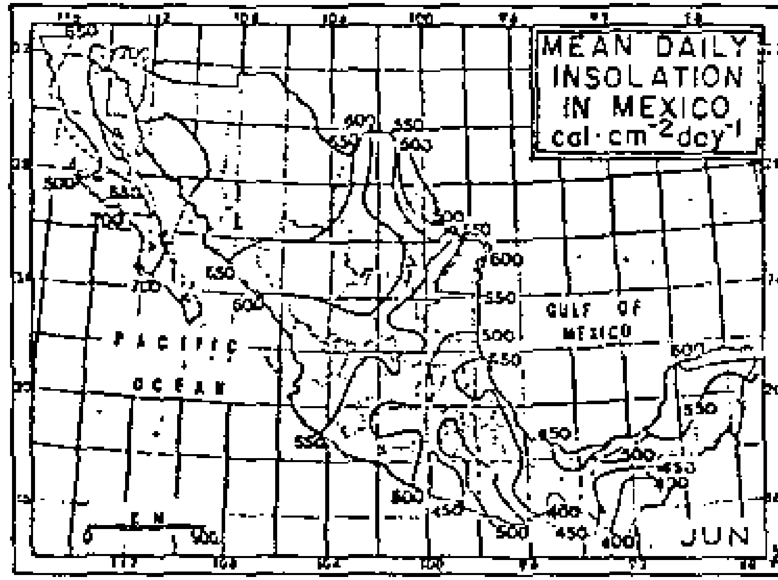
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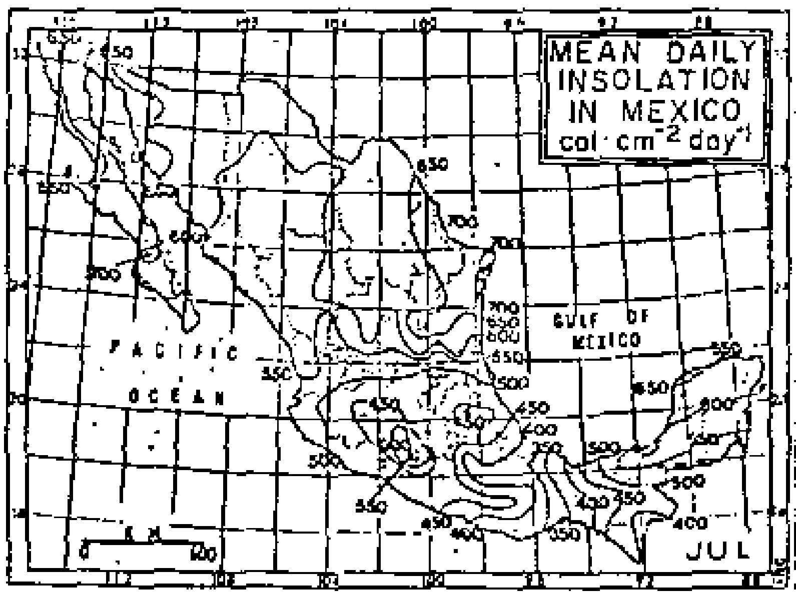
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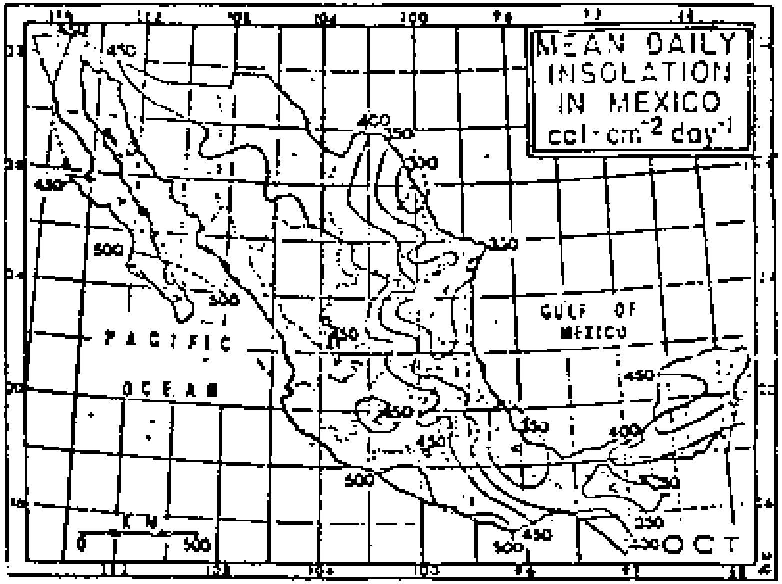
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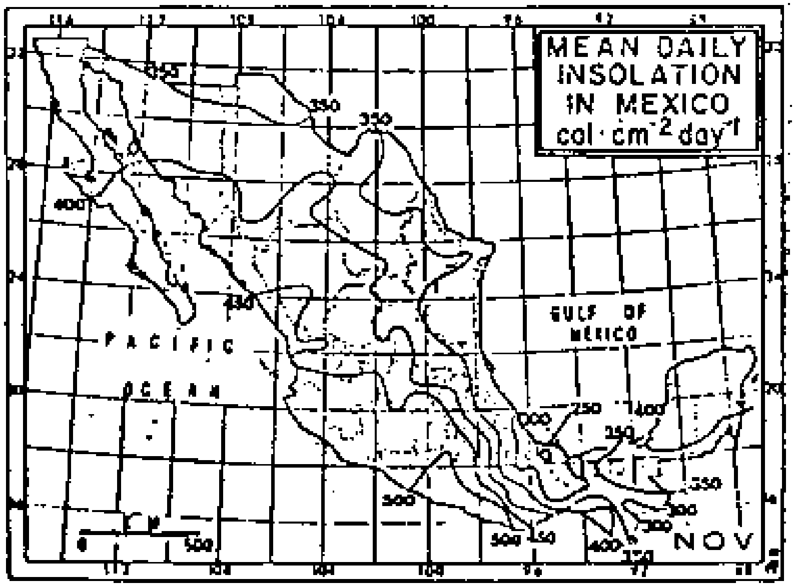
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$cal \cdot cm^{-2} day^{-1}$
GULF OF MEXICO
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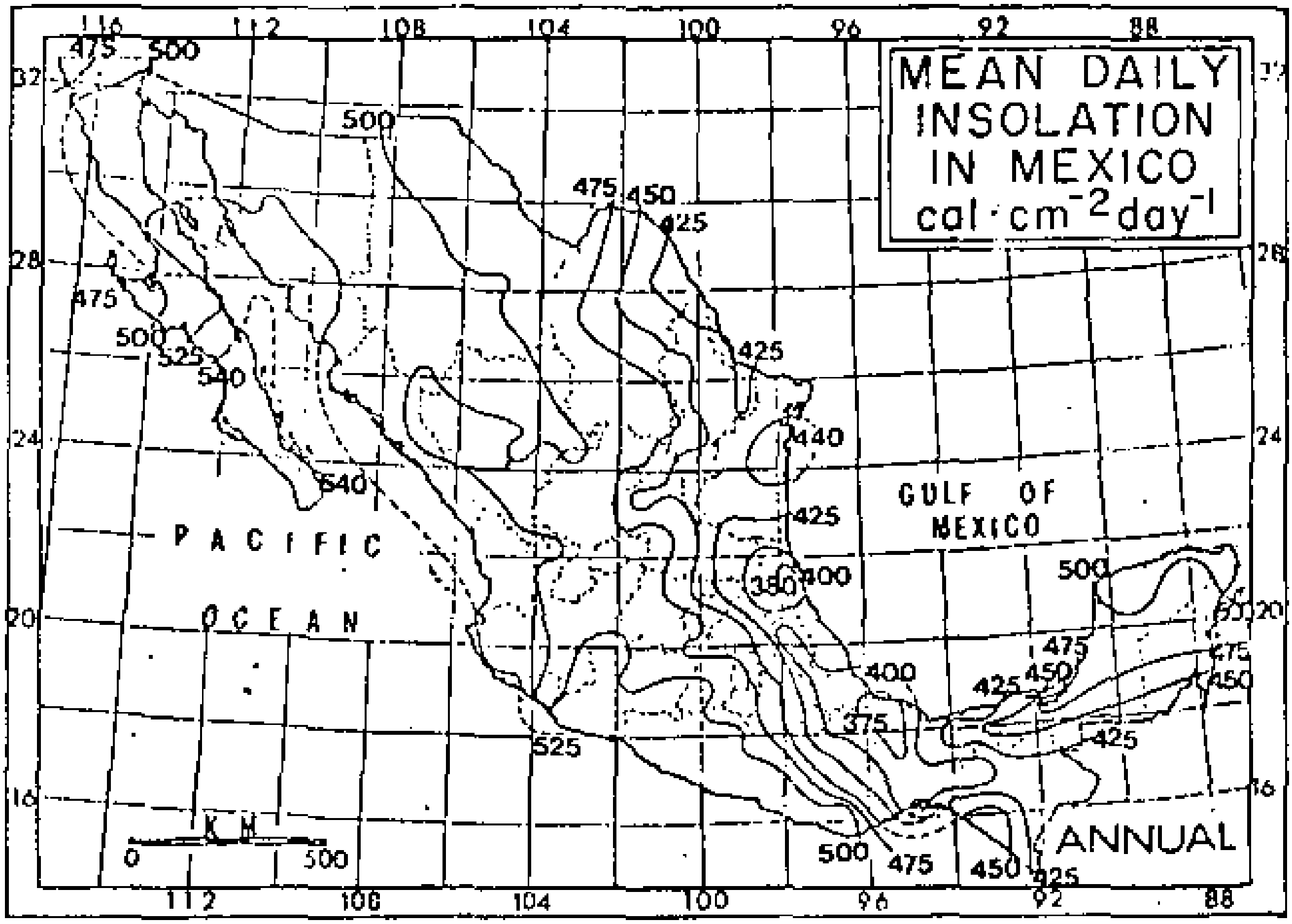
DEC


MEAN DAILY INSOLATION IN MEXICO cal·cm-2 day-1
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100
96
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32
28
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20
16
475
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525
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450
425
440
400
380
375

VOLUME ONE
TOPICS COVERED IN SECTIONS 1-13
SOLAR COLLECTORS
HEATING AND COOLING SYSTEMS

PROCEEDINGS OF THE 1977 ANNUAL MEETING

ORLANDO, FLORIDA / JUNE 6-10, 1977

AMERICAN SECTION OF THE INTERNATIONAL SOLAR ENERGY SOCIETY

SELECTING OPTIMUM TILTS FOR SOLAR COLLECTORS AS A FUNCTION OF CLOUDINESS .

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ABSTRACT

As it is well known, in order to reach the maximum insolation on fixed solar collectors during the year, these are generally tilted toward the equator at an angle which depends on the latitude of the place.

From pure geometrical considerations between the daily sun's path above the horizon and the collector orientation, it can be easily demonstrated that the optimum tilt angle is equal to the latitude of the place. However, this determination is not always the best as commonly has been suggested due to cloudiness.

Cloudiness may reach considerable values during those periods of the year of high sun altitudes in which the maximum annual insolation would be expected if the sky were cloudless.

In this paper, the optimum tilt angle to collect the maximum energy during the year is obtained through a mean weighted optimum tilt, which besides of the sun's altitudes includes the effect of regional cloudiness.

The intensity of real insolation on the collector, is monthly and seasonally examined. The comparison of the computed optimum tilt angles, shows a dependence on the annual distribution of the cloud cover.

INTRODUCTION

The effect of the tilt angle on a solar collector has its main influence in the amount of energy intercepted.

The importance of cloudiness in selecting optimum tilt angles in particular for fixed panels, is generally ignored notwithstanding that this meteorological phenomenon produces the major attenuation of solar energy reaching the earth's surface.

In most of the cases the selected tilt angle at a place of latitude ϕ, arises from pure geometrical considerations. These are based on the semiannual shifting of the sun in the sky to the north and south respectively.

It is trivial that the maximum amount of solar energy that could be intercepted by a collector will occur when it is normally oriented towards the incoming solar flux. However in the case of stationary collectors a fixed optimum tilt angle must be selected.

It is a fact that the most widely tilt angle used at the present time is that which has been long time suggested in literature and which is equal- or almost equal- to the latitude of the place. However, due to cloudiness, this proposed angle may be inadequate as will be seen from the real cloud cover conditions determined for serveral sites in Mexico

In this paper a method for determining an optimum tilt angle which includes the effect of regional cloudiness is developed. Although the random nature of cloudiness, there is a climatological well defined pattern of it during the year whose knowledge allows the calculation of the tilt angle for fixed solar collectors.

OPTIMUM TILT ANGLE AS OBTAINED FROM GEOMETRICAL CONSIDERATIONS ONLY

The closer to the normal of the collector surface is the incoming radiation, the greater the energy intercepted will be sc[illegible] us examine what happens for a fixed panel.

First it is convenient to describe the angles involved in the mathematical expressions derived from the nature of the problem.

The apparent motion of the sun in the sky and related angles, can be seen from the celestial sphere of figure 1 in which an observer is located at O, and the main angles are the following:

- ϕ latitude
- δ solar declination
- h solar altitude above the horizon
- Z Zenith
- o azimuth
- Z' nadir
- α Zenital altitude
- ω hour angle
- γ colatitude
- β complement of δ

By applying the law of the cosines to the spherical triangle KZP formed by the position vectors $\vec{a}$, $\vec{b}$ and $\vec{c}$, it can be easily obtained the following expression:

$$\sin h = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad (1)$$

This means that the altitude of the sun above the horizon depends on three basic angles; one of them, the latitude (ϕ) is fixed; the solar declination (δ) changes its value slowly from day to day so that it can be practically considered constant for a one day period; finally the hour angle (ω) changes continuosly during the day (15° per hour).

The relationship between the normally incident solar flux In at an angle h respect to horizontal and the flux I_H falling on a horizontal plane A_H can be written as:

$$I_N A = I_H A_H \qquad (2)$$

where:

$$A = A_H \ \sin h$$

then:

I_H becomes: $I_H = I \sin h \qquad (3)$

Neglecting the effect of the atmosphere, the daily amount of solar energy falling on an horizontal surface can be expressed as:

$$Q_H = \frac{I_o}{R^{*2}} \int_{t_o}^{t_o} \sin h \, dt \qquad (4)$$

where:

I_o is the solar constant, whose value is

$I_o = 1.94 \text{ cal cm}^{-2} \text{ day}^{-1} = 1453 \text{ watt m}^{-2}$

R^*, is the correction factor for the Earth-Sun distance defined as:

$$R^* = \frac{R}{R_o} \qquad (5)$$

where:

R_o, is the mean and R, any arbitrary Earth-Sun distance.

If the hour angle is expressed in terms of both the Earth rotation period and the time t' elapsed since noon, we obtain:

$$\omega = \frac{2\pi t'}{\tau} \qquad (6)$$

then by sustitution of equations (1) and (4) and integrating, Q_H can be expressed as:

$$Q_H = f \frac{I_o}{R^{*2}} \ t_o \sin\phi \sin\delta + \frac{\tau}{2\pi} \cos\phi \cos\delta \sin\frac{2\pi t_o}{\tau} \qquad (7)$$

where:

f: is a constant depending on the scale of units employed. ($= \frac{1}{30}$, for Q_H in cal. $cm^{-2} day^{-1}$,

and:

$f = 38.76 \times 10^{-3}$, for Q_H in Kwh m^{-2} day^{-1}.

To calculate the solar radiation flux incident on a tilted plane (facing to the south in the Northern hemisphere), a geometrical simplification can be used; the direct insolation (Qi) on a tilted plane at an angle i respect to the horizontal in a place of latitude ϕ, is considered equal to the direct insolation striking horizontally (Q_H) at a place of latitude (ϕ-i).

From this, it results that equation (7) may be written as:

$$Qi = K \frac{I_o}{R^{*2}} \ t_o \sin(\phi - i) \sin\delta + \frac{\tau}{2\pi} \cos(\phi - i) \cos\delta \ \sin\frac{2\pi t_o}{\tau} \qquad (8)$$

the maximum value of Qi will occur when:

$$\left.\frac{dQi}{di}\right|_{i=i_o} = 0$$

After differentiating equation (8), settings $\omega_o = \frac{2\pi t_o}{\tau}$, and rearrangement of the terms, i_o results equal to:

$$i_o = \phi - \tan^{-1}\left(\frac{\omega_o \tan\delta}{\sin\omega_o}\right) \qquad (9)$$

During the whole year δ fluctuates between:

$$-23° \ 27' \leq \delta \leq + \ 23° \ 27'$$

and the average value occurs at the time of the equinoxes ($\delta = 0°$). At this time, the sunrise and sunset occur exactly on the East-West line, and the corresponding sunrise-sunset hour angle is: $\omega_o = 90°$. Hence the yearly average optimum tilt angle for a fixed solar collector from the geometrical point of view is:

$$i = \phi \qquad (10)$$

Although the daily determination of the cloud distribution in the sky is a random problem, annualy there is a well defined regional pattern which enables us to predict the months or seasons of the year when the sky is more or less cloudy.

Under cloudless conditions, the maximum intensities of the incoming solar radiation will occur at those periods of the year when the sun's altitudes above the horizon are maximum too (minimum optical paths). However if both periods of maximum cloudiness and solar altitudes occur at the same time, the optimum tilt angle obtained only from geometrical considerations will be affected by this weather situation.

Cloudiness is characterized by the fractional (decimal) amount of cloud cover c; so, $c = o$, represent a complete cloudless sky; and $c = 1$, an overcast sky. Now using equation (1), let $\bar{h}$ be the mean monthly value of h and similarly let $\bar{Q}max$ and $\bar{Q}_R$ be respectively, the mean monthly values of the maximum and real global radiation. $\bar{Q}_R$ depends on the daily weather conditions, hence on c. In order to compare the relative importance of cloudiness and solar altitude, we will take into account the amount of incoming energy finally intercepted after its depletion, $\bar{Q}_R$. By relating h and $\bar{Q}_R$ through the following weighted arithmetic mean:

$$\bar{\bar{h}} = \left(\sum_{i=1}^{12} \bar{Q}_{Ri} \ \bar{h}_i\right) / \left(\sum_{i=1}^{12} \bar{Q}_{Ri}\right) \qquad (11)$$

obtain the angle above the horizon at which incoming solar radiation will be annually ma-mum. Thus the optimum position of the panel is tained by setting it perpendicular to this direction. The optimum tilt angle I_r under real average cloudiness condition is then given by:

$$I_r = 90° - \bar{h} \qquad (12)$$

In order to see the difference between I_o and I_r, we have studied the effect of cloudiness at seven places in Mexico. The corresponding values of Q_{max}, $\bar{Q}_R$ and $\bar{E}$ were taken from references (1) and (3) and reported in tables 1 to 7.

The results can be summarized in table 8 where we present the calculated values of I_r compared to the corresponding latitude of each locality. From the results obtained we can see that only at one place (San Luis de la Loma, Gro.) I_r approaches to I_o. In other places there exist some deviation of I_r from I_o although those are relatively small.

CONCLUSIONS:

As we have seen the method proposed does not show a very significant deviation from the generally accepted rule of setting the solar collector at a tilt: $i = \phi$. However we feel that it allows to determine the optimum tilt in a much more realistic way. i.e., under consideration of the main ather factor affecting the incoming solar ra-tion.

Information about cloudiness all over the Mexican Territory will be used all together with the values of the total insolation (3) to find a correlation between the recommended tilt angle for collecting the maximum energy during the year and other geographical and climatic conditions. Such information could be helpful in all countries were a minimum of information is available.

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REFERENCES

(1) Hernández E., Regolado E., (1977) "La Distribución de la Nubosidad Regional en México" publicación del Centro de Investigación de Materiales U.N.A.M.

(2) Thekaekara, M.P., and Drummond, A.J. (1971), "Standard Values for the Solar Constant and its Spectral Components", Nat. Phys. Sci.229, vol. 6.

) Hernández, E. (1976) "On the Numerical Computation of Solar Radiation Parameters satellite Cloud Cover Data", Proceedings of the UNESCO/WMO - Solar Energy Symposium, Geneva, Switzerland.

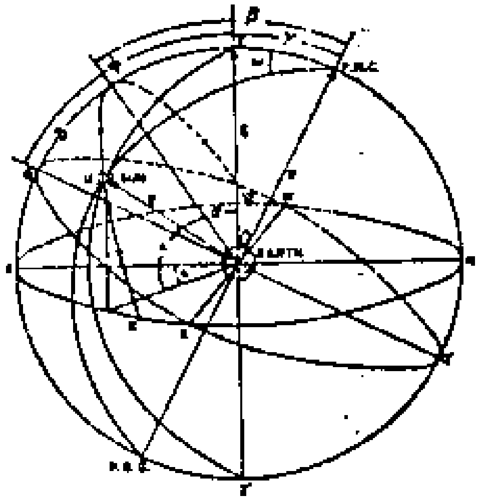

FIG. 1 - PROJECTION ON THE CELESTIAL SPHERE OF THE SUN'S PATH SHOWING THE POSITION VECTORS [illegible] AND [illegible] AND THE CORRESPONDING HOUR ANGLE [illegible]

TABLE [illegible]

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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TABLE [illegible]

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
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TABLE 4

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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TABLE [illegible]

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE [illegible]

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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TABLE [illegible]

LOCALITY: [illegible] LATITUDE: [illegible] LONGITUDE: [illegible]

	SPRING			SUMMER			FALL			WINTER		
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 8

LOCALITY	LATITUDE ϕ	OPTIMUM TILT ANGLE i_r
VILLA FLORES, CHIH.	16° 14'	18° 51'
SAN LUIS DE LA LOMA, GRO.	17° 10'	17° 11'
COSAMALOAPAN, VER.	18° 22'	15° 36'
OZULUAMA, VER.	21° 40'	18° 45'
JIMENEZ, TAM.	24° 03'	29° 24'
MATAMOROS, TAM.	25° 53'	30° 16'
PALO VERDE, COAH.	26° 20'	22° 26'

TABLE B

LOCALITY	LATITUDE ϕ	OPTIMUM TILT ANGLE i_r
VILLA FLORES, CHIH.	16° 14'	18° 51'
SAN LUIS DE LA LOMA, GRO.	17° 10'	17° 11'
COSAMALOAPAN, VER.	18° 22'	15° 36'
OZULUAMA, VER.	21° 40'	18° 45'
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facultad de ingeniería, unam

PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

LAS COORDENADAS HORARIAS DE LA TRAYECTORIA DIARIA DEL SOL SOBRE EL HORIZONTE Y SU REPRESENTACION POLAR EN LA REPUBLICA MEXICANA.

AGOSTO, 1979

Rodolfo Martínez Strevel

LAS COORDENADAS HORARIAS DE LA TRAYECTORIA DIARIA DEL SOL SOBRE EL HORIZONTE Y SU REPRESENTACION POLAR EN LA REPUBLICA MEXICANA

e v e r a r d o   a. h e r n á n d e z

1. INTRODUCCION.

En este trabajo se estudia la marcha anual de la trayectoria diaria del sol en su movimiento aparente sobre el horizonte.

Para esto, se ha considerado la franja latitudinal que corresponde a nuestro país, comprendida entre los paralelos de 14° 32' 45"N y 32° 43' 05'N respectivamente.

Como los factores astronómicos de posición que determinan esta trayectoria varían lentamente día con día, se han considerado trayectorias medias diarias correspondientes a períodos de diez días. De esta manera se han calculado los valores horarios correspondientes del acimut y altura solar para 36 períodos del año. Los resultados se han enlistado grado por grado de latitud, y con el propósito de visualizar las trayectorias, se han elaborado además algunos diagramas polares con los valores medios mensuales de la posición del sol para ciertas latitudes. Mediante éstos, es posible apreciar también la duración de la iluminación solar (insolación) en diferentes épocas del año.

2. PROPOSITOS.

Se pretende que la información obtenida resulte aplicable con un buen grado de aproximación a la solución de múltiples problemas en los que las coordenadas solares son un parámetro fundamental. Tal es el caso de la selección de orientaciones preferentes en sistemas de captación de radiación solar; diseño arquitectónico en función del clima solar regional (helioarquitectura); variaciones en la iluminación natural solar; luz crepuscular y reflectividad de superficies respecto al ángulo de incidencia de la radiación solar.

Arquitectónicamente, los beneficios que pueden obtenerse al construir conforme a orientaciones preferentes son notables. Sobre todo en cuanto se refiere a la optimización de la iluminación natural y confort térmico de interiores.

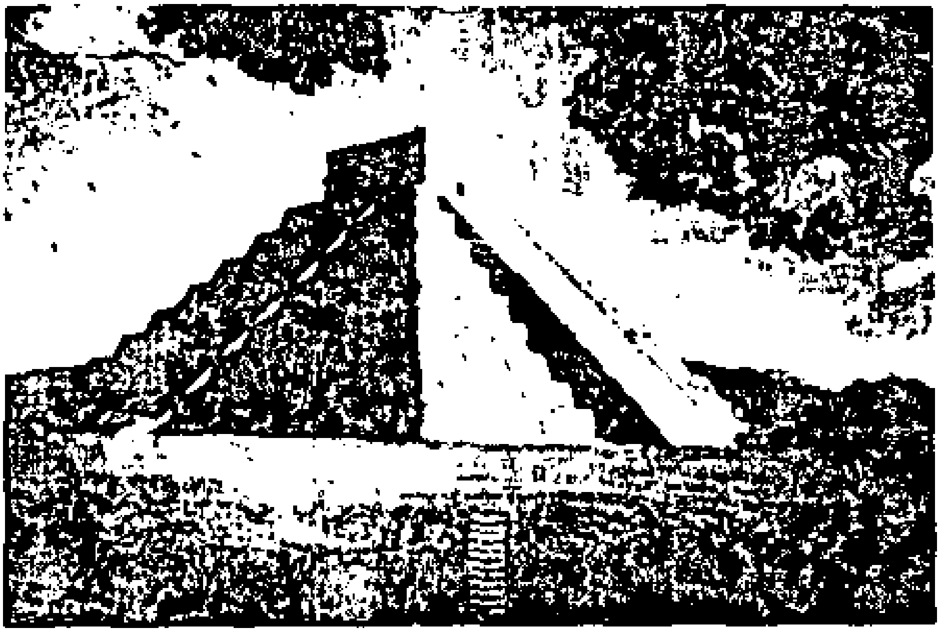
Ya desde la antigüedad diversas culturas han aprovechado los efectos de una buena orientación respecto al sol en sus construcciones, e inclusive se ha llegado a la sofistificación. Tal es el caso de los efectos logrados en la Pirámide de Kukulkán en Chichen-Itza, Yucatán, en la cual los mayas lograron que en el transcurso de los días deequinoccio, el sol proyectase sombras de los bordes de cada nivel de la pirámide sobre las paredes laterales de las escaleras centrales, dando así la impresión de una serpiente en movimiento ascendente ó descendente (Foto 1).(1)

Sin duda en nuestros días, un mejor conocimiento de las trayectorias diarias del sol en nuestras latitudes, ayudaria a normalizar criterios respecto a la optimización de varios factores de construcción determinantes en el comfort de las viviendas, tal como la orientación de paredes y techos y las dimensiones de ventanas.

Un estudio completo de la proyección de sombras originadas por interposición de construcciones con los rayos solares puede ser útil inclusive, para regular naturalmente la temperatura de interiores, según lo requieran las condiciones climáticas estacionales del lugar.

Respecto al cada día más escencial e inobjetable aprovechamiento de la energía solar, hay que considerar que una eficiente captación de la radiación solar depende básicamente de la orientación de la superficie receptora, compatible además con sus dimensiones y factores de diseño.

La forma más eficiente de captar la radiación solar, resulta ser obviamente la de orientar la superficie del captador normalmente a la dirección de los rayos solares. Sin embargo, ésto implica el uso de heliotropos, cuyo mecanismo generalmente es complicado, costoso y que requiere un mantenimiento casi continuo.



El profundo conocimiento Maya sobre el movimiento de los cuerpos celestes, puede apreciarse en la Pirámide de Chichén-Itza al través del singular efecto de luz y sombra que se produce en los días de equinoccio al interponerse a los rayos solares las aristas de la pirámide. En la fotografía puede verse como esta interposición produce en los costados de la escalera principal, una serie de triángulos isósceles que rematan en su parte inferior en la cabeza de una serpiente. Así, la serpiente emplumada, Kukulcán, resurge dos veces al año para iniciar el fuego nuevo del calendario solar Maya. (Fotografía cortesía de L. Arochi) .

Generalmente se decide seguir al sol cuando se trabaja con heliostatos ó con captadores-concentradores (espejos cilíndricos y parabólicos, lentes de Fresnel, etc.) capaces de alcanzar temperaturas relativamente altas comparadas con las que pueden alcanzarse con colectores planos. El colector plano comunmente se diseña para que sus dimensiones y características de construcción permitan captar eficientemente la radiación solar con un mínimo de cambios de orientación durante el año, lo cual requiere un conocimiento previo de la trayectoria anual del sol respecto al sitio escogido. En muchos casos, estos colectores se fijan a los techos o paredes de las casas con una orientación optimizada respecto a la posición media anual del sol al medio día.

Resumiendo, puede decirse que la información presentada en este trabajo puede ser de gran utilidad a los estudiosos de un sinnúmero de fenómenos relacionados con la posición del sol, incluyendo aquellos fenómenos biológicos intimamente relacionados con el heliotropismo.

Se ha querido complementar éste estudio con una sección dedicada al movimiento aparente del sol sobre la esféra celeste, mediante la cual sea posible familiarizarse con los principales ángulos que determinan la trayectoria solar sobre el horizonte del observador. Además, puesto que en muchos estudios concernientes al aprovechamiento de la energía solar es necesario referir los fenómenos que se estudian respecto al tiempo solar, se ha hecho énfasis en la transformación del tiempo civil común en tiempo solar.

3. MOVIMIENTO APARENTE DEL SOL SOBRE EL HORIZONTE.

En la Figura 1, se muestra la trayectoria diaria del sol tal y como es vista por un observador situado en el punto O, para el cual; el circulo SWNE es su horizonte; z el cenit; h el ángulo de la altura solar instantánea, y a el acimut correspondiente (medio respecto al sur).

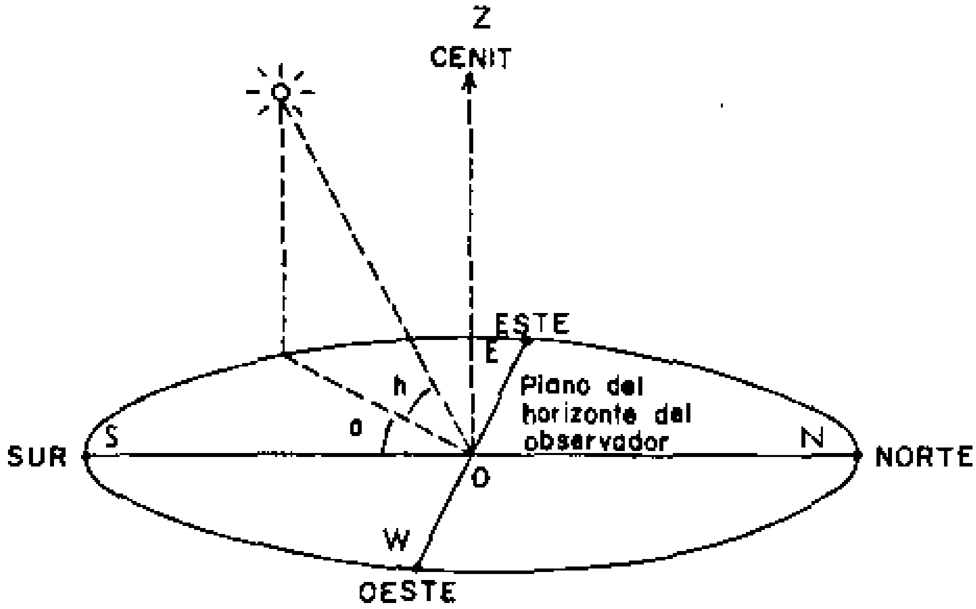


FIG. 1

Acimut y Altura Solar

Los factores astronómicos y geográficos que determinan la trayectoria diaria del sol K, en su movimiento aparente sobre la esfera celeste para un observador situado a la latitud geográfica ϕ, puede observarse usando el sistema de coordenadas horizontales de la Figura 2.

Sea z, el punto de intersección de la esfera celeste con el cenit del lugar; correspondientemente, z' representa el nadir.

El plano perpendicular a la línea cenit-nadir $\overline{zz'}$ que pasa por O intersectando a la esféra celeste, representa el círculo NESW del horizonte del observador O.

El ángulo emprendido entre Z O K es la altura cenital C, tal que el ángulo complementario K O A es la altura solar h. En consecuencia, la dirección de incidencia KO de la radiación solar, queda determinada por el valor instantáneo de la algura solar h, la cual durante el día varía de cero a la salida y puesta del sol, hasta un valor máximo al medio día referido al tiempo solar verdadero (TSV) también llamado tiempo solar aparente (TSA).

Dado que es común referirse al tiempo solar verdadero, es importante definir respecto a que puntos de referencia se acostumbra medir el período de rotación terrestre.

Un sistema de referencia absoluto es el estelar. En éste, el día siderio ó sideral, se define como el período de tiempo requerido por una estrella para ser vista en la misma posición después de una rotación completa de la esféra celeste (movimiento aparente).

El día solar, en cambio, se define como el período de tiempo transcurrido para que el sol sea observado en la misma posición después de que la tierra ha rotado una vuelta completa.

De la Figura 3, vemos que la duración del día medida respecto al paso consecutivo de una estrella y del sol por el meridiano del lugar de referencia, difiere por un ángulo muy pequeño (aproximadamente 1°).

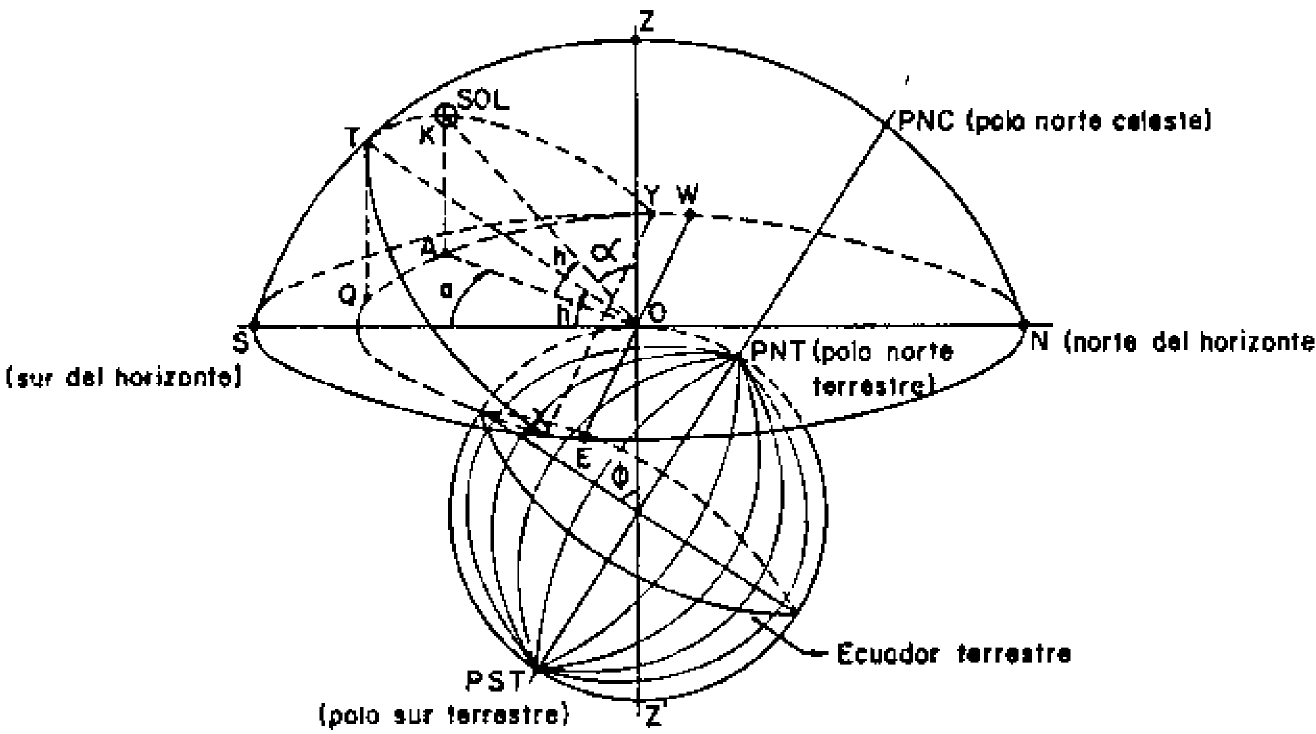


FIG. 2.- TRAYECTORIA DIARIA DEL SOL POR ENCIMA DEL HORIZONTE VISTA POR UN OBSERVADOR SITUADO EN O A LA LATITUD GEOGRAFICA Φ.

En la Figura 3, podemos claramente apreciar por qué el día solar es cerca de 4 minutos más largo que el día sideral. No obstante, tanto el día sideral como el día solar se subdividen en períodos de 24 horas, estableciéndose entre ambos las siguientes relaciones:

24 h. (tiempo sideral)= 23h. 56 min. 4.09 seg. (tiempo solar medio).

24 h. (tiempo solar medio)= 24h. 03 min. 56.555 seg. (tiempo sideral).

1 día sideral = 86,400 (segundos siderales)= 86,164 segundos solares medios.

1 día solar medio = 86,400 segundos solares medios = 86,636.5 segundos siderales.

Debido a las variaciones de la velocidad angular de rotación de la tierra y a la órbita oblicua y elíptica de la misma, el tiempo medio con respecto a dos pasajes consecutivos del sol por el meridiano local ψ sufre variaciones diarias.

Al tratar de determinar la duración de pasos consecutivos del sol por el meridiano local (mediante un reloj astronómico preciso) se encuentra que ciertos períodos del año, el intervalo de tiempo transcurrido es mayor que las 24 horas del día solar medio. Durante los períodos semanales ó mensuales en los que el día solar verdadero es mayor de 24 horas, los excesos de tiempo - correspondientes, producen una divergencia entre el tiempo en el que el sol debiera (respecto al tiempo solar medio) cruzar el meridiano local y el tiempo en el que el sol realmente viene cruzando este meridiano. En tales circunstancias, parecerá que el sol se ha venido desplazando más lentamente, pudiéndosele entonces considerar retrasado respecto al horario de 24 horas del tiempo solar medio. El sol se desplaza más lentamente durante dos períodos del año; uno en Febrero, alcanzando un retraso máximo de 14 min., y el otro en Julio, en el que el retraso es de cerca de 7 minutos.

Por el contrario, cuando los días solares verdaderos son más cortos que el promedio (de mayo a julio y de noviembre a diciembre), el sol cruza por el meridiano local antes del mediodía del tiempo solar medio.

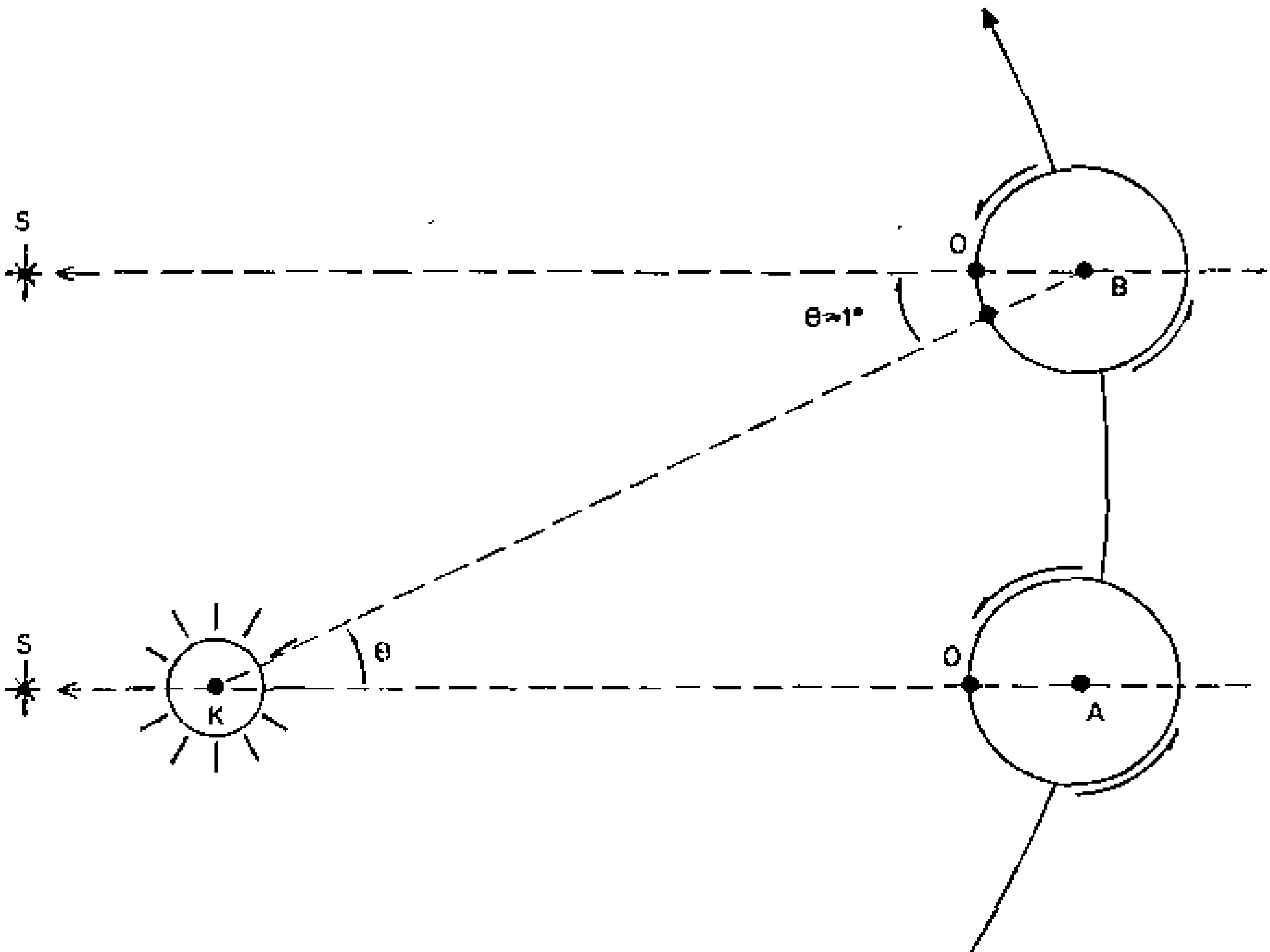


FIG. 3.

Fig. 3. Cuando la tierra se encuentra en A, tanto el sol como una estrella S se encuentran situados colinealmente con el meridiano del punto de observación O. Al día siguiente después de que la tierra ha girado una vuelta completa, puede observarse que la estrella se encuentra en la misma dirección (día sideral), es decir, exactamente sobre el meridiano local, sin embargo, el sol se ve ligeramente desplazado respecto al día anterior. Esto se debe a que en ese tiempo la tierra se ha desplazado a lo largo de su órbita traslacional cerca de un grado. De esta manera, para que el sol quede nuevamente situado sobre el meridiano local del punto O, necesita girar casi un grado adicional, que en tiempo efectivo representa cerca de cuatro minutos.

Así, en Noviembre el sol alcanza un adelanto máximo de 16 minutos, en cambio en Mayo sólo es aproximadamente 4 minutos. Estos efectos pueden verse al examinar la Figura 4 (analema).

El intervalo de tiempo correspondiente al adelanto ó retraso del paso del sol verdadero respecto al sol medio imaginario, es lo que se conoce como ecuación del tiempo, e. t.

e.t.= Tiempo Solar Medio (TSM) - Tiempo Solar Verdadero (TSV)

cuya gráfica puede apreciarse de la figura 5. Los valores diarios precisos de la ecuación del tiempo en cada año, pueden tomarse del almanaque publicado por el Instituto de Astronomía de la U.N.A.M. (2).

Cabe hacer notar, que en las Figuras 4 y 5 se encuentran graficados los valores de la diferencia: TSV-TSM, mientras que en el almanaque del Instituto de Astronomía se reporta la diferencia: TSM-TSV: Esta aclaración resulta importante para evitar confusiones al aplicar la ecuación del tiempo (3).

Como es común en este tipo de estudios, las coordenadas (h, a) del sol, se han obtenido respecto al TSV. Debido a que nuestros relojes se ajustan respecto al tiempo civil, TC (ó tiempo estandar TS), hay que recordar que el TC es el tiempo al cual se ajustan los relojes para que indiquen la misma hora dentro de la zona correspondiente a una franja longitudinal de 15° de amplitud. En la República Mexicana se han tomado dos husos horarios referidos a los meridianos de 90° y 105°W. respectivamente, (el de 105° sólo rige en: Nayarit, Sinaloa, Sonora y Península de Baja California). En tales condiciones para transformar el TSV en TC, tendrá que hacerse uso de la siguiente relación:

$$TSV = TC \pm \psi_c \pm e.t. \qquad ..(1)$$

donde ψ_c, es la corrección de tiempo que hay que hacer respecto a la diferencia angular entre la longitud geográfica del meridiano de referencia y el meridiano de la localidad.

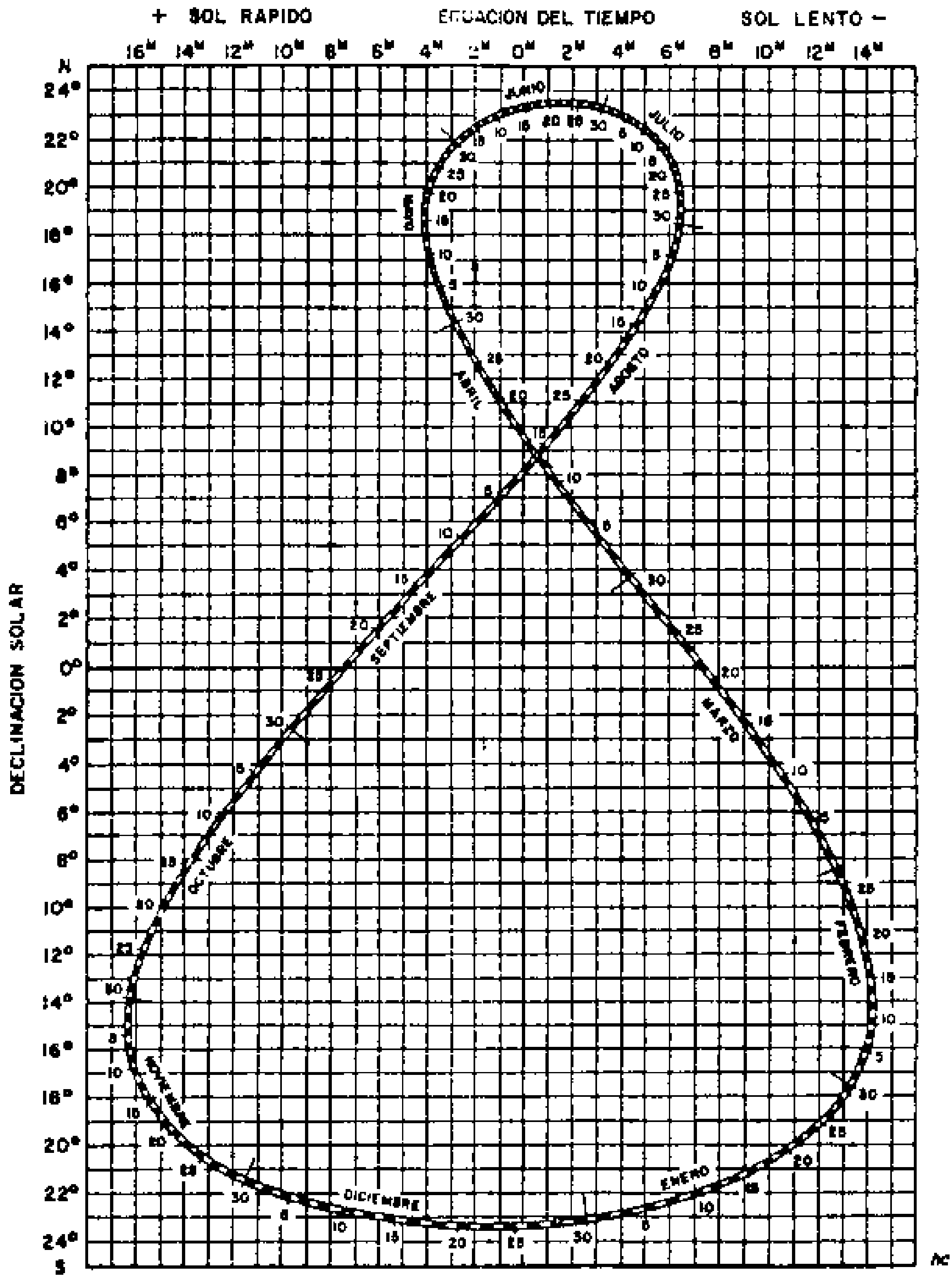

+ SOL RAPIDO
ECUACION DEL TIEMPO
SOL LENTO −
16M 14M 12M 10M 8M 6M 4M 2M 0M 2M 4M 6M 8M 10M 12M 14M
N
24° 22° 20° 18° 16° 14° 12° 10° 8° 6° 4° 2° 0° 2° 4° 6° 8° 10° 12° 14° 16° 18° 20° 22° 24°
S
DECLINACION SOLAR
JUNIO
JULIO
MAYO
ABRIL
AGOSTO
SEPTIEMBRE
MARZO
OCTUBRE
FEBRERO
NOVIEMBRE
DICIEMBRE
ENERO

FIG. 4

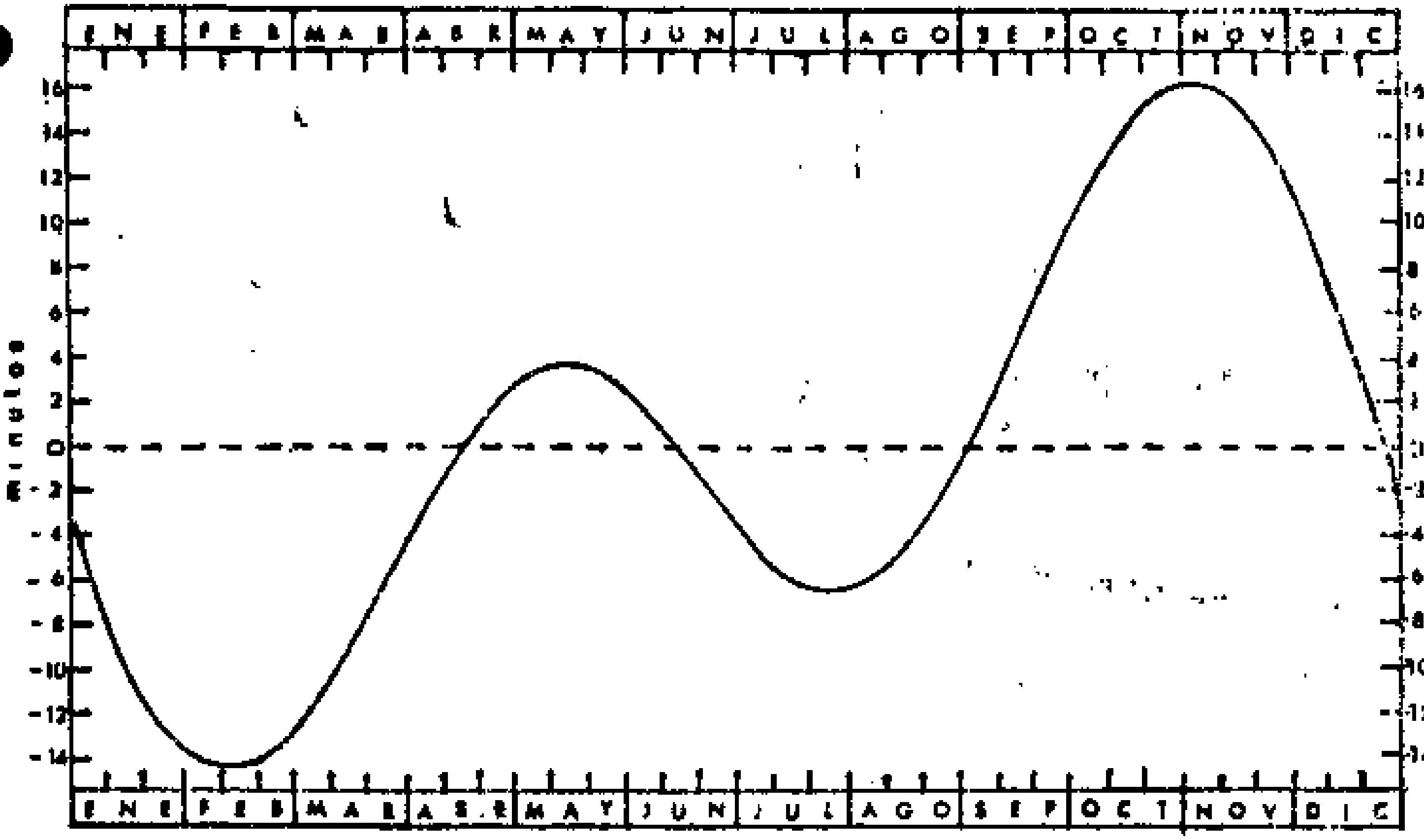


FIGURA 5. GRAFICA DE LA ECUACION DEL TIEMPO

(aparente - medio)

Tabla 1

Angulo	15"	15'	1°	15°	360°
Tiempo	1seg.	1min.	4min.	1hora	24hrs.

Debido al sentido de rotación de la tierra, ésta corrección se considera positiva para puntos localizados hacia el oeste del meridiano de referencia y negativa hacia el este. Así para la ciudad de México (catedral) cuya longitud es ψ= 99° 07' 58", de la tabla 1 ó del Apéndice I, la corrección en tiempo viene a ser de 36 min., 31.9 seg ≈ 32 seg. Si por ejemplo deseamos calcular la hora en TSV correspondiente a las 11 hrs. 15 min. a.m. (TC), del día 13 de Noviembre, se tendrá que para esa fecha la ec. del tiempo tomada de la Figura 4 ó 5, sería de: + 15 min. (sol adelantado respecto al sol medio), por lo que de la ec. (1), obtenemos:

TSV = 11 hrs. 15 min. + 36 min. 32seg. + 15 min.

y las 11 hrs. 15 min. (TC) = 12 hrs. 6 min. 32seg. (TSV)

Un problema que frecuentemente se presenta, es el de expresar la hora en TC del paso del sol verdadero por el meridiano del lugar en cuestión (culminación local del sol). Para ilustrar este caso, sirvan como datos los siguientes:

Fecha: 1o. de Enero; lugar: Ciudad Universitaria, México, D. F.; longitud: 99° 10' 54"; hora solar verdadera: 12h.

Como el valor de la ecuación del tiempo tomado de las Figuras 4 ó 5 tiene signo negativo, ésto implica que el sol verdadero tiene un retraso de aproximadamente -3 min. respecto al sol medio. Como antes se mencionó, los relojes comunes se regulan respecto a las 24 horas del sol medio ficticio, por lo que en este caso como el sol verdadero viene retrasado, éste pasará efectivamente por el meridiano de referencia 3 min. después del medio día del sol medio ó sea, a las 12 h. 3 min. TSM. Dado que la ecuación (1) también puede expresarse como:

$$TSV = TC + e.t. + (\psi_r - \psi_{loc}) \quad (2)$$

donde ψ_r = longitud del meridiano de referencia

y ψ_{loc} = longitud del meridiano local

Se tiene que si la longitud del sitio en cuestión es: ψ_{loc} = 99° 10' 54", la diferencia $\psi_r - \psi_{loc}$ en tiempo viene a ser:

$$\psi_r - \psi_{loc} = 36 \text{ min. } 43.6 \text{ seg.}$$

Por lo que despejamos a TC de la ec. (2) y sustituyendo, tenemos que la hora del paso del sol por el meridiano local en TSV, ocurre a las:

TC = 12 hrs. - (-3 min.) - (-36 min. 43.6 seg.)

TC = 12 hrs. 39 min. 43.6 seg.

Transladando el plano del horizonte SWNE a la esfera celeste completa de la Figura 6, la variación de $\vec{h}$ podrá ser descrita de manera más completa. La esféra ficticia de radio infinito PZE'A'H'P'NEAHP, es concéntrica a la tierra y sobre ella se proyectan todos los cuerpos celestes. Puede apreciarse que el punto O, correspondiente al observador, se determina por su longitud geográfica ψ, contada a partir del meridiano terrestre de longitud cero y por la latitud geográfica ϕ considerada positiva en el hemisferio norte y negativa en el hemisferio sur. Prolongando el eje de rotación del planeta hasta los puntos de intersección N y N' de la esféra celeste, se tiene que una paralela a éste eje trazada por el punto O, contendrá a los puntos P y P'. Como las dimensiones del planeta son infinitamente menores que las de la esféra celeste, a estos dos puntos se les llama polos celestes, norte y sur respectivamente.

Al gran círculo ABA', cuyos polos son P y P', se le llama ecuador celeste. Su plano es normal al eje del planeta y puede confundirse con el plano ecuatorial del mismo debido a las pequeñas dimensiones de éste antes señaladas.

El gran círculo HPZH'P'Z', que pasa por el cenit Z y el polo P, es el meridiano correspondiente al observador O. La altura del polo P por encima del horizonte (arco HP) y que es igual al arco ZA' (ángulo ZOA' formado por la vertical al punto O respecto al plano ecuatorial) es la latitud geográfica ϕ. Su ángulo complementario es la colatitud .

Para el observador en O, K será la posición del sol sobre la esféra celeste, tal que el arco ZK del gran círculo ZKD que pasa por Z y K representa la distancia cenital Z, referida anteriormente en la Figura 2.

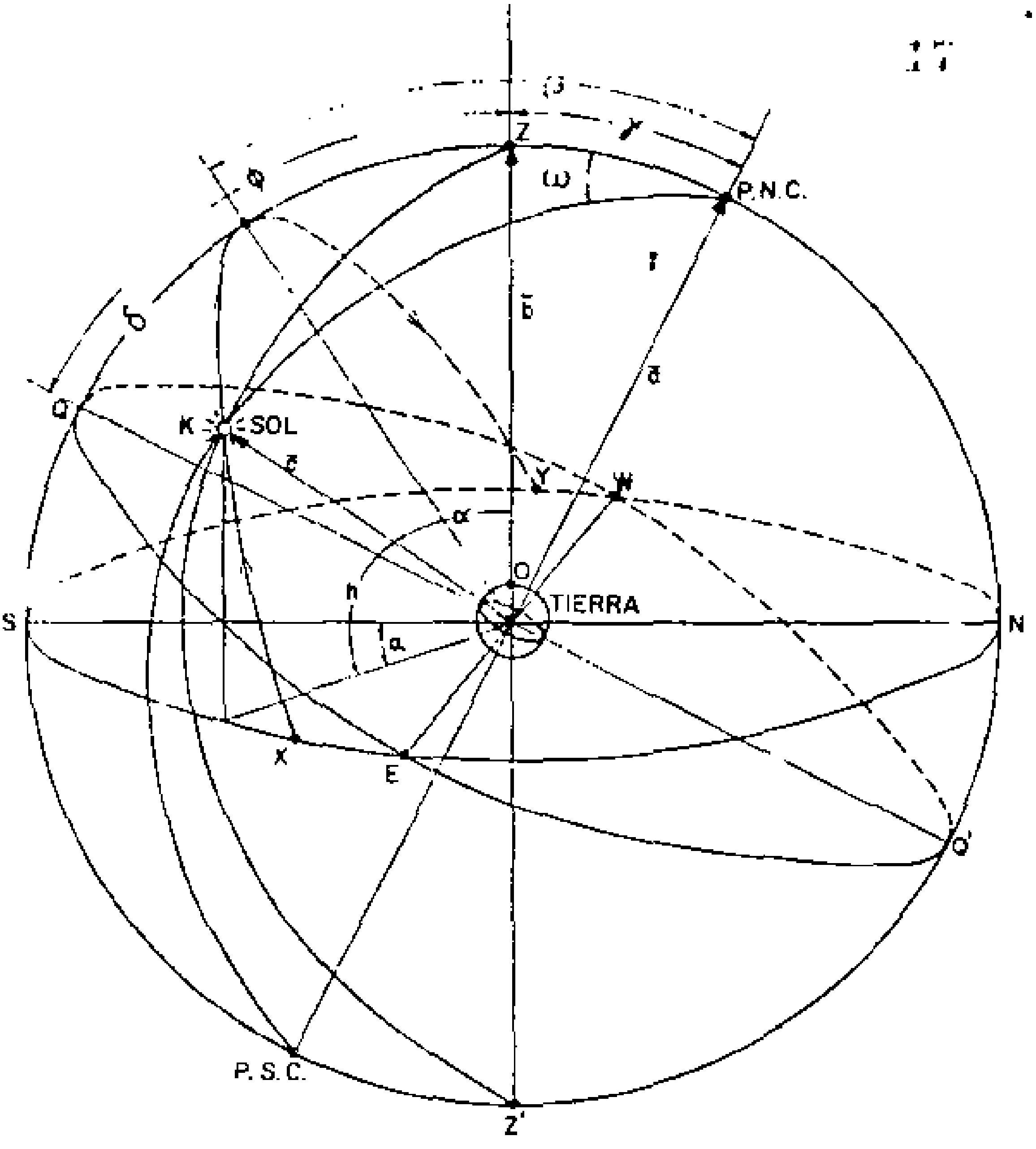


FIG. 6 - TRAYECTORIA DIARIA DEL SOL PROYECTADA EN LA ESFERA CELESTE Y VISTA POR UN OBSERVADOR SITUADO EN O A LA LATITUD GEOGRAFICA Φ.

El arco KB del gran círculo que pasa por el sol, representa la declinación solar , positiva cuando el sol se encuentra en el hemisferio norte. La declinación solar es equivalente a la posición angular del sol al medio día verdadero (T.S.V.) con respecto al plano ecuarial (ángulo formado entre la línea tierra-sol y el plano ecuatorial). La variación anual de la declinación solar y de la ecuación del tiempo puede verse del analema de la Figura 4 .

El ángulo esférico ZPS, formado entre los planos OPS y OPZ, es el ángulo horario ω del sol. En otras palabras, ω es el ángulo comprendido en cierto instante del día entre el plano meridiano del lugar y el plano meridional que intersecta al sol en su posición instantánea.

En consecuencia, al medio día verdadero, estos planos meridianos coinciden y se tiene que $\omega = 0°$. Como el período de rotación terrestre es de 24 horas, 1 hora equivale a un ángulo horario de 15º El ángulo horario (Figura 6), se mide a partir del medio día verdadero, considerándosele positivo en la mañana y negativo por la tarde, aunque también se acostumbra medirlo conforme a la Tabla 2.

Tabla 2 Relación entre el ángulo horario y la hora T.S.V.

Tiempo Solar Verdadero o tiempo solar local	6 hrs.	9 hrs.	12 hrs.	15 hrs.	18 hrs.	21 hrs.	24 hrs.
Angulo horario w correspondiente	270°	315°	0°	45°	90°	135°	180°

Trasladando los vectores $\bar{a}, \bar{b}, \bar{c}$ de la Figura 4 a la Figura 7, puede verse que, la relación que guardan entre sí éstos vectores de posición en el triángulo esférico, puede obtenerse a partir del triple producto vectorial, el cual se expresa para cuatro vectores $\bar{a}$, $\bar{b}$, $\bar{c}$ y $\bar{d}$ cualesquiera, como:

$$(\bar{a} \times \bar{b}) \cdot (\bar{c} \times \bar{d}) = (\bar{b} \cdot \bar{d})(\bar{a} \cdot \bar{c}) - (\bar{b} \cdot \bar{c})(\bar{a} \cdot \bar{d})$$

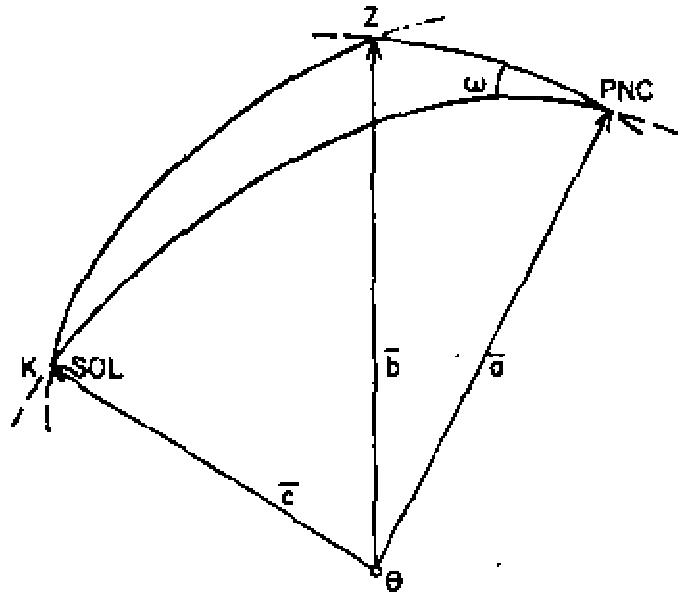


FIG. 7.- VECTORES DE POSICION AL SOL, POLO NORTE CELESTE Y CENIT.

En el caso particular de la esféra celeste, se tiene que:

$(\bar{a} \times \bar{b}).(\bar{a} \times \bar{c}) = (\bar{b}.\bar{c})\ (\bar{a}.\bar{a}) - (\bar{b}.\bar{a})\ (\bar{a}.\bar{c})$

Tomando magnitudes:

$(|\bar{a}|\ |\bar{b}|\ \text{sen}\gamma)(|\bar{a}|\ |\bar{b}|\ \text{sen}\beta)\cos\omega = (|\bar{b}|\ |\bar{c}|\ \cos\alpha)a^2 -$

$(|\bar{b}|\ |\bar{a}|\ \cos\gamma)\ (|\bar{a}|\ |\bar{b}|\ \cos\beta)$

y haciendo la esféra de radio unitario se obtiene:

$\text{Sen}\gamma\ \text{sen}\beta\ \cos\omega = \cos\alpha - \cos\gamma\ \cos\beta$

Como: $\alpha + h = \beta + \delta = \gamma + \phi' = \pi/2$

Se obtiene finalmente la expresión para la altura solar h.

$h = \text{sen}^{-1}\ (\ \text{sen}\ \phi\ \text{sen}\ \delta + \cos\ \phi\ \cos\ \delta\ \cos\omega\ )$ ..(3)

Observando la misma Figura 7 y procediendo de manera semejante, se obtiene que el acimut a queda expresado como:

$$a = sen^{-1} \left(\frac{\cos \delta \ sen \ \omega}{\text{Cos } h.} \right) \qquad ..(4)$$

éste se acostumbra medir partiendo del sur hacia el oeste.

La declinación solar en cualquier día del año, puede ser obtenida de la Figura 5 ó puede ser evaluada mediante la expresión de Cooper (4).

$$= 23.45 \ sen \left(360 \ \frac{284 + i}{365} \right) \qquad ..(5)$$

donde i es el día del año.

En los cómputos se han considerado períodos de diez días para los cuales se han escogido los valores sugeridos por P. de Brichambaut y G. Lamboley (5), Tabla 3).

Tabla 3

Valores de la declinación solar para períodos de diez días.

	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC
1a dec.	-22	-16	-6	+6	+16	+22	+23	+17	+7	-5	-16	-22
2a dec.	-21	-13	-2	+10	+19	+23	+21	+14	+3	-9	-18	-23
3a dec.	-19	-9	+2	+13	+24	+23	+20	+11	-1	-12	-21	-23

4. INTERPRETACION DE LOS RESULTADOS.

Con el fin de interpretar más clara y rápidamente los valores horarios enlistados de la trayectoria media solar sobre el horizonte a nuestras latitudes, conviene antes analizar detalladamente la Figura 8.

De la Figura 8, puede observarse que a la latitud correspondiente (23°27'), la altura máxima del sol al medio día (T.S.V.) coincide con el cenit del lugar sólo en la fecha correspondiente al solsticio de Verano. De ésta manera, se tiene que sólo en aquellos lugares cuya latitud sea inferior o igual al valor máximo de la declinación solar (23°27'), se dará el caso de que el sol pase por el cenit de ese punto.

En tal situación se tiene que cuando $\omega=0°$ (mediodía T.S.V.); $h=90°-(\phi - \delta)$; por lo que si $\phi=\delta$, entonces $h=90°$

Esto significa, que el sol pasará dos veces al año por el cenit del lugar para cualquier punto situado entre los trópicos (entre +23° 27' y -23° 27'). Esto ocurrirá en las fechas en que el valor de la declinación solar coincida con el valor de la latitud del lugar. En particular, el sol nunca alcanza el cenit en las regiones de nuestro país situadas al norte del trópico de cáncer, por lo que éste siempre será visto a mediodía desplazado hacia el sur.

También cabe indicar, que durante el período del año en que el valor de δ sea mayor que el de ϕ, la altura solar h tendrá que medirse respecto al cuadrante adyacente, ya que h max = 90°. Un ejemplo es el caso de la ciudad de México (ϕ = 19° 17' N.) en la que de acuerdo con la tabla correspondiente a los 19°(Pag.37), la altura máxima del sol crece desde Enero hasta la segunda decena de Mayo. Luego este valor decrece hasta llegar a la primera decena de Agosto, en que nuevamente se aproxima a los 90° para después decrecer a su valor mínimo en Diciembre (Figura 9).

Respecto al acimut a, podemos ver en la misma Figura 8, que este ángulo medido desde el sur, varía respecto a la línea Este-Oeste, según la época del año, y que sólo en las fechas de los equinoccios, el sol sale y se oculta justamente sobre esta línea. Así, del equinoccio de Primavera (21 de marzo) al equinoccio de Otoño (23 de Septiembre), el acimut de salida y puesta del sol será mayor que 90°; los valores horarios en el transcurso del día pueden no serlo. Esto se debe a que conforme transcurre la mañana ó tarde, el sol al elevarse ó

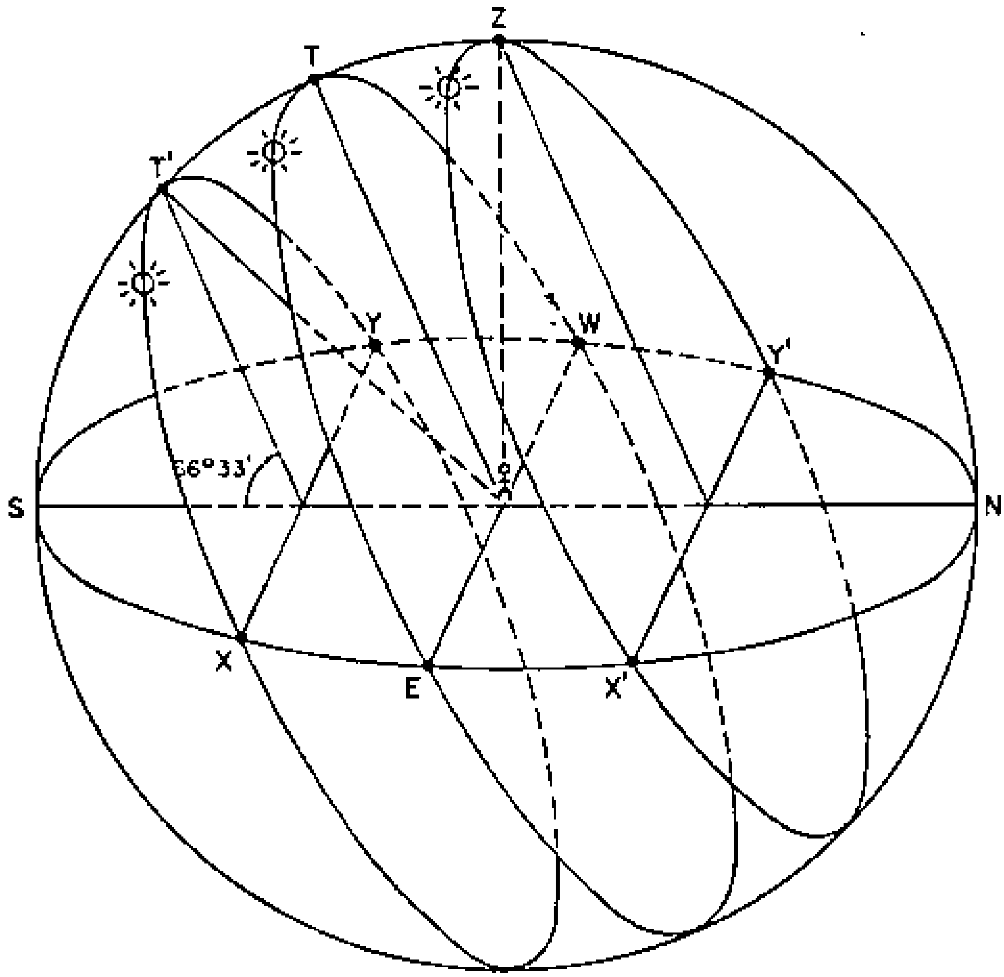


FIG. 8: TRAYECTORIA DIARIA DEL SOL A LA LATITUD DEL TRÓPICO DE CANCER EN DIFERENTES FECHAS: XT'Y – SOLSTICIO DE INVIERNO; ETW EQUINOCCIOS; X'ZY' – SOLSTICIO DE VERANO.

hc

descender cruza el plano vertical Este-Oeste del lugar. De esta manera, a determinada hora del día el acimut podrá ser mayor o igual que 90°de acuerdo con las siguientes condiciones que determinan los respectivos cuadrantes de ocurrencia. (Tabla 4).

tabla 4. Cuadrantes de Ocurrencia de a (T.S.V.)

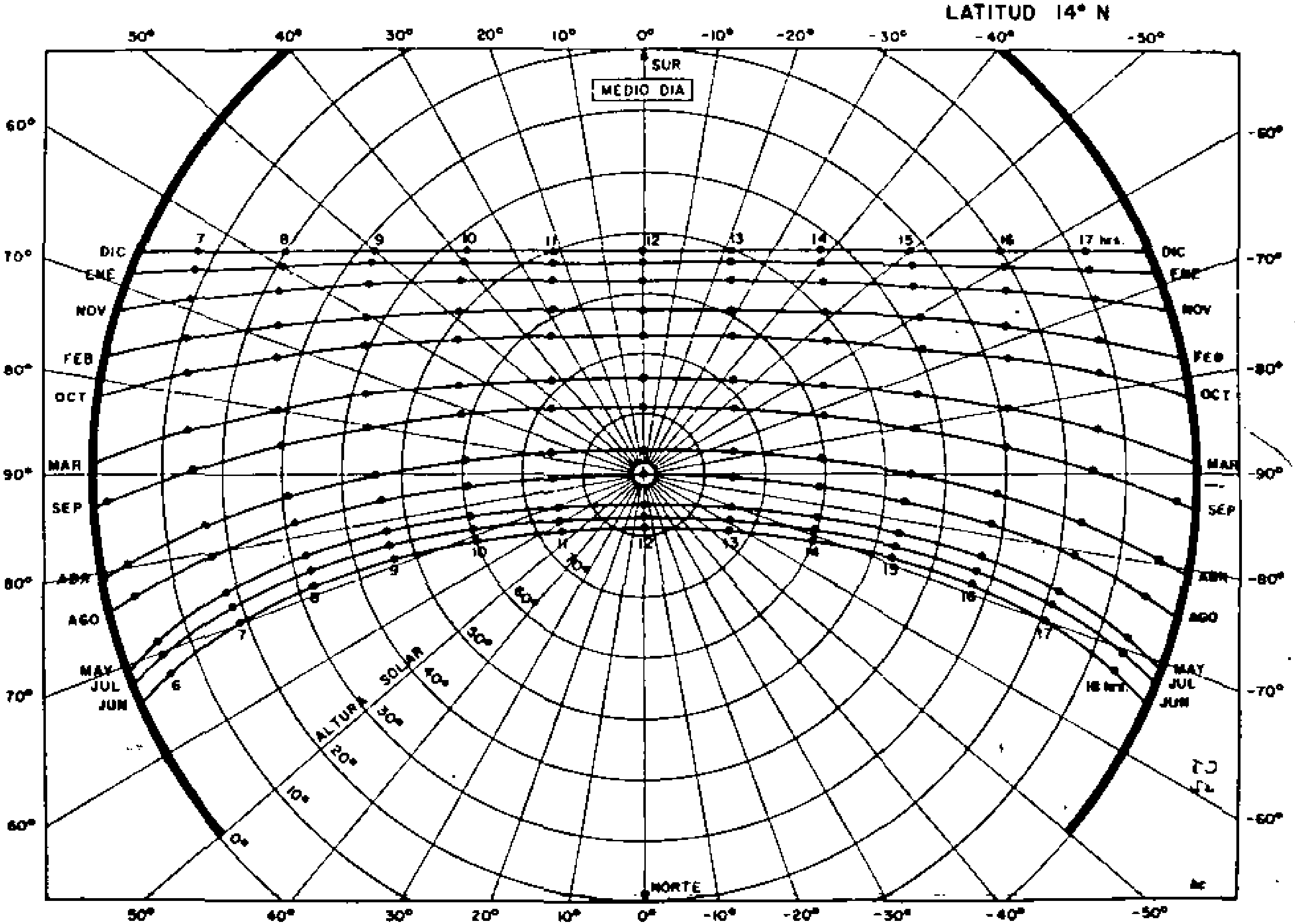
SI: Sen h	A.M.	P.M.
$>$ Senδ/Senϕ	I	II
$<$ Senδ/Senϕ	IV	III

Los valores horarios del acimut que aparecen enmarcados en las páginas siguientes, corresponden a valores que sobrepasan los 90°del 1er. y 2o. cuadrante y que en consecuencia se han medido respecto al 3er. y 4o. cuadrante.

5. CONCLUSIONES:

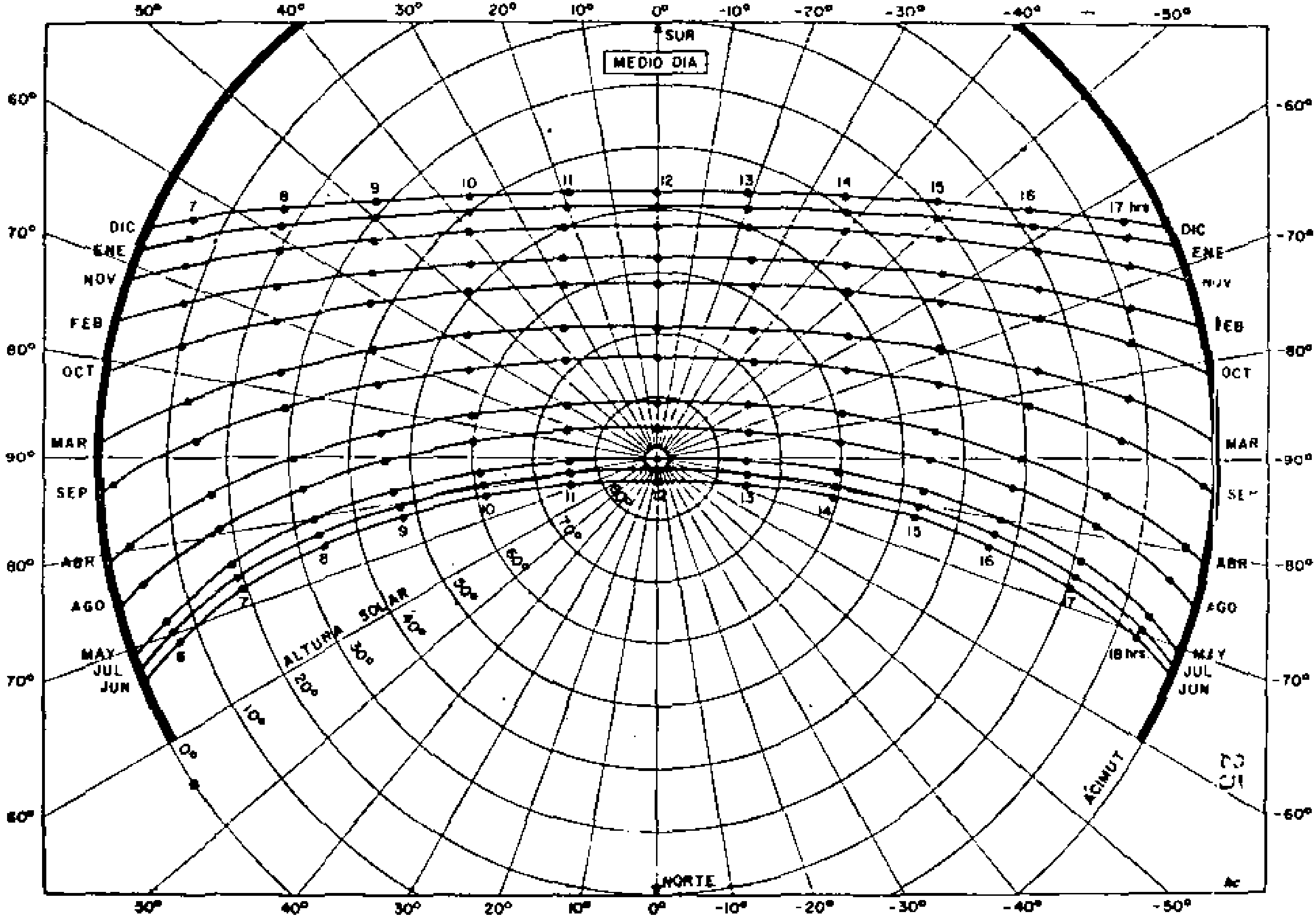
Como puede constatarse en las formulaciones que permiten el computo de las coordenadas horarias del sol, el parámetro cuya variación es determinante durante los períodos considerados, es la declinación solar. Aunque su variación diaria es pequeña (ver analema), ésta puede ser apreciable en períodos de diez días. Por consiguiente, en éste estudio se ha procurado introducir los valores más representativos de ésta, de tal forma que las coordenadas horarias así obtenidas, sean lo suficientemente significativas del período decadario en cuestión. Así, a menos que el fenómeno que se estudie requiera de una precisión mayor, se sugiere hacer uso de los valores enlistados a continuación en problemas como los mencionados al principio de este trabajo.

Por otro lado, una representación decadaria de las coordenadas horarias del sol, resulta ser en la mayoría de los casos, más completa y conveniente que la representación que generalmente se acostumbra hacer en este tipo de estudios, en las que se toman como fechas de referencia los días: 1o., 11 y 21 de cada mes. En caso que se desee interpolar algún valor, se sugiere hacer uso de los diagramas polares. No obstante que en èste trabajo se presentan solamente tres de ellos, su construcción gráfica para otras latitudes es simple.

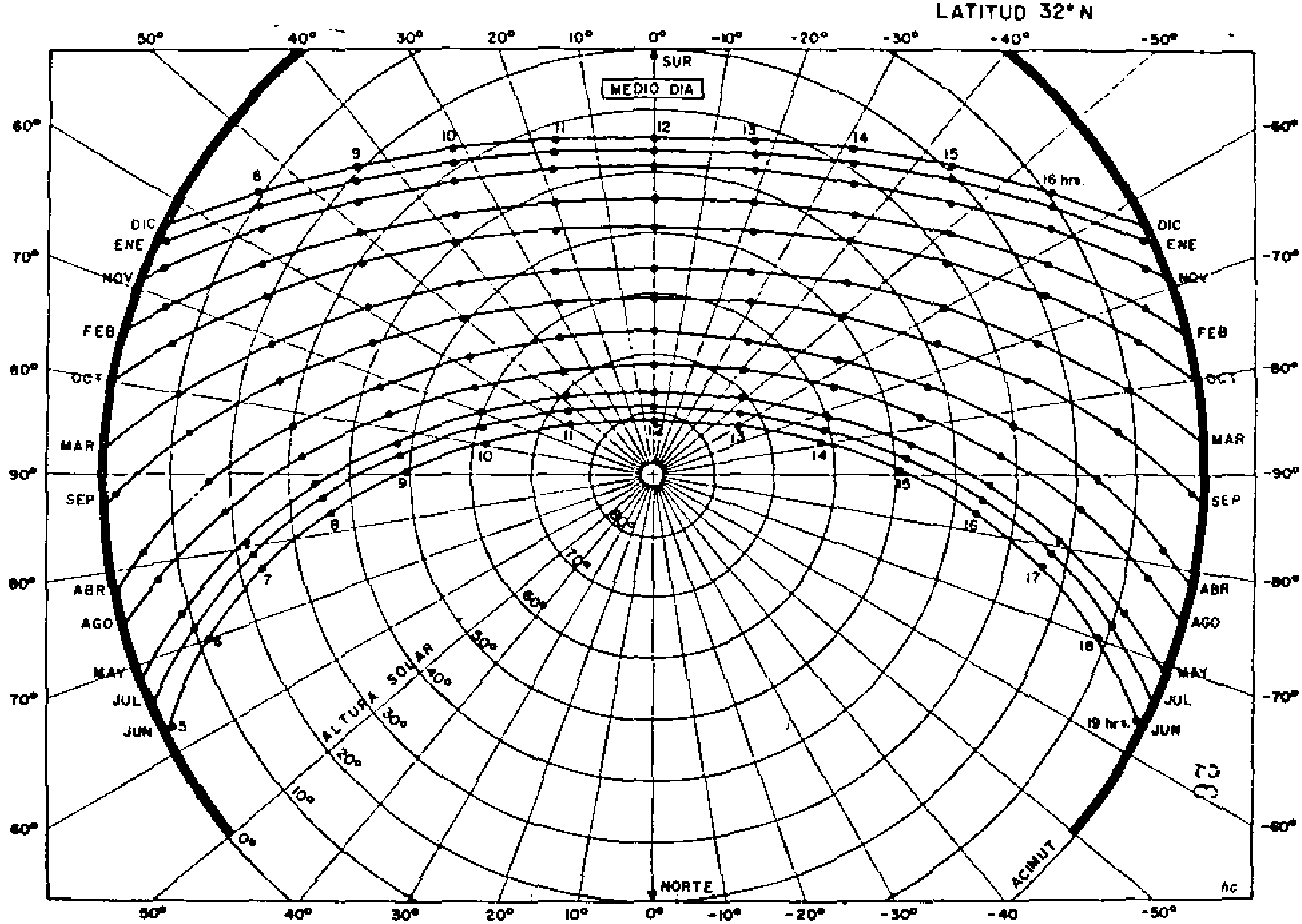


PROYECCION SOBRE EL PLANO DEL HORIZONTE DE LAS TRAYECTORIAS DEL SOL

LATITUD 19° N



PROYECCION SOBRE EL PLANO DEL HORIZONTE DE LAS TRAYECTORIAS DEL SOL



PROYECCION SOBRE EL PLANO DEL HORIZONTE DE LAS TRAYECTORIAS DEL SOL

REFERENCIAS

{ 1} Arochi, L., (1976) "La Pirámide de Kukulkán y su simbología solar". Editorial Orión, México, D. F.

{ 2} Guerra, M., Falcón, A., Flores, D., Anuario del Observatorio Astronómico Nacional, Instituto de Astronomía, U.N.A.M., México, D. F.

{ 3} Guerra, M., (1977), Comunicación Personal, Instituto de Astronomía, U.N.A.M.

{ 4} Cooper, P., (1969), The Absorption of Solar Radiation in Solar Stills, Solar Energy, Vol. 12, No. 3.

{ 5} Perrin de Brichambaut,Ch., (1963),Rayonnement Solaire et Echanges Radiatifs Naturels,ed. Gauthier-Villard, Paris VIe.

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CONVERSION DE ARCO A TIEMPO

0°–59°		60°–119°		120°–179°		180°–239°		240°–299°		300°–359°			0'·00	0'·25	0'·50	0'·75
°	h m	°	h m	°	h m	°	h m	°	h m	°	h m	'	m s	m s	m s	m s
0	0 00	60	4 00	120	8 00	180	12 00	240	16 00	300	20 00	0	0 00	0 01	0 02	0 03
1	0 04	61	4 04	121	8 04	181	12 04	241	16 04	301	20 04	1	0 04	0 05	0 06	0 07
2	0 08	62	4 08	122	8 08	182	12 08	242	16 08	302	20 08	2	0 08	0 09	0 10	0 11
3	0 12	63	4 12	123	8 12	183	12 12	243	16 12	303	20 12	3	0 12	0 13	0 14	0 15
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5	0 20	65	4 20	125	8 20	185	12 20	245	16 20	305	20 20	5	0 20	0 21	0 22	0 23
6	0 24	66	4 24	126	8 24	186	12 24	246	16 24	306	20 24	6	0 24	0 25	0 26	0 27
7	0 28	67	4 28	127	8 28	187	12 28	247	16 28	307	20 28	7	0 28	0 29	0 30	0 31
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9	0 36	69	4 36	129	8 36	189	12 36	249	16 36	309	20 36	9	0 36	0 37	0 38	0 39
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12	0 48	72	4 48	132	8 48	192	12 48	252	16 48	312	20 48	12	0 48	0 49	0 50	0 51
13	0 52	73	4 52	133	8 52	193	12 52	253	16 52	313	20 52	13	0 52	0 53	0 54	0 55
14	0 56	74	4 56	134	8 56	194	12 56	254	16 56	314	20 56	14	0 56	0 57	0 58	0 59
15	1 00	75	5 00	135	9 00	195	13 00	255	17 00	315	21 00	15	1 00	1 01	1 02	1 03
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59	3 56	119	7 56	179	11 56	239	15 56	299	19 56	359	23 56	59	3 56	3 57	3 58	3 59

LATITUD=14.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	8.18	21.05	33.06	43.51	51.11	54.00	51.11	43.51	33.06	21.05	8.18	0.00	0.00
ENE.	D2	0.00	0.00	8.50	21.48	33.63	44.25	52.03	55.00	52.03	44.25	33.63	21.48	8.50	0.00	0.00
ENE.	D3	0.00	0.00	9.13	22.33	34.75	45.71	53.84	57.00	53.84	45.71	34.75	22.33	9.13	0.00	0.00
FEB.	D1	0.00	0.00	10.06	23.56	36.36	47.82	56.54	60.00	56.54	47.82	36.36	23.56	10.06	0.00	0.00
FEB.	D2	0.00	0.00	10.97	24.73	37.89	49.85	59.18	63.00	59.18	49.85	37.89	24.73	10.97	0.00	0.00
FEB.	D3	0.00	0.00	12.13	26.19	39.78	52.38	62.60	67.00	62.60	52.38	39.78	26.19	12.13	0.00	0.00
MAR.	D1	0.00	0.00	12.97	27.21	41.08	54.14	65.77	73.00	65.77	54.14	41.08	27.21	12.97	0.00	0.00
MAR.	D2	0.00	0.00	14.04	28.45	42.63	56.24	68.16	76.00	68.16	56.24	42.63	28.45	14.04	0.00	0.00
MAR.	D3	0.00	0.48	15.04	29.56	43.96	58.02	70.93	78.00	70.93	58.02	43.96	29.56	15.04	0.48	0.00
ABR.	D1	0.00	1.45	15.96	30.52	45.04	59.43	73.21	82.00	73.21	59.43	45.04	30.52	15.96	1.45	0.00
ABR.	D2	0.00	2.41	16.82	31.37	45.86	60.41	74.80	86.00	74.80	60.41	45.86	31.37	16.82	2.41	0.00
ABR.	D3	0.00	3.12	17.40	31.81	46.30	60.83	75.38	89.00	75.38	60.83	46.30	31.81	17.40	3.12	0.00
MAY.	D1	0.00	3.82	17.94	32.21	46.57	60.98	75.38	88.00	75.38	60.98	46.57	32.21	17.94	3.82	0.00
MAY.	D2	0.00	4.52	18.43	32.51	46.68	60.84	74.78	85.00	74.78	60.84	46.68	32.51	18.43	4.52	0.00
MAY.	D3	0.00	4.97	18.73	32.66	46.65	60.60	74.09	83.00	74.09	60.60	46.65	32.66	18.73	4.97	0.00
JUN.	D1	0.00	5.23	18.97	32.71	46.62	60.43	73.66	82.00	73.66	60.43	46.62	32.71	18.97	5.23	0.00
JUN.	D2	0.00	5.42	19.01	32.76	46.56	60.23	73.19	81.00	73.19	60.23	46.56	32.76	19.01	5.42	0.00
JUN.	D3	0.00	5.42	19.01	32.76	46.56	60.23	73.19	81.00	73.19	60.23	46.56	32.76	19.01	5.42	0.00
JUL.	D1	0.00	5.42	19.01	32.76	46.56	60.23	73.19	81.00	73.19	60.23	46.56	32.76	19.01	5.42	0.00
JUL.	D2	0.00	4.97	18.73	32.66	46.65	60.60	74.09	83.00	74.09	60.60	46.65	32.66	18.73	4.97	0.00
JUL.	D3	0.00	4.75	18.59	32.59	46.67	60.73	74.46	84.00	74.46	60.73	46.67	32.59	18.59	4.75	0.00
AGO.	D1	0.00	4.06	18.11	32.32	46.62	60.96	75.24	87.00	75.24	60.96	46.62	32.32	18.11	4.06	0.00
AGO.	D2	0.00	3.36	17.59	31.96	46.41	60.91	75.45	93.50	75.45	60.91	46.41	31.96	17.59	3.36	0.00
AGO.	D3	0.00	2.65	17.02	31.49	46.03	60.58	75.06	87.00	75.06	60.58	46.03	31.49	17.02	2.65	0.00
SEP.	D1	0.00	1.69	16.19	30.73	45.27	59.71	73.68	83.00	73.68	59.71	45.27	30.73	16.19	1.69	0.00
SEP.	D2	0.00	0.73	15.27	29.81	44.25	58.41	71.55	79.00	71.55	58.41	44.25	29.81	15.27	0.73	0.00
SEP.	D3	0.00	0.00	14.29	28.74	42.98	56.71	68.89	75.00	68.89	56.71	42.98	28.74	14.29	0.00	0.00
OCT.	D1	0.00	0.00	13.24	27.51	41.48	54.69	65.86	71.00	65.86	54.69	41.48	27.51	13.24	0.00	0.00
OCT.	D2	0.00	0.00	12.13	26.19	39.78	52.33	62.60	67.00	62.60	52.33	39.78	26.19	12.13	0.00	0.00
OCT.	D3	0.00	0.00	11.26	25.10	38.38	50.50	60.05	64.00	60.05	50.50	38.38	25.10	11.26	0.00	0.00
NOV.	D1	0.00	0.00	10.06	23.56	36.36	47.82	56.54	60.00	56.54	47.82	36.36	23.56	10.06	0.00	0.00
NOV.	D2	0.00	0.00	9.44	22.75	35.29	46.42	54.75	58.00	54.75	46.42	35.29	22.75	9.44	0.00	0.00
NOV.	D3	0.00	0.00	8.53	21.48	33.63	44.25	52.03	55.00	52.03	44.25	33.63	21.48	8.50	0.00	0.00
DIC.	D1	0.00	0.00	8.18	21.05	33.06	43.51	51.11	54.00	51.11	43.51	33.06	21.05	8.18	0.00	0.00
DIC.	D2	0.00	0.00	7.85	20.61	32.48	42.76	50.19	53.00	50.19	42.76	32.48	20.61	7.85	0.00	0.00
DIC.	D3	0.00	0.00	7.85	20.61	32.48	42.76	50.19	53.00	50.19	42.76	32.48	20.61	7.85	0.00	0.00

LATITUD= 14.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.0	59.4	51.5	39.7	22.5	0.0	-22.5	-39.7	-51.5	-59.4	-64.9	******	******
ENE.	D2	******	******	65.0	60.3	52.5	40.7	23.1	0.0	-23.1	-40.7	-52.5	-60.3	-65.8	******	******
ENE.	D3	******	******	67.7	62.3	54.5	42.6	24.5	0.0	-24.5	-42.6	-54.5	-62.3	-67.7	******	******
FEB.	D1	******	******	70.6	65.3	57.6	45.7	26.8	0.0	-26.8	-45.7	-57.6	-65.3	-70.6	******	******
FEB.	D2	******	******	73.5	68.3	60.8	49.1	29.5	0.0	-29.5	-49.1	-60.8	-68.3	-73.5	******	******
FEB.	D3	******	******	77.4	72.4	65.3	54.0	33.7	0.0	-33.7	-54.0	-65.3	-72.4	-77.4	******	******
MAR.	D1	******	******	80.3	75.6	68.9	58.1	37.6	0.0	-37.6	-58.1	-68.9	-75.6	-80.3	******	******
MAR.	D2	******	******	84.3	79.9	73.5	64.0	44.0	0.0	-44.0	-64.0	-73.5	-79.9	-84.3	******	******
MAR.	D3	******	88.1	87.3	84.3	79.0	70.6	52.3	0.0	-52.3	-70.6	-79.0	-84.3	-88.3	-88.1	******
ABR.	D1	******	84.2	87.7	88.7	84.4	77.9	63.0	0.0	-63.0	-77.9	-84.4	-88.7	-87.7	-84.2	******
ABR.	D2	******	80.3	83.6	86.7	90.0	85.6	76.4	0.0	-76.4	-85.6	-90.0	-86.7	-83.6	-80.3	******
ABR.	D3	******	77.4	80.5	83.2	85.7	88.3	87.9	0.0	-87.9	-88.3	-85.7	-83.2	-80.5	-77.4	******
MAY.	D1	******	74.5	77.4	79.7	81.4	82.2	80.2	0.0	-80.2	-82.2	-81.4	-79.7	-77.4	-74.5	******
MAY.	D2	******	71.5	74.3	76.2	77.0	76.0	68.8	0.0	-68.8	-76.0	-77.0	-76.2	-74.3	-71.5	******
MAY.	D3	******	69.5	72.2	73.8	74.1	71.9	61.8	0.0	-61.8	-71.9	-74.1	-73.8	-72.2	-69.6	******
JUN.	D1	******	68.6	71.3	72.6	72.6	69.9	58.5	0.0	-58.5	-69.9	-72.6	-72.6	-71.2	-68.6	******
JUN.	D2	******	67.6	70.1	71.4	71.2	68.0	55.5	0.0	-55.5	-68.0	-71.2	-71.4	-70.1	-67.6	******
JUN.	D3	******	67.6	70.1	71.4	71.2	68.0	55.5	0.0	-55.5	-68.0	-71.2	-71.4	-70.1	-67.6	******
JUL.	D1	******	67.6	70.1	71.4	71.2	68.0	55.5	0.0	-55.5	-68.0	-71.2	-71.4	-70.1	-67.6	******
JUL.	D2	******	69.5	72.2	73.8	74.1	71.9	61.8	0.0	-61.8	-71.9	-74.1	-73.8	-72.2	-69.6	******
JUL.	D3	******	70.5	73.3	75.0	75.6	74.0	65.2	0.0	-65.2	-74.0	-75.6	-75.0	-73.3	-70.5	******
AGO.	D1	******	73.5	76.4	78.5	79.9	80.1	76.3	0.0	-76.3	-80.1	-79.9	-78.5	-76.4	-73.5	******
AGO.	D2	******	76.4	79.5	82.0	84.3	86.1	84.2	0.0	-84.2	-86.3	-84.3	-82.0	-79.5	-76.4	******
AGO.	D3	******	79.3	82.6	85.5	88.6	87.6	80.1	0.0	-80.1	-87.6	-88.6	-85.5	-82.6	-79.3	******
SEP.	D1	******	83.2	86.7	89.9	85.8	79.8	66.1	0.0	-66.1	-79.8	-85.8	-89.9	-86.7	-83.2	******
SEP.	D2	******	87.1	89.3	85.4	80.4	72.4	54.8	0.0	-54.8	-72.4	-80.4	-85.4	-89.3	-87.1	******
SEP.	D3	******	******	85.3	81.0	75.1	65.6	45.9	0.0	-45.9	-65.6	-75.1	-81.0	-85.3	******	******
OCT.	D1	******	******	81.3	76.6	70.1	59.5	39.1	0.0	-39.1	-59.5	-70.1	-76.6	-81.3	******	******
OCT.	D2	******	******	77.4	72.4	65.3	54.0	33.7	0.0	-33.7	-54.0	-65.3	-72.4	-77.4	******	******
OCT.	D3	******	******	74.4	69.3	61.9	50.3	30.5	0.0	-30.5	-50.3	-61.9	-69.3	-74.4	******	******
NOV.	D1	******	******	70.6	65.3	57.6	45.7	26.8	0.0	-26.8	-45.7	-57.6	-65.3	-70.6	******	******
NOV.	D2	******	******	68.6	63.3	55.5	43.6	25.2	0.0	-25.2	-43.6	-55.5	-63.3	-68.6	******	******
NOV.	D3	******	******	65.8	60.3	52.5	40.7	23.1	0.0	-23.1	-40.7	-52.5	-60.3	-65.8	******	******
DIC.	D1	******	******	64.8	59.4	51.5	39.7	22.5	0.0	-22.5	-39.7	-51.5	-59.4	-64.8	******	******
DIC.	D2	******	******	63.8	58.4	50.5	38.8	21.8	0.0	-21.8	-38.8	-50.5	-58.4	-63.8	******	******
DIC.	D3	******	******	63.8	58.4	50.5	38.8	21.8	0.0	-21.8	-38.8	-50.5	-58.4	-63.8	******	******

LATITUD=15.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	7.75	20.54	32.43	42.74	50.19	53.00	50.19	42.74	32.43	20.54	7.75	0.00	0.00
ENE.	D2	0.00	0.00	8.09	20.99	33.02	43.49	51.10	54.00	51.10	43.49	33.02	20.99	8.09	0.00	0.00
ENE.	D3	0.00	0.00	8.75	21.86	34.16	44.97	52.73	56.00	52.73	44.97	34.16	21.86	8.75	0.00	0.00
FEB.	D1	0.00	0.00	9.73	23.14	35.82	47.12	55.64	59.00	55.64	47.12	35.82	23.14	9.73	0.00	0.00
FEB.	D2	0.00	0.00	10.68	24.35	37.39	49.19	58.31	62.00	58.31	49.19	37.39	24.35	10.68	0.00	0.00
FEB.	D3	0.00	0.00	11.91	25.88	39.35	51.79	61.77	66.00	61.77	51.79	39.35	25.88	11.91	0.00	0.00
MAR.	D1	0.00	0.00	12.80	26.95	40.71	53.60	64.27	69.00	64.27	53.60	40.71	26.95	12.80	0.00	0.00
MAR.	D2	0.00	0.00	13.93	28.27	42.34	55.79	67.43	73.00	67.43	55.79	42.34	28.27	13.93	0.00	0.00
MAR.	D3	0.00	0.57	15.00	29.45	43.76	57.68	70.30	77.00	70.30	57.68	43.76	29.45	15.00	0.57	0.00
ABR.	D1	0.00	1.55	16.00	30.49	44.94	59.20	72.74	81.00	72.74	59.20	44.94	30.49	16.00	1.55	0.00
ABR.	D2	0.00	2.58	16.93	31.37	45.86	60.31	74.53	85.00	74.53	60.31	45.86	31.37	16.93	2.58	0.00
ABR.	D3	0.00	3.33	17.57	31.92	46.36	60.84	75.31	88.00	75.31	60.84	46.36	31.92	17.57	3.34	0.00
MAY.	D1	0.00	4.09	18.16	32.38	46.71	61.10	75.51	89.00	75.51	61.10	46.71	32.38	18.16	4.09	0.00
MAY.	D2	0.00	4.83	18.70	32.75	46.89	61.07	75.12	86.00	75.12	61.07	46.89	32.75	18.70	4.83	0.00
MAY.	D3	0.00	5.32	19.04	32.93	46.92	60.89	74.54	84.00	74.54	60.89	46.92	32.93	19.04	5.32	0.00
JUN.	D1	0.00	5.56	19.19	33.01	46.91	60.76	74.16	83.00	74.16	60.76	46.91	33.01	19.19	5.56	0.00
JUN.	D2	0.00	5.80	19.34	33.07	46.87	60.59	73.73	82.00	73.73	60.59	46.87	33.07	19.34	5.80	0.00
JUN.	D3	0.00	5.80	19.34	33.07	46.87	60.59	73.73	82.00	73.73	60.59	46.87	33.07	19.34	5.80	0.00
JUL.	D1	0.00	5.80	19.34	33.07	46.87	60.59	73.73	82.00	73.73	60.59	46.87	33.07	19.34	5.80	0.00
JUL.	D2	0.00	5.32	19.04	32.93	46.92	60.89	74.54	84.00	74.54	60.89	46.92	32.93	19.04	5.32	0.00
JUL.	D3	0.00	5.08	18.87	32.86	46.92	61.00	74.85	85.00	74.85	61.00	46.92	32.86	18.87	5.08	0.00
AGO.	D1	0.00	4.34	18.35	32.55	46.79	61.12	75.45	86.00	75.45	61.12	46.79	32.55	18.35	4.34	0.00
AGO.	D2	0.00	3.59	17.77	32.09	46.50	60.96	75.45	89.00	75.45	60.96	46.50	32.09	17.77	3.59	0.00
AGO.	D3	0.00	2.83	17.15	31.57	46.04	60.52	74.85	86.00	74.85	60.52	46.04	31.57	17.15	2.83	0.00
SEP.	D1	0.00	1.81	16.24	30.72	45.19	59.52	73.26	82.00	73.26	59.52	45.19	30.72	16.24	1.81	0.00
SEP.	D2	0.00	0.78	15.26	29.73	44.08	58.09	70.96	78.00	70.96	58.09	44.08	29.73	15.26	0.78	0.00
SEP.	D3	0.00	0.00	14.21	28.58	42.72	56.29	68.18	74.00	68.18	56.29	42.72	28.58	14.21	0.00	0.00
OCT.	D1	0.00	0.00	13.09	27.29	41.14	54.17	65.08	70.00	65.08	54.17	41.14	27.29	13.09	0.00	0.00
OCT.	D2	0.00	0.00	11.91	25.88	39.35	51.79	61.77	66.00	61.77	51.79	39.35	25.88	11.91	0.00	0.00
OCT.	D3	0.00	0.00	11.00	24.75	37.90	49.86	59.18	63.00	59.18	49.86	37.90	24.75	11.00	0.00	0.00
NOV.	D1	0.00	0.00	9.73	23.14	35.82	47.12	55.64	59.00	55.64	47.12	35.82	23.14	9.73	0.00	0.00
NOV.	D2	0.00	0.00	9.08	22.29	34.72	45.69	53.84	57.00	53.84	45.69	34.72	22.29	9.08	0.00	0.00
NOV.	D3	0.00	0.00	8.09	20.99	33.02	43.49	51.10	54.00	51.10	43.49	33.02	20.99	8.09	0.00	0.00
DIC.	D1	0.00	0.00	7.75	20.54	32.43	42.74	50.19	53.00	50.19	42.74	32.43	20.54	7.75	0.00	0.00
DIC.	D2	0.00	0.00	7.41	20.09	31.84	41.98	49.26	52.00	49.26	41.98	31.84	20.09	7.41	0.00	0.00
DIC.	D3	0.00	0.00	7.41	20.09	31.84	41.98	49.26	52.00	49.26	41.98	31.84	20.09	7.41	0.00	0.00

LATITUDE 15.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.7	59.0	51.0	39.1	22.0	0.0	-22.0	-39.1	-51.0	-59.0	-64.7	******	******
ENE.	D2	******	******	65.6	60.0	51.9	40.0	22.6	0.0	-22.6	-40.0	-51.9	-60.0	-65.6	******	******
ENE.	D3	******	******	67.5	61.9	53.9	41.9	24.0	0.0	-24.0	-41.9	-53.9	-61.9	-67.5	******	******
FEB.	D1	******	******	70.4	64.9	57.0	44.9	26.2	0.0	-26.2	-44.9	-57.0	-64.9	-70.4	******	******
FEB.	D2	******	******	73.3	67.9	60.1	48.2	28.7	0.0	-28.7	-48.2	-60.1	-67.9	-73.3	******	******
FEB.	D3	******	******	77.2	71.9	64.6	53.0	32.7	0.0	-32.7	-53.0	-64.6	-71.9	-77.2	******	******
MAR.	D1	******	******	80.1	75.1	68.3	56.9	36.4	0.0	-36.4	-56.9	-68.3	-75.1	-80.1	******	******
MAR.	D2	******	******	84.0	79.3	73.0	62.7	42.4	0.0	-42.4	-62.7	-73.0	-79.3	-84.0	******	******
MAR.	D3	******	88.1	88.0	83.7	78.1	69.2	50.1	0.0	-50.1	-69.2	-78.1	-83.7	-88.0	-88.1	******
ABR.	D1	******	84.2	88.0	88.2	83.8	76.2	60.2	0.0	-60.2	-76.2	-83.8	-88.2	-88.0	-84.2	******
ABR.	D2	******	80.3	83.9	87.3	89.0	81.9	72.9	0.0	-72.9	-81.9	-89.0	-87.3	-83.9	-80.3	******
ABR.	D3	******	77.4	80.8	83.6	86.8	89.9	84.0	0.0	-84.0	-89.9	-86.8	-83.6	-80.8	-77.4	******
MAY.	D1	******	74.5	77.7	80.3	82.4	84.0	84.0	0.0	-84.0	-84.0	-82.4	-80.3	-77.7	-74.5	******
MAY.	D2	******	71.6	74.6	76.8	78.1	77.8	72.3	0.0	-72.3	-77.8	-78.1	-76.8	-74.6	-71.6	******
MAY.	D3	******	69.7	72.5	74.4	75.1	73.7	65.0	0.0	-65.0	-73.7	-75.1	-74.4	-72.5	-69.7	******
JUN.	D1	******	68.7	71.5	73.2	73.7	71.6	61.5	0.0	-61.5	-71.6	-73.7	-73.2	-71.5	-68.7	******
JUN.	D2	******	67.7	70.4	72.0	72.2	69.6	58.3	0.0	-58.3	-69.6	-72.2	-72.0	-70.4	-67.7	******
JUN.	D3	******	67.7	70.4	72.0	72.2	69.6	58.3	0.0	-58.3	-69.6	-72.2	-72.0	-70.4	-67.7	******
JUL.	D1	******	67.7	70.4	72.0	72.2	69.6	58.3	0.0	-58.3	-69.6	-72.2	-72.0	-70.4	-67.7	******
JUL.	D2	******	69.7	72.5	74.4	75.1	73.7	65.0	0.0	-65.0	-73.7	-75.1	-74.4	-72.5	-69.7	******
JUL.	D3	******	70.6	73.6	75.6	76.6	75.7	68.6	0.0	-68.6	-75.7	-76.6	-75.6	-73.6	-70.6	******
AGO.	D1	******	73.5	76.7	79.2	81.0	81.9	80.1	0.0	-80.1	-81.9	-81.0	-79.2	-76.7	-73.5	******
AGO.	D2	******	76.5	79.8	82.7	85.3	88.1	88.0	0.0	-88.0	-88.1	-85.3	-82.7	-79.8	-76.5	******
AGO.	D3	******	79.4	82.9	86.1	89.6	85.8	76.5	0.0	-76.5	-85.8	-89.6	-86.1	-82.9	-79.4	******
SEP.	D1	******	83.2	86.9	89.3	84.8	78.1	63.1	0.0	-63.1	-78.1	-84.8	-89.3	-86.9	-83.2	******
SEP.	D2	******	87.1	89.0	84.8	79.4	70.9	52.4	0.0	-52.4	-70.9	-79.4	-84.8	-89.0	-87.1	******
SEP.	D3	******	******	85.0	80.4	74.2	64.3	44.1	0.0	-44.1	-64.3	-74.2	-80.4	-85.0	******	******
OCT.	D1	******	******	81.1	76.1	69.3	58.3	37.7	0.0	-37.7	-58.3	-69.3	-76.1	-81.1	******	******
OCT.	D2	******	******	77.2	71.9	64.6	53.0	32.7	0.0	-32.7	-53.0	-64.6	-71.9	-77.2	******	******
OCT.	D3	******	******	74.3	65.9	61.2	49.3	29.6	0.0	-29.6	-49.3	-61.2	-65.9	-74.3	******	******
NOV.	D1	******	******	70.4	64.9	57.0	44.9	26.2	0.0	-26.2	-44.9	-57.0	-64.9	-70.4	******	******
NOV.	D2	******	******	68.5	62.9	53.9	42.9	24.7	0.0	-24.7	-42.9	-53.9	-62.9	-68.5	******	******
NOV.	D3	******	******	65.6	60.0	51.9	40.0	22.6	0.0	-22.6	-40.0	-51.9	-60.0	-65.6	******	******
DIC.	D1	******	******	64.7	59.0	51.0	39.1	22.0	0.0	-22.0	-39.1	-51.0	-59.0	-64.7	******	******
DIC.	D2	******	******	63.7	58.1	50.0	38.3	21.4	0.0	-21.4	-38.3	-50.0	-58.1	-63.7	******	******
DIC.	D3	******	******	63.7	58.1	50.0	38.3	21.4	0.0	-21.4	-38.3	-50.0	-58.1	-63.7	******	******

LATITUD=16.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	7.32	20.02	31.80	41.96	49.26	52.00	49.26	41.96	31.80	20.02	7.32	0.00	0.00
ENE.	D2	0.00	0.00	7.67	20.48	32.40	42.72	50.18	53.00	50.18	42.72	32.40	20.48	7.67	0.00	0.00
ENE.	D3	0.00	0.00	8.37	21.39	33.57	44.22	52.02	55.00	52.02	44.22	33.57	21.39	8.37	0.00	0.00
FEB.	D1	0.00	0.00	9.39	22.71	35.27	46.41	54.74	58.00	54.74	46.41	35.27	22.71	9.39	0.00	0.00
FEB.	D2	0.00	0.00	10.39	23.97	36.89	48.57	57.43	61.00	57.43	48.57	36.89	23.97	10.39	0.00	0.00
FEB.	D3	0.00	0.00	11.69	25.57	38.92	51.18	60.92	65.00	60.92	51.18	38.92	25.57	11.69	0.00	0.00
MAR.	D1	0.00	0.00	12.63	26.69	40.33	53.04	63.46	68.00	63.46	53.04	40.33	26.69	12.63	0.00	0.00
MAR.	D2	0.00	0.00	13.83	28.08	42.04	55.32	66.68	72.00	66.68	55.32	42.04	28.08	13.83	0.00	0.00
MAR.	D3	0.00	0.55	14.97	29.34	43.54	57.31	69.65	76.00	69.65	57.31	43.54	29.34	14.97	0.55	0.00
ABR.	D1	0.00	1.65	16.04	30.45	44.81	58.95	72.72	80.00	72.72	58.95	44.81	30.45	16.04	1.65	0.00
ABR.	D2	0.00	2.74	17.03	31.41	45.83	60.19	74.21	84.00	74.21	60.19	45.83	31.41	17.03	2.74	0.00
ABR.	D3	0.00	3.55	17.72	32.03	46.41	60.83	75.18	87.00	75.18	60.83	46.41	32.03	17.72	3.55	0.00
MAY.	D1	0.00	4.36	18.37	32.55	46.83	61.19	75.58	90.00	75.58	61.19	46.83	32.55	18.37	4.36	0.00
MAY.	D2	0.00	5.15	18.96	32.97	47.09	61.27	75.39	87.00	75.39	61.27	47.09	32.97	18.96	5.15	0.00
MAY.	D3	0.00	5.67	19.33	33.19	47.17	61.16	74.93	85.00	74.93	61.16	47.17	33.19	19.33	5.67	0.00
JUN.	D1	0.00	5.93	19.51	33.29	47.18	61.06	74.61	84.00	74.61	61.06	47.18	33.29	19.51	5.93	0.00
JUN.	D2	0.00	6.18	19.68	33.38	47.17	60.93	74.24	83.00	74.24	60.93	47.17	33.38	19.68	6.18	0.00
JUN.	D3	0.00	6.18	19.68	33.38	47.17	60.93	74.24	83.01	74.24	60.93	47.17	33.38	19.68	6.18	0.00
JUL.	D1	0.00	6.18	19.68	33.38	47.17	60.93	74.24	83.00	74.24	60.93	47.17	33.38	19.68	6.18	0.00
JUL.	D2	0.00	5.67	19.33	33.19	47.17	61.16	74.93	85.00	74.93	61.16	47.17	33.19	19.33	5.67	0.00
JUL.	D3	0.00	5.41	19.15	33.09	47.14	61.23	75.19	86.00	75.19	61.23	47.14	33.09	19.15	5.41	0.00
AGO.	D1	0.00	4.62	18.57	32.70	46.94	61.25	75.59	89.00	75.59	61.25	46.94	32.70	18.57	4.62	0.00
AGO.	D2	0.00	3.82	17.94	32.21	46.57	60.98	75.38	88.00	75.38	60.98	46.57	32.21	17.94	3.82	0.00
AGO.	D3	0.00	3.01	17.27	31.63	46.04	60.43	74.59	85.00	74.59	60.43	46.04	31.63	17.27	3.01	0.00
SEP.	D1	0.00	1.93	16.29	30.71	45.09	59.30	72.78	81.00	72.78	59.30	45.09	30.71	16.29	1.93	0.00
SEP.	D2	0.00	0.83	15.24	29.63	43.88	57.75	70.33	77.00	70.33	57.75	43.88	29.63	15.24	0.83	0.00
SEP.	D3	0.00	0.00	14.12	28.41	42.44	55.85	67.45	73.00	67.45	55.85	42.44	28.41	14.12	0.00	0.00
OCT.	D1	0.00	0.00	12.93	27.05	40.78	53.64	64.28	69.00	64.28	53.64	40.78	27.05	12.93	0.00	0.00
OCT.	D2	0.00	0.00	11.69	25.57	38.92	51.18	60.92	65.00	60.92	51.18	38.92	25.57	11.69	0.00	0.00
OCT.	D3	0.00	0.00	10.72	24.38	37.41	49.20	58.31	62.00	58.31	49.20	37.41	24.38	10.72	0.00	0.00
NOV.	D1	0.00	0.00	9.39	22.71	35.27	46.41	54.74	58.00	54.74	46.41	35.27	22.71	9.39	0.00	0.00
NOV.	D2	0.00	0.00	8.71	21.83	34.14	44.96	52.93	56.00	52.93	44.96	34.14	21.83	8.71	0.00	0.00
NOV.	D3	0.00	0.00	7.67	20.48	32.40	42.72	50.18	53.00	50.18	42.72	32.40	20.48	7.67	0.00	0.00
DIC.	D1	0.00	0.00	7.32	20.02	31.80	41.96	49.26	52.00	49.26	41.96	31.80	20.02	7.32	0.00	0.00
DIC.	D2	0.00	0.00	6.97	19.56	31.20	41.19	48.33	51.00	48.33	41.19	31.20	19.56	6.97	0.00	0.00
DIC.	D3	0.00	0.00	6.97	19.56	31.20	41.19	48.33	51.00	48.33	41.19	31.20	19.56	6.97	0.00	0.00

LATITUDE 1.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.5	58.7	50.5	38.6	21.6	0.0	-21.6	-38.6	-50.5	-58.7	-64.5	******	******
ENE.	D2	******	******	65.5	59.7	51.4	39.4	22.2	0.0	-22.2	-39.4	-51.4	-59.7	-65.5	******	******
ENE.	D3	******	******	67.4	61.6	53.4	41.3	23.4	0.0	-23.4	-41.3	-53.4	-61.6	-67.4	******	******
FEB.	D1	******	******	70.2	64.5	56.4	44.2	25.5	0.0	-25.5	-44.2	-56.4	-64.5	-70.2	******	******
FEB.	D2	******	******	73.1	67.4	59.5	47.3	27.9	0.0	-27.9	-47.3	-59.5	-67.4	-73.1	******	******
FEB.	D3	******	******	77.0	71.5	63.9	52.0	31.7	0.0	-31.7	-52.0	-63.9	-71.5	-77.0	******	******
MAR.	D1	******	******	79.9	74.6	67.3	55.8	35.2	0.0	-35.2	-55.8	-67.3	-74.6	-79.9	******	******
MAR.	D2	******	******	83.8	78.8	72.1	61.4	40.8	0.0	-40.8	-61.4	-72.1	-78.8	-83.8	******	******
MAR.	D3	******	88.1	87.8	83.1	77.1	67.7	48.0	0.0	-48.0	-67.7	-77.1	-83.1	-87.8	-88.1	******
ABR.	D1	******	88.2	86.2	87.4	82.4	74.6	57.4	0.0	-57.4	-74.6	-82.4	-87.4	-86.2	-88.2	******
ABR.	D2	******	80.4	84.2	87.9	87.9	82.1	69.5	0.0	-69.5	-82.1	-87.9	-87.9	-84.2	-80.4	******
ABR.	D3	******	77.5	81.1	84.5	87.8	88.1	80.3	0.0	-80.3	-88.1	-87.8	-84.5	-81.1	-77.5	******
MAY.	D1	******	74.6	78.1	81.0	83.5	85.8	87.9	0.0	-87.9	-85.8	-83.5	-81.0	-78.1	-74.6	******
MAY.	D2	******	71.7	75.0	77.4	79.1	79.5	76.0	0.0	-76.0	-79.5	-79.1	-77.4	-75.0	-71.7	******
MAY.	D3	******	69.7	72.9	75.1	76.2	75.4	68.3	0.0	-68.3	-75.4	-76.2	-75.1	-72.9	-69.7	******
JUN.	D1	******	68.3	71.6	73.9	74.7	73.3	64.7	0.0	-64.7	-73.3	-74.7	-73.9	-71.6	-68.3	******
JUN.	D2	******	67.8	70.8	72.7	73.2	71.3	61.3	0.0	-61.3	-71.3	-73.2	-72.7	-70.8	-67.8	******
JUN.	D3	******	67.8	70.8	72.7	73.2	71.3	61.3	0.0	-61.3	-71.3	-73.2	-72.7	-70.8	-67.8	******
JUL.	D1	******	67.8	70.8	72.7	73.2	71.3	61.3	0.0	-61.3	-71.3	-73.2	-72.7	-70.8	-67.8	******
JUL.	D2	******	69.7	72.9	75.1	76.2	75.4	68.3	0.0	-68.3	-75.4	-76.2	-75.1	-72.9	-69.7	******
JUL.	D3	******	70.7	73.9	76.2	77.6	77.5	72.1	0.0	-72.1	-77.5	-77.6	-76.2	-73.9	-70.7	******
AGO.	D1	******	73.6	77.0	79.8	82.0	83.7	83.9	0.0	-83.9	-83.7	-82.0	-79.8	-77.0	-73.6	******
AGO.	D2	******	76.5	80.1	83.3	86.4	89.9	84.1	0.0	-84.1	-89.9	-86.4	-83.3	-80.1	-76.5	******
AGO.	D3	******	79.4	83.2	86.8	89.3	84.1	72.9	0.0	-72.9	-84.1	-89.3	-86.8	-83.2	-79.4	******
SEP.	D1	******	83.3	87.2	88.7	83.8	76.4	60.2	0.0	-60.2	-76.4	-83.8	-88.7	-87.2	-83.3	******
SEP.	D2	******	87.1	88.8	84.2	78.4	69.4	50.2	0.0	-50.2	-69.4	-78.4	-84.2	-88.8	-87.1	******
SEP.	D3	******	******	84.8	79.9	73.3	62.9	42.4	0.0	-42.4	-62.9	-73.3	-79.9	-84.8	******	******
OCT.	D1	******	******	80.9	75.6	68.5	57.2	36.5	0.0	-36.5	-57.2	-68.5	-75.6	-80.9	******	******
OCT.	D2	******	******	77.0	71.5	63.9	52.0	31.7	0.0	-31.7	-52.0	-63.9	-71.5	-77.0	******	******
OCT.	D3	******	******	74.1	68.4	60.5	48.5	28.8	0.0	-28.8	-48.5	-60.6	-68.4	-74.1	******	******
NOV.	D1	******	******	70.2	64.5	56.4	44.2	25.5	0.0	-25.5	-44.2	-56.4	-64.5	-70.2	******	******
NOV.	D2	******	******	68.3	62.5	54.3	42.2	24.1	0.0	-24.1	-42.2	-54.3	-62.5	-68.3	******	******
NOV.	D3	******	******	65.5	59.7	51.4	39.4	22.2	0.0	-22.2	-39.4	-51.4	-59.7	-65.5	******	******
DIC.	D1	******	******	64.5	58.7	50.5	38.6	21.6	0.0	-21.6	-38.6	-50.5	-58.7	-64.5	******	******
DIC.	D2	******	******	63.6	57.8	49.5	37.7	21.0	0.0	-21.0	-37.7	-49.5	-57.8	-63.6	******	******
DIC.	D3	******	******	63.6	57.8	49.5	37.7	21.0	0.0	-21.0	-37.7	-49.5	-57.8	-63.6	******	******

LATITUD=17.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	6.89	19.50	31.16	41.17	48.33	51.00	48.33	41.17	31.16	19.50	6.89	0.00	0.00
ENE.	D2	0.00	0.00	7.26	19.96	31.77	41.94	49.25	52.00	49.25	41.94	31.77	19.96	7.26	0.00	0.00
ENE.	D3	0.00	0.00	7.98	20.91	32.97	43.46	51.10	54.00	51.10	43.46	32.97	20.91	7.98	0.00	0.00
FEB.	D1	0.00	0.00	9.05	22.27	34.71	45.69	53.84	57.00	53.84	45.69	34.71	22.27	9.05	0.00	0.00
FEB.	D2	0.00	0.00	10.10	23.59	36.38	47.83	56.54	60.00	56.54	47.83	36.38	23.59	10.10	0.00	0.00
FEB.	D3	0.00	0.00	11.46	25.25	38.47	50.56	60.07	64.00	60.07	50.56	38.47	25.25	11.46	0.00	0.00
MAR.	D1	0.00	0.00	12.45	26.49	39.94	52.47	62.64	67.00	62.64	52.47	39.94	26.49	12.45	0.00	0.00
MAR.	D2	0.00	0.00	13.72	27.88	41.73	54.83	65.92	71.00	65.92	54.83	41.73	27.88	13.72	0.00	0.00
MAR.	D3	0.00	0.58	14.93	29.21	43.31	56.92	68.96	75.00	68.96	56.92	43.31	29.21	14.93	0.58	0.00
ABR.	D1	0.00	1.75	16.06	30.46	44.67	58.67	71.66	79.00	71.66	58.67	44.67	30.46	16.06	1.75	0.00
ABR.	D2	0.00	2.91	17.13	31.44	45.78	60.04	73.83	83.00	73.83	60.04	45.78	31.44	17.13	2.91	0.00
ABR.	D3	0.00	3.77	17.87	32.12	46.44	60.78	74.98	86.00	74.98	60.78	46.44	32.12	17.87	3.77	0.00
MAY.	D1	0.00	4.62	18.57	32.70	46.94	61.25	75.59	89.00	75.59	61.25	46.94	32.70	18.57	4.62	0.00
MAY.	D2	0.00	5.46	19.22	33.18	47.27	61.43	75.60	88.00	75.60	61.43	47.27	33.18	19.22	5.46	0.00
MAY.	D3	0.00	6.01	19.62	33.45	47.40	61.40	75.27	86.00	75.27	61.40	47.40	33.45	19.62	6.01	0.00
JUN.	D1	0.00	6.29	19.82	33.56	47.43	61.33	75.01	85.00	75.01	61.33	47.43	33.56	19.82	6.29	0.00
JUN.	D2	0.00	6.56	20.00	33.67	47.45	61.23	74.69	84.00	74.69	61.23	47.45	33.67	20.00	6.56	0.00
JUN.	D3	0.00	6.56	20.00	33.67	47.45	61.23	74.69	84.00	74.69	61.23	47.45	33.67	20.00	6.56	0.00
JUL.	D1	0.00	6.56	20.00	33.67	47.45	61.23	74.69	84.00	74.69	61.23	47.45	33.67	20.00	6.56	0.00
JUL.	D2	0.00	6.01	19.62	33.45	47.40	61.40	75.27	86.00	75.27	61.40	47.40	33.45	19.62	6.01	0.00
JUL.	D3	0.00	5.74	19.43	33.32	47.34	61.43	75.47	87.00	75.47	61.43	47.34	33.32	19.43	5.74	0.00
AGO.	D1	0.00	4.90	18.79	32.87	47.07	61.34	75.66	90.00	75.66	61.34	47.07	32.87	18.79	4.90	0.00
AGO.	D2	0.00	4.06	18.11	32.32	46.62	60.96	75.24	87.00	75.24	60.96	46.62	32.32	18.11	4.06	0.00
AGO.	D3	0.00	3.20	17.38	31.68	46.02	60.31	74.27	84.00	74.27	60.31	46.02	31.68	17.38	3.20	0.00
SEP.	D1	0.00	2.04	16.34	30.68	44.98	59.05	72.26	80.00	72.26	59.05	44.98	30.68	16.34	2.04	0.00
SEP.	D2	0.00	0.88	15.22	29.52	43.68	57.39	69.68	76.00	69.68	57.39	43.68	29.52	15.22	0.88	0.00
SEP.	D3	0.00	0.00	14.03	28.23	42.14	55.38	66.70	72.00	66.70	55.38	42.14	28.23	14.03	0.00	0.00
OCT.	D1	0.00	0.00	12.77	26.86	40.46	53.09	63.47	68.00	63.47	53.09	40.46	26.86	12.77	0.00	0.00
OCT.	D2	0.00	0.00	11.46	25.25	38.47	50.56	60.07	64.00	60.07	50.56	38.47	25.25	11.46	0.00	0.00
OCT.	D3	0.00	0.00	10.45	24.01	36.92	48.53	57.43	61.00	57.43	48.53	36.92	24.01	10.45	0.00	0.00
NOV.	D1	0.00	0.00	9.05	22.27	34.71	45.69	53.84	57.00	53.84	45.69	34.71	22.27	9.05	0.00	0.00
NOV.	D2	0.00	0.00	8.34	21.37	33.56	44.21	52.01	55.00	52.01	44.21	33.56	21.37	8.34	0.00	0.00
NOV.	D3	0.00	0.00	7.26	19.96	31.77	41.94	49.25	52.00	49.25	41.94	31.77	19.96	7.26	0.00	0.00
DIC.	D1	0.00	0.00	6.89	19.50	31.16	41.17	48.33	51.00	48.33	41.17	31.16	19.50	6.89	0.00	0.00
DIC.	D2	0.00	0.00	6.52	19.02	30.55	40.40	47.40	50.00	47.40	40.40	30.55	19.02	6.52	0.00	0.00
DIC.	D3	0.00	0.00	6.52	19.02	30.55	40.40	47.40	50.00	47.40	40.40	30.55	19.02	6.52	0.00	0.00

LATITUD= 17.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.4	58.4	50.0	38.0	21.2	0.0	-21.2	-38.0	-50.0	-58.4	-64.4	******	******
ENE.	D2	******	******	65.4	59.3	50.9	38.9	21.7	0.0	-21.7	-38.9	-50.9	-59.3	-65.4	******	******
ENE.	D3	******	******	67.3	61.2	52.8	40.6	22.9	0.0	-22.9	-40.6	-52.8	-61.2	-67.3	******	******
FEB.	D1	******	******	70.1	64.1	55.8	43.5	24.9	0.0	-24.9	-43.5	-55.8	-64.1	-70.1	******	******
FEB.	D2	******	******	72.9	67.0	58.8	46.5	27.2	0.0	-27.2	-46.5	-58.8	-67.0	-72.9	******	******
FEB.	D3	******	******	76.8	71.0	63.1	51.0	30.8	0.0	-30.8	-51.0	-63.1	-71.0	-76.8	******	******
MAR.	D1	******	******	79.7	74.1	66.5	54.7	34.1	0.0	-34.1	-54.7	-66.5	-74.1	-79.7	******	******
MAR.	D2	******	******	83.6	78.3	71.2	60.2	39.3	0.0	-39.3	-60.2	-71.2	-78.3	-83.6	******	******
MAR.	D3	******	88.1	87.5	82.6	76.2	66.3	46.1	0.0	-46.1	-66.3	-76.2	-82.6	-87.5	-88.1	******
ABR.	D1	******	84.3	88.5	87.0	81.5	73.0	54.9	0.0	-54.9	-73.0	-81.5	-87.0	-88.5	-84.3	******
ABR.	D2	******	80.4	84.5	88.5	86.9	80.4	66.3	0.0	-66.3	-80.4	-86.9	-88.5	-84.5	-80.4	******
ABR.	D3	******	77.5	81.5	85.1	88.9	86.3	76.6	0.0	-76.6	-86.3	-88.9	-85.1	-81.5	-77.5	******
MAY.	D1	******	74.7	78.4	81.6	84.5	87.6	88.2	0.0	-88.2	-87.6	-84.5	-81.6	-78.4	-74.7	******
MAY.	D2	******	71.8	75.3	78.1	80.2	81.3	79.7	0.0	-79.7	-81.3	-80.2	-78.1	-75.3	-71.8	******
MAY.	D3	******	69.8	73.2	75.7	77.2	77.2	71.9	0.0	-71.9	-77.2	-77.2	-75.7	-73.2	-69.8	******
JUN.	D1	******	68.9	72.2	74.5	75.7	75.1	68.1	0.0	-68.1	-75.1	-75.7	-74.5	-72.2	-68.9	******
JUN.	D2	******	67.9	71.1	73.3	74.3	73.0	64.5	0.0	-64.5	-73.0	-74.3	-73.3	-71.1	-67.9	******
JUN.	D3	******	67.9	71.1	73.3	74.3	73.0	64.5	0.0	-64.5	-73.0	-74.3	-73.3	-71.1	-67.9	******
JUL.	D1	******	67.9	71.1	73.3	74.3	73.0	64.5	0.0	-64.5	-73.0	-74.3	-73.3	-71.1	-67.9	******
JUL.	D2	******	69.8	73.2	75.7	77.2	77.2	71.9	0.0	-71.9	-77.2	-77.2	-75.7	-73.2	-69.8	******
JUL.	D3	******	70.8	74.3	76.9	78.7	79.3	75.8	0.0	-75.8	-79.3	-78.7	-76.9	-74.3	-70.8	******
AGO.	D1	******	73.7	77.4	80.4	83.1	85.5	87.8	0.0	-87.8	-85.5	-83.1	-80.4	-77.4	-73.7	******
AGO.	D2	******	76.6	80.4	83.9	87.4	88.3	80.4	0.0	-80.4	-88.3	-87.4	-83.9	-80.4	-76.6	******
AGO.	D3	******	79.5	83.5	87.4	88.3	82.1	69.5	0.0	-69.5	-82.3	-88.3	-87.4	-83.5	-79.5	******
SEP.	D1	******	83.3	87.5	88.1	82.8	74.8	57.5	0.0	-57.5	-74.8	-82.8	-88.1	-87.5	-83.3	******
SEP.	D2	******	87.1	88.5	83.7	77.5	67.9	48.1	0.0	-48.1	-67.9	-77.5	-83.7	-88.5	-87.1	******
SEP.	D3	******	******	84.5	79.3	72.5	61.6	40.9	0.0	-40.9	-61.6	-72.5	-79.3	-84.5	******	******
OCT.	D1	******	******	80.6	75.1	67.7	56.0	35.3	0.0	-35.3	-56.0	-67.7	-75.1	-80.6	******	******
OCT.	D2	******	******	76.8	71.0	63.1	51.0	30.8	0.0	-30.8	-51.0	-63.1	-71.0	-76.8	******	******
OCT.	D3	******	******	73.9	68.0	59.9	47.6	28.1	0.0	-28.1	-47.6	-59.9	-68.0	-73.9	******	******
NOV.	D1	******	******	70.1	64.1	55.8	43.5	24.9	0.0	-24.9	-43.5	-55.8	-64.1	-70.1	******	******
NOV.	D2	******	******	68.2	62.2	53.8	41.6	23.6	0.0	-23.6	-41.6	-53.8	-62.2	-68.2	******	******
NOV.	D3	******	******	65.4	59.3	50.9	38.9	21.7	0.0	-21.7	-38.9	-50.9	-59.3	-65.4	******	******
DIC.	D1	******	******	64.4	58.4	50.0	38.0	21.2	0.0	-21.2	-38.0	-50.0	-58.4	-64.4	******	******
DIC.	D2	******	******	63.5	57.5	49.1	37.2	20.6	0.0	-20.6	-37.2	-49.1	-57.5	-63.5	******	******
DIC.	D3	******	******	63.5	57.5	49.1	37.2	20.6	0.0	-20.6	-37.2	-49.1	-57.5	-63.5	******	******

LATITUD=18.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	6.46	18.97	30.52	40.38	47.39	50.00	47.39	40.38	30.52	18.97	6.46	0.00	0.00
ENE.	D2	0.00	0.00	6.84	19.46	31.14	41.16	48.32	51.00	48.32	41.16	31.14	19.46	6.84	0.00	0.00
ENE.	D3	0.00	0.00	7.59	20.43	32.36	42.70	50.17	53.00	50.17	42.70	32.36	20.43	7.59	0.00	0.00
FEB.	D1	0.00	0.00	8.71	21.83	34.14	44.96	52.93	56.00	52.93	44.96	34.14	21.83	8.71	0.00	0.00
FEB.	D2	0.00	0.00	9.81	23.19	35.86	47.14	55.65	59.00	55.65	47.14	35.86	23.19	9.81	0.00	0.00
FEB.	D3	0.00	0.00	11.23	24.92	38.02	49.92	59.20	63.00	59.20	49.92	38.02	24.92	11.23	0.00	0.00
MAR.	D1	0.00	0.00	12.27	26.14	39.53	51.89	61.50	66.00	61.50	51.89	39.53	26.14	12.27	0.00	0.00
MAR.	D2	0.00	0.00	13.60	27.67	41.40	54.33	65.14	70.00	65.14	54.33	41.40	27.67	13.60	0.00	0.00
MAR.	D3	0.00	0.62	14.88	29.08	43.07	56.50	68.26	74.00	68.26	56.50	43.07	29.08	14.88	0.62	0.00
ABR.	D1	0.00	1.85	16.09	30.35	44.52	58.37	71.07	78.00	71.07	58.37	44.52	30.35	16.09	1.85	0.00
ABR.	D2	0.00	3.08	17.22	31.46	45.72	59.86	73.41	82.00	73.41	59.86	45.72	31.46	17.22	3.08	0.00
ABR.	D3	0.00	3.99	18.02	32.20	46.45	60.70	74.71	85.00	74.71	60.70	46.45	32.20	18.02	3.99	0.00
MAY.	D1	0.00	4.89	18.77	32.84	47.02	61.27	75.52	88.00	75.52	61.27	47.02	32.84	18.77	4.89	0.00
MAY.	D2	0.00	5.77	19.47	33.38	47.43	61.57	75.74	89.00	75.74	61.57	47.43	33.38	19.47	5.77	0.00
MAY.	D3	0.00	6.36	19.91	33.69	47.61	61.60	75.55	87.00	75.55	61.60	47.61	33.69	19.91	6.36	0.00
JUN.	D1	0.00	6.65	20.12	33.83	47.67	61.57	75.36	86.00	75.36	61.57	47.67	33.83	20.12	6.65	0.00
JUN.	D2	0.00	6.93	20.32	33.95	47.71	61.51	75.10	85.00	75.10	61.51	47.71	33.95	20.32	6.93	0.00
JUN.	D3	0.00	6.93	20.32	33.95	47.71	61.51	75.10	85.00	75.10	61.51	47.71	33.95	20.32	6.93	0.00
JUL.	D1	0.00	6.93	20.32	33.95	47.71	61.51	75.10	85.00	75.10	61.51	47.71	33.95	20.32	6.93	0.00
JUL.	D2	0.00	6.36	19.91	33.69	47.61	61.60	75.55	87.00	75.55	61.60	47.61	33.69	19.91	6.36	0.00
JUL.	D3	0.00	6.07	19.69	33.54	47.53	61.60	75.68	88.00	75.68	61.60	47.53	33.54	19.69	6.07	0.00
AGO.	D1	0.00	5.18	19.01	33.03	47.18	61.40	75.66	89.00	75.66	61.40	47.18	33.03	19.01	5.18	0.00
AGO.	D2	0.00	4.29	18.28	32.47	46.66	60.92	75.04	86.00	75.04	60.92	46.66	32.47	18.28	4.29	0.00
AGO.	D3	0.00	3.38	17.49	31.72	45.98	60.17	73.89	83.00	73.89	60.17	45.98	31.72	17.49	3.38	0.00
SEP.	D1	0.00	2.16	16.38	30.64	44.84	58.78	71.71	79.00	71.71	58.78	44.84	30.64	16.38	2.16	0.00
SEP.	D2	0.00	0.93	15.19	29.41	43.45	57.00	69.00	75.00	69.00	57.00	43.45	29.41	15.19	0.93	0.00
SEP.	D3	0.00	0.00	13.93	28.04	41.84	54.90	65.94	71.00	65.94	54.90	41.84	28.04	13.93	0.00	0.00
OCT.	D1	0.00	0.00	12.61	26.54	40.02	52.57	62.65	67.00	62.65	52.57	40.02	26.54	12.61	0.00	0.00
OCT.	D2	0.00	0.00	11.23	24.92	38.02	49.92	59.20	63.00	59.20	49.92	38.02	24.92	11.23	0.00	0.00
OCT.	D3	0.00	0.00	10.17	23.61	36.41	47.85	56.55	60.00	56.55	47.85	36.41	23.61	10.17	0.00	0.00
NOV.	D1	0.00	0.00	8.71	21.83	34.14	44.96	52.93	56.00	52.93	44.96	34.14	21.83	8.71	0.00	0.00
NOV.	D2	0.00	0.00	7.97	20.90	32.96	43.46	51.10	54.00	51.10	43.46	32.96	20.90	7.97	0.00	0.00
NOV.	D3	0.00	0.00	6.84	19.46	31.14	41.16	48.32	51.00	48.32	41.16	31.14	19.46	6.84	0.00	0.00
DIC.	D1	0.00	0.00	6.46	18.97	30.52	40.38	47.39	50.00	47.39	40.38	30.52	18.97	6.46	0.00	0.00
DIC.	D2	0.00	0.00	6.08	18.40	29.89	39.60	46.46	49.00	46.46	39.60	29.89	18.40	6.08	0.00	0.00
DIC.	D3	0.00	0.00	6.08	18.40	29.89	39.60	46.46	49.00	46.46	39.60	29.89	18.40	6.08	0.00	0.00

LATITUD= 18.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.3	58.1	49.6	37.5	20.8	0.0	-20.8	-37.5	-49.6	-58.1	-64.3	******	******
ENE.	D2	******	******	65.3	59.0	50.5	38.3	21.3	0.0	-21.3	-38.3	-50.5	-59.0	-65.3	******	******
ENE.	D3	******	******	67.1	60.9	52.3	40.0	22.5	0.0	-22.5	-40.0	-52.3	-60.9	-67.1	******	******
FEB.	D1	******	******	69.9	63.7	55.2	42.8	24.4	0.0	-24.4	-42.8	-55.2	-63.7	-69.9	******	******
FEB.	D2	******	******	72.8	66.6	58.2	45.7	26.5	0.0	-26.5	-45.7	-58.2	-66.6	-72.8	******	******
FEB.	D3	******	******	76.6	70.6	62.4	50.1	30.0	0.0	-30.0	-50.1	-62.4	-70.6	-76.6	******	******
MAR.	D1	******	******	79.4	73.6	65.8	53.7	33.0	0.0	-33.0	-53.7	-65.8	-73.6	-79.4	******	******
MAR.	D2	******	******	83.3	77.8	70.4	59.0	38.0	0.0	-38.0	-59.0	-70.4	-77.8	-83.3	******	******
MAR.	D3	******	88.1	87.2	82.0	75.3	64.9	44.3	0.0	-44.3	-64.9	-75.3	-82.0	-87.2	-88.1	******
ABR.	D1	******	84.3	88.0	86.4	80.5	71.5	52.5	0.0	-52.5	-71.5	-80.5	-86.4	-88.0	-84.3	******
ABR.	D2	******	80.5	84.8	89.1	85.9	78.7	63.2	0.0	-63.2	-78.7	-85.9	-89.1	-84.8	-80.5	******
ABR.	D3	******	77.6	81.8	85.7	89.9	84.5	73.0	0.0	-73.0	-84.5	-89.9	-85.7	-81.8	-77.6	******
MAY.	D1	******	74.7	78.7	82.2	85.6	89.4	88.3	0.0	-88.3	-89.4	-85.6	-82.2	-78.7	-74.7	******
MAY.	D2	******	71.9	75.6	78.7	81.2	83.2	83.6	0.0	-83.6	-83.2	-81.2	-78.7	-75.6	-71.9	******
MAY.	D3	******	69.9	73.6	76.3	78.3	79.0	75.6	0.0	-75.6	-79.0	-78.3	-76.3	-73.6	-69.9	******
JUN.	D1	******	69.0	72.5	75.1	76.8	76.9	71.7	0.0	-71.7	-76.9	-76.8	-75.1	-72.5	-69.0	******
JUN.	D2	******	68.0	71.5	73.9	75.3	74.8	67.9	0.0	-67.9	-74.8	-75.3	-73.9	-71.5	-68.0	******
JUN.	D3	******	68.0	71.5	73.9	75.3	74.8	67.9	0.0	-67.9	-74.8	-75.3	-73.9	-71.5	-68.0	******
JUL.	D1	******	68.0	71.5	73.9	75.3	74.8	67.9	0.0	-67.9	-74.8	-75.3	-73.9	-71.5	-68.0	******
JUL.	D2	******	69.9	73.6	76.3	78.3	79.0	75.6	0.0	-75.6	-79.0	-78.3	-76.3	-73.6	-69.9	******
JUL.	D3	******	70.9	74.6	77.5	79.8	81.1	79.6	0.0	-79.6	-81.1	-79.8	-77.5	-74.6	-70.9	******
AGO.	D1	******	73.8	77.7	81.1	84.2	87.3	88.3	0.0	-88.3	-87.3	-84.2	-81.1	-77.7	-73.8	******
AGO.	D2	******	76.7	80.8	84.6	88.5	86.5	76.7	0.0	-76.7	-86.5	-88.5	-84.6	-80.8	-76.7	******
AGO.	D3	******	79.5	83.8	88.0	87.3	80.6	66.3	0.0	-66.3	-80.6	-87.3	-88.0	-83.8	-79.5	******
SEP.	D1	******	83.3	87.8	87.5	81.8	73.2	54.9	0.0	-54.9	-73.2	-81.8	-87.5	-87.8	-83.3	******
SEP.	D2	******	87.1	85.2	83.1	76.6	66.5	46.1	0.0	-46.1	-66.5	-76.6	-83.1	-85.2	-87.1	******
SEP.	D3	******	******	84.3	78.8	71.6	60.4	39.4	0.0	-39.4	-60.4	-71.6	-78.8	-84.3	******	******
OCT.	D1	******	******	80.4	74.7	66.9	54.9	34.1	0.0	-34.1	-54.9	-66.9	-74.7	-80.4	******	******
OCT.	D2	******	******	76.6	70.6	62.4	50.1	30.0	0.0	-30.0	-50.1	-62.4	-70.6	-76.6	******	******
OCT.	D3	******	******	73.7	67.6	59.3	46.8	27.3	0.0	-27.3	-46.8	-59.3	-67.6	-73.7	******	******
NOV.	D1	******	******	69.9	63.7	55.2	42.8	24.4	0.0	-24.4	-42.8	-55.2	-63.7	-69.9	******	******
NOV.	D2	******	******	68.1	61.8	53.3	40.9	23.1	0.0	-23.1	-40.9	-53.3	-61.8	-68.1	******	******
NOV.	D3	******	******	65.3	59.0	50.5	38.3	21.3	0.0	-21.3	-38.3	-50.5	-59.0	-65.3	******	******
DIC.	D1	******	******	64.3	58.1	49.6	37.5	20.8	0.0	-20.8	-37.5	-49.6	-58.1	-64.3	******	******
DIC.	D2	******	******	63.4	57.2	48.7	36.7	20.2	0.0	-20.2	-36.7	-48.7	-57.2	-63.4	******	******
DIC.	D3	******	******	63.4	57.2	48.7	36.7	20.2	0.0	-20.2	-36.7	-48.7	-57.2	-63.4	******	******

LATITUD=19.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	6.02	18.44	29.86	39.59	46.46	49.00	46.46	39.59	29.86	18.44	6.02	0.00	0.00
ENE.	02	0.00	0.00	6.42	18.95	30.50	40.37	47.39	50.00	47.39	40.37	30.50	18.95	6.42	0.00	0.00
ENE.	03	0.00	0.00	7.20	19.94	31.75	41.93	49.25	52.00	49.25	41.93	31.75	19.94	7.20	0.00	0.00
FEB.	01	0.00	0.00	8.37	21.39	33.57	44.22	52.02	55.00	52.02	44.22	33.57	21.39	8.37	0.00	0.00
FEB.	02	0.00	0.00	9.51	22.79	35.32	46.44	54.75	58.00	54.75	46.44	35.32	22.79	9.51	0.00	0.00
FEB.	03	0.00	0.00	11.00	24.58	37.55	49.27	58.33	62.00	58.33	49.27	37.55	24.58	11.00	0.00	0.00
MAR.	01	0.00	0.00	12.08	25.86	39.12	51.29	60.96	65.00	60.96	51.29	39.12	25.86	12.08	0.00	0.00
MAR.	02	0.00	0.00	13.49	27.46	41.06	53.80	64.34	69.00	64.34	53.80	41.06	27.46	13.49	0.00	0.00
MAR.	03	0.00	0.65	14.83	28.94	42.81	56.07	67.53	73.00	67.53	56.07	42.81	28.94	14.83	0.65	0.00
ABR.	01	0.00	1.95	16.11	30.28	44.34	58.04	70.45	77.00	70.45	58.04	44.34	30.28	16.11	1.95	0.00
ABR.	02	0.00	3.24	17.31	31.47	45.64	59.65	72.93	81.00	72.93	59.65	45.64	31.47	17.31	3.24	0.00
ABR.	03	0.00	4.20	18.16	32.27	46.44	60.59	74.39	84.00	74.39	60.59	46.44	32.27	18.16	4.20	0.00
MAY.	01	0.00	5.15	18.96	32.97	47.09	61.27	75.39	87.00	75.39	61.27	47.09	32.97	18.96	5.15	0.00
MAY.	02	0.00	6.08	19.72	33.57	47.57	61.67	75.82	90.00	75.82	61.67	47.57	33.57	19.72	6.08	0.00
MAY.	03	-0.00	6.70	20.19	33.92	47.80	61.78	75.77	88.00	75.77	61.78	47.80	33.92	20.19	6.70	0.00
JUN.	01	0.00	7.01	20.42	34.08	47.89	61.78	75.64	87.00	75.64	61.78	47.89	34.08	20.42	7.01	0.00
JUN.	02	0.00	7.31	20.64	34.22	47.96	61.76	75.45	86.00	75.45	61.76	47.96	34.22	20.64	7.31	0.00
JUN.	03	0.00	7.31	20.64	34.22	47.96	61.76	75.45	86.00	75.45	61.76	47.96	34.22	20.64	7.31	0.00
JUL.	01	0.00	7.31	20.64	34.22	47.96	61.76	75.45	86.00	75.45	61.76	47.96	34.22	20.64	7.31	0.00
JUL.	02	0.00	6.70	20.19	33.92	47.80	61.78	75.77	88.00	75.77	61.78	47.80	33.92	20.19	6.70	0.00
JUL.	03	0.00	6.39	19.96	33.75	47.70	61.74	75.83	89.00	75.83	61.74	47.70	33.75	19.96	6.39	0.00
AGO.	01	0.00	5.46	19.22	33.18	47.27	61.43	75.60	88.00	75.60	61.43	47.27	33.18	19.22	5.46	0.00
AGO.	02	0.00	4.52	18.43	32.51	46.68	60.84	74.78	85.00	74.78	60.84	46.68	32.51	18.43	4.52	0.00
AGO.	03	0.00	3.56	17.60	31.75	45.92	59.99	73.46	82.00	73.46	59.99	45.92	31.75	17.60	3.56	0.00
SEP.	01	0.00	2.27	16.41	30.59	44.69	58.48	71.11	78.00	71.11	58.48	44.69	30.59	16.41	2.27	0.00
SEP.	02	0.00	0.98	15.15	29.28	43.21	56.59	68.29	74.00	68.29	56.59	43.21	29.28	15.15	0.98	0.00
SEP.	03	0.00	0.00	13.83	27.88	41.51	54.39	65.16	70.00	65.16	54.39	41.51	27.88	13.83	0.00	0.00
OCT.	01	0.00	0.00	12.44	26.27	39.62	51.94	61.82	66.00	61.82	51.94	39.62	26.27	12.44	0.00	0.00
OCT.	02	0.00	0.00	11.00	24.58	37.55	49.27	58.33	62.00	58.33	49.27	37.55	24.58	11.00	0.00	0.00
OCT.	03	0.00	0.00	9.89	23.25	35.89	47.16	55.65	59.00	55.65	47.16	35.89	23.25	9.89	0.00	0.00
NOV.	01	0.00	0.00	8.37	21.39	33.57	44.22	52.02	55.00	52.02	44.22	33.57	21.39	8.37	0.00	0.00
NOV.	02	0.00	0.00	7.59	20.43	32.36	42.70	50.17	53.00	50.17	42.70	32.36	20.43	7.59	0.00	0.00
NOV.	03	0.00	0.00	6.42	18.95	30.50	40.37	47.39	50.00	47.39	40.37	30.50	18.95	6.42	0.00	0.00
DIC.	01	0.00	0.00	6.02	18.44	29.86	39.59	46.46	49.00	46.46	39.59	29.86	18.44	6.02	0.00	0.00
DIC.	02	0.00	0.00	5.63	17.94	29.22	38.80	45.52	48.00	45.52	38.80	29.22	17.94	5.63	0.00	0.00
DIC.	03	0.00	0.00	5.63	17.94	29.22	38.80	45.52	48.00	45.52	38.80	29.22	17.94	5.63	0.00	0.00

LATITUD= 19.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.2	57.8	49.1	37.0	20.4	0.0	-20.4	-37.0	-49.1	-57.8	-64.2	******	******
ENE.	D2	******	******	65.2	58.7	50.0	37.8	20.9	0.0	-20.9	-37.8	-50.0	-58.7	-65.2	******	******
ENE.	D3	******	******	67.0	60.6	51.8	39.5	22.0	0.0	-22.0	-39.5	-51.8	-60.6	-67.0	******	******
FEB.	D1	******	******	69.8	63.4	54.7	42.1	23.8	0.0	-23.8	-42.1	-54.7	-63.4	-69.8	******	******
FEB.	D2	******	******	72.6	66.2	57.6	45.0	25.9	0.0	-25.9	-45.0	-57.6	-66.2	-72.6	******	******
FEB.	D3	******	******	76.4	70.2	61.7	49.2	29.1	0.0	-29.1	-49.2	-61.7	-70.2	-76.4	******	******
MAR.	D1	******	******	79.2	73.5	65.0	52.7	32.0	0.0	-32.0	-52.7	-65.0	-73.2	-79.7	******	******
MAR.	D2	******	******	83.1	77.1	69.6	57.8	36.7	0.0	-36.7	-57.8	-69.6	-77.1	-83.1	******	******
MAR.	D3	******	[illegible]	87.0	81.5	74.4	63.5	42.6	0.0	-42.6	-63.5	-74.4	-81.5	-87.0	-88.1	******
ABR.	D1	******	84.3	89.1	85.8	79.5	69.9	50.3	0.0	-50.3	-69.9	-79.5	-85.8	-89.1	-86.3	******
ABR.	D2	******	80.5	85.1	89.7	84.9	77.0	60.3	0.0	-60.3	-77.0	-84.9	-89.7	-85.1	-80.5	******
ABR.	D3	******	77.7	82.1	86.3	89.0	82.7	69.6	0.0	-69.6	-82.7	-89.0	-86.3	-82.1	-77.7	******
MAY.	D1	******	74.5	79.1	82.9	86.7	88.8	80.5	0.0	-80.5	-88.8	-86.7	-82.9	-79.1	-74.8	******
MAY.	D2	******	72.3	76.0	79.4	82.3	85.0	87.5	0.0	-87.5	-85.0	-82.3	-79.4	-76.0	-72.0	******
MAY.	D3	******	70.1	73.9	77.0	79.4	80.8	79.4	0.0	-79.4	-80.8	-79.4	-77.0	-73.9	-70.1	******
JUN.	D1	******	69.1	72.9	75.8	77.9	78.7	75.4	0.0	-75.4	-78.7	-77.9	-75.8	-72.9	-69.1	******
JUN.	D2	******	68.1	71.6	74.6	76.4	76.6	71.4	0.0	-71.4	-76.6	-76.4	-74.6	-71.8	-68.1	******
JUN.	D3	******	68.1	71.8	74.6	76.4	76.6	71.4	0.0	-71.4	-76.6	-76.4	-74.6	-71.8	-68.1	******
JUL.	D1	******	68.1	71.4	74.6	76.4	76.6	71.4	0.0	-71.4	-76.6	-76.4	-74.6	-71.5	-68.1	******
JUL.	D2	******	70.1	73.9	77.0	79.4	80.8	79.4	0.0	-79.4	-80.8	-79.4	-77.0	-73.9	-70.1	******
JUL.	D3	******	71.0	74.9	78.2	80.8	82.9	83.5	0.0	-83.5	-82.9	-80.9	-78.2	-74.9	-71.0	******
AGO.	D1	******	73.9	78.0	81.7	85.2	89.2	84.4	0.0	-84.4	-89.2	-85.2	-81.7	-78.0	-73.9	******
AGO.	D2	******	76.7	81.1	85.2	89.6	84.7	73.1	0.0	-73.1	-84.7	-89.6	-85.2	-81.1	-76.7	******
AGO.	D3	******	79.6	84.1	88.6	86.2	78.9	63.2	0.0	-63.2	-78.9	-86.2	-88.6	-84.1	-79.6	******
SEP.	D1	******	83.4	88.1	86.9	80.8	71.6	52.5	0.0	-52.5	-71.6	-80.8	-86.9	-88.1	-83.4	******
SEP.	D2	******	87.2	87.9	82.6	75.7	65.1	44.3	0.0	-44.3	-65.1	-75.7	-82.6	-87.9	-87.2	******
SEP.	D3	******	******	84.0	78.3	70.8	59.2	38.0	0.0	-38.0	-59.2	-70.8	-78.3	-84.0	******	******
OCT.	D1	******	******	80.2	74.2	66.1	53.9	33.1	0.0	-33.1	-53.9	-66.1	-74.2	-80.2	******	******
OCT.	D2	******	******	76.4	70.2	61.7	49.2	29.1	0.0	-29.1	-49.2	-61.7	-70.2	-76.4	******	******
OCT.	D3	******	******	73.5	67.7	58.6	46.0	26.7	0.0	-26.7	-46.0	-58.6	-67.7	-73.5	******	******
NOV.	D1	******	******	69.8	63.4	54.7	42.1	23.8	0.0	-23.8	-42.1	-54.7	-63.4	-69.8	******	******
NOV.	D2	******	******	67.9	61.5	52.8	40.3	22.6	0.0	-22.6	-40.3	-52.8	-61.5	-67.9	******	******
NOV.	D3	******	******	65.2	58.7	50.0	37.8	20.9	0.0	-20.9	-37.8	-50.0	-58.7	-65.2	******	******
DIC.	D1	******	******	64.2	57.8	49.1	37.0	20.4	0.0	-20.4	-37.0	-49.1	-57.8	-64.2	******	******
DIC.	D2	******	******	63.3	56.9	48.2	36.2	19.9	0.0	-19.9	-36.2	-48.2	-56.9	-63.3	******	******
DIC.	D3	******	******	63.3	56.9	48.2	36.2	19.9	0.0	-19.9	-36.2	-48.2	-56.9	-63.3	******	******

LATITUD=20.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	5.59	17.91	29.21	38.79	45.52	48.00	45.52	38.79	29.21	17.91	5.59	0.00	0.00
ENE.	D2	0.00	0.00	6.00	18.43	29.85	39.58	46.45	49.00	46.45	39.58	29.85	18.43	6.00	0.00	0.00
ENE.	D3	0.00	0.00	6.81	19.44	31.13	41.16	48.32	51.00	48.32	41.16	31.13	19.44	6.81	0.00	0.00
FEB.	D1	0.00	0.00	8.02	20.94	32.99	43.47	51.10	54.00	51.10	43.47	32.99	20.94	8.02	0.00	0.00
FEB.	D2	0.00	0.00	9.21	22.39	34.78	45.73	53.85	57.00	53.85	45.73	34.78	22.39	9.21	0.00	0.00
FEB.	D3	0.00	0.00	10.76	24.24	37.07	48.61	57.46	61.00	57.46	48.61	37.07	24.24	10.76	0.00	0.00
MAR.	D1	0.00	0.00	11.90	25.56	38.69	50.68	60.11	64.00	60.11	50.68	38.69	25.56	11.90	0.00	0.00
MAR.	D2	0.00	0.00	13.36	27.23	40.70	53.26	63.53	68.00	63.53	53.26	40.70	27.23	13.36	0.00	0.00
MAR.	D3	0.00	0.68	14.77	28.78	42.53	55.61	66.79	72.00	66.79	55.61	42.53	28.78	14.77	0.68	0.00
ABR.	D1	0.00	2.05	16.12	30.20	44.15	57.68	69.79	76.00	69.79	57.68	44.15	30.20	16.12	2.05	0.00
ABR.	D2	0.00	3.40	17.39	31.47	45.54	59.41	72.42	80.00	72.42	59.41	45.54	31.47	17.39	3.40	0.00
ABR.	D3	0.00	4.41	18.30	32.33	46.42	60.44	74.02	83.00	74.02	60.44	46.42	32.33	18.30	4.41	0.00
MAY.	D1	0.00	5.41	19.15	33.09	47.14	61.23	75.19	86.00	75.19	61.23	47.14	33.09	19.15	5.41	0.00
MAY.	D2	0.00	6.39	19.96	33.75	47.70	61.74	75.83	89.00	75.83	61.74	47.70	33.75	19.96	6.39	0.00
MAY.	D3	0.00	7.04	20.46	34.14	47.98	61.92	75.92	89.00	75.92	61.92	47.98	34.14	20.46	7.04	0.00
JUN.	D1	0.00	7.36	20.71	34.32	48.09	61.97	75.86	88.00	75.86	61.97	48.09	34.32	20.71	7.36	0.00
JUN.	D2	0.00	7.68	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
JUN.	D3	0.00	7.68	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
JUL.	D1	0.00	7.68	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
JUL.	D2	0.00	7.04	20.46	34.14	47.98	61.92	75.92	89.00	75.92	61.92	47.98	34.14	20.46	7.04	0.00
JUL.	D3	0.00	6.72	20.21	33.95	47.85	61.85	75.91	90.00	75.91	61.85	47.85	33.95	20.21	6.72	0.00
AGO.	D1	0.00	5.74	19.43	33.32	47.34	61.43	75.47	87.00	75.47	61.43	47.34	33.32	19.43	5.74	0.00
AGO.	D2	0.00	4.75	18.59	32.59	46.67	60.73	74.46	84.00	74.46	60.73	46.67	32.59	18.59	4.75	0.00
AGO.	D3	0.00	3.74	17.70	31.77	45.85	59.78	72.99	81.00	72.99	59.78	45.85	31.77	17.70	3.74	0.00
SEP.	D1	0.00	2.39	16.44	30.53	44.52	58.15	70.49	77.00	70.49	58.15	44.52	30.53	16.44	2.39	0.00
SEP.	D2	0.00	1.03	15.12	29.15	42.96	56.16	67.57	73.00	67.57	56.16	42.96	29.15	15.12	1.03	0.00
SEP.	D3	0.00	0.00	13.72	27.63	41.18	53.87	64.36	69.00	64.36	53.87	41.18	27.63	13.72	0.00	0.00
OCT.	D1	0.00	0.00	12.27	25.99	39.21	51.34	60.98	65.00	60.98	51.34	39.21	25.99	12.27	0.00	0.00
OCT.	D2	0.00	0.00	10.76	24.24	37.07	48.61	57.46	61.00	57.46	48.61	37.07	24.24	10.76	0.00	0.00
OCT.	D3	0.00	0.00	9.60	22.84	35.37	46.46	54.76	58.00	54.76	46.46	35.37	22.84	9.60	0.00	0.00
NOV.	D1	0.00	0.00	8.02	20.94	32.99	43.47	51.10	54.00	51.10	43.47	32.99	20.94	8.02	0.00	0.00
NOV.	D2	0.00	0.00	7.22	19.95	31.75	41.93	49.25	52.00	49.25	41.93	31.75	19.95	7.22	0.00	0.00
NOV.	D3	0.00	0.00	6.00	18.43	29.85	39.58	46.45	49.00	46.45	39.58	29.85	18.43	6.00	0.00	0.00
DIC.	D1	0.00	0.00	5.59	17.91	29.21	38.79	45.52	48.00	45.52	38.79	29.21	17.91	5.59	0.00	0.00
DIC.	D2	0.00	0.00	5.18	17.39	28.56	37.99	44.58	47.00	44.58	37.99	28.56	17.39	5.18	0.00	0.00
DIC.	D3	0.00	0.00	5.18	17.39	28.56	37.99	44.58	47.00	44.58	37.99	28.56	17.39	5.18	0.00	0.00

LATITUD 20.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.1	57.9	48.7	37.5	20.0	0.0	-20.0	-36.5	-48.7	-57.5	-64.1	******	******
ENE.	D2	******	******	65.1	59.5	49.6	37.3	20.5	0.0	-20.5	-37.3	-49.6	-58.5	-65.1	******	******
ENE.	D3	******	******	66.9	60.3	51.4	38.9	21.6	0.0	-21.6	-38.9	-51.4	-60.3	-66.9	******	******
FEB.	D1	******	******	69.7	63.0	54.1	41.5	23.3	0.0	-23.3	-41.5	-54.1	-63.0	-69.7	******	******
FEB.	D2	******	******	72.5	65.9	57.0	44.3	25.3	0.0	-25.3	-44.3	-57.0	-65.9	-72.5	******	******
FEB.	D3	******	******	76.2	69.7	61.1	48.1	28.4	0.0	-28.4	-48.1	-61.1	-69.7	-76.2	******	******
MAR.	D1	******	******	79.3	72.7	64.3	51.7	31.1	0.0	-31.1	-51.7	-64.3	-72.7	-79.0	******	******
MAR.	D2	******	******	82.8	76.8	68.8	56.7	35.5	0.0	-35.5	-56.7	-68.8	-76.8	-82.8	******	******
MAR.	D3	******	89.1	86.7	80.9	73.5	62.2	41.0	0.0	-41.0	-62.2	-73.5	-80.9	-86.7	-89.1	******
ABR.	D1	******	84.4	89.8	85.2	78.6	68.5	48.2	0.0	-48.2	-68.5	-78.6	-85.2	-89.8	-84.4	******
ABR.	D2	******	80.5	85.4	89.6	83.9	75.4	57.5	0.0	-57.5	-75.4	-83.9	-89.6	-85.4	-80.6	******
ABR.	D3	******	77.3	82.4	87.0	88.0	81.0	66.3	0.0	-66.3	-81.0	-88.0	-87.0	-82.4	-77.8	******
MAY.	D1	******	74.9	79.4	83.5	87.8	86.9	76.8	0.0	-76.8	-86.9	-87.8	-83.5	-79.4	-74.9	******
MAY.	D2	******	72.1	77.3	80.0	83.4	86.9	88.5	0.0	-88.5	-86.9	-83.4	-80.0	-76.3	-72.1	******
MAY.	D3	******	70.2	74.3	77.8	80.5	82.6	83.3	0.0	-83.3	-82.6	-80.5	-77.6	-74.3	-70.2	******
JUN.	D1	******	67.2	73.2	76.5	79.0	80.5	79.2	0.0	-79.2	-80.5	-79.0	-76.5	-73.2	-69.2	******
JUN.	D2	******	67.3	72.2	75.3	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.3	-72.2	-68.3	******
JUN.	D3	******	67.3	72.2	75.3	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.3	-72.2	-68.3	******
JUL.	D1	******	67.3	72.2	75.3	77.5	78.4	75.2	0.0	-75.2	-78.4	-77.5	-75.3	-72.2	-68.3	******
JUL.	D2	******	70.2	74.3	77.6	80.5	82.6	83.3	0.0	-83.3	-82.6	-80.5	-77.6	-74.3	-70.2	******
JUL.	D3	******	71.1	75.3	78.8	81.5	84.8	87.4	0.0	-87.4	-84.8	-81.9	-78.8	-75.3	-71.1	******
AGO.	D1	******	74.0	78.4	82.4	86.3	89.0	80.6	0.0	-80.6	-89.0	-86.3	-82.4	-78.4	-74.0	******
AGO.	D2	******	76.3	81.4	85.8	89.4	82.9	69.6	0.0	-69.6	-82.9	-89.4	-85.8	-81.4	-76.8	******
AGO.	D3	******	79.6	84.4	89.2	85.2	77.2	60.3	0.0	-60.3	-77.2	-85.2	-89.2	-84.4	-79.8	******
SEP.	D1	******	83.1	85.4	86.3	79.9	70.1	50.3	0.0	-50.3	-70.1	-79.9	-86.3	-88.4	-83.4	******
SEP.	D2	******	87.2	87.7	82.0	74.8	63.7	42.6	0.0	-42.6	-63.7	-74.8	-82.0	-87.7	-87.2	******
SEP.	D3	******	******	83.8	77.8	69.9	58.0	36.7	0.0	-36.7	-58.0	-69.9	-77.8	-83.8	******	******
OCT.	D1	******	******	80.0	73.7	65.4	52.9	32.1	0.0	-32.1	-52.9	-65.4	-73.7	-80.0	******	******
OCT.	D2	******	******	76.2	69.7	61.1	48.3	28.4	0.0	-28.4	-48.3	-61.1	-69.7	-76.2	******	******
OCT.	D3	******	******	73.4	66.8	58.0	45.2	26.0	0.0	-26.0	-45.2	-58.0	-66.8	-73.4	******	******
NOV.	D1	******	******	69.7	63.0	54.1	41.5	23.3	0.0	-23.3	-41.5	-54.1	-63.0	-69.7	******	******
NOV.	D2	******	******	67.5	61.5	52.3	39.7	22.2	0.0	-22.2	-39.7	-52.3	-61.5	-67.8	******	******
NOV.	D3	******	******	65.1	59.5	49.6	37.3	20.5	0.0	-20.5	-37.3	-49.6	-58.5	-65.1	******	******
DIC.	D1	******	******	[illegible]	57.5	48.7	36.5	20.0	0.0	-20.0	-36.5	-48.7	-57.5	-64.1	******	******
DIC.	D2	******	******	63.2	56.7	47.8	35.7	19.5	0.0	-19.5	-35.7	-47.8	-56.7	-63.2	******	******
DIC.	D3	******	******	63.2	56.7	47.8	35.7	19.5	0.0	-19.5	-35.7	-47.8	-56.7	-63.2	******	******

LATITUD=22.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	4.71	16.93	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.93	4.71	0.00	0.00
ENE.	02	0.00	0.00	5.15	17.37	28.54	37.98	44.58	47.00	44.58	37.98	28.54	17.37	5.15	0.00	0.00
ENE.	03	0.00	0.00	6.22	18.44	29.86	39.59	46.46	49.00	46.46	39.59	29.86	18.44	6.22	0.00	0.00
FEB.	01	0.00	0.00	7.32	20.02	31.80	41.96	49.26	52.00	49.26	41.96	31.80	20.02	7.32	0.00	0.00
FEB.	02	0.00	0.00	8.60	21.58	33.68	44.28	52.03	55.00	52.03	44.28	33.68	21.58	8.60	0.00	0.00
FEB.	03	0.00	0.00	10.28	23.53	36.08	47.26	55.69	59.00	55.69	47.26	36.08	23.53	10.28	0.00	0.00
MAR.	01	0.00	0.00	11.51	24.95	37.80	49.41	58.38	62.00	58.38	49.41	37.80	24.95	11.51	0.00	0.00
MAR.	02	0.00	0.00	13.11	26.76	39.95	52.13	61.88	66.00	61.88	52.13	39.95	26.76	13.11	0.00	0.00
MAR.	03	0.00	0.75	14.65	28.45	41.94	54.64	65.25	70.00	65.25	54.64	41.94	28.45	14.65	0.75	0.00
ABR.	01	0.00	2.24	16.13	30.01	43.72	56.90	68.41	74.00	68.41	56.90	43.72	30.01	16.13	2.24	0.00
ABR.	02	0.00	3.73	17.54	31.44	45.29	58.85	71.27	78.00	71.27	58.85	45.29	31.44	17.54	3.73	0.00
ABR.	03	0.00	4.83	18.55	32.41	46.31	60.07	73.12	81.00	73.12	60.07	46.31	32.41	18.55	4.83	0.00
MAY.	01	0.00	5.93	19.51	33.29	47.18	61.06	74.61	84.00	74.61	61.06	47.18	33.29	19.51	5.93	0.00
MAY.	02	0.00	7.01	20.42	34.08	47.89	61.79	75.64	87.00	75.64	61.79	47.89	34.08	20.42	7.01	0.00
MAY.	03	0.00	7.72	20.99	34.54	48.27	62.11	76.01	89.00	76.01	62.11	48.27	34.54	20.99	7.72	0.00
JUN.	01	0.00	8.07	21.27	34.76	48.44	62.23	76.10	90.00	76.10	62.23	48.44	34.76	21.27	8.07	0.00
JUN.	02	0.00	8.42	21.55	34.97	48.58	62.31	76.11	89.00	76.11	62.31	48.58	34.97	21.55	8.42	0.00
JUN.	03	0.00	8.42	21.55	34.97	48.58	62.31	76.11	89.00	76.11	62.31	48.58	34.97	21.55	8.42	0.00
JUL.	01	0.00	8.42	21.55	34.97	48.58	62.31	76.11	89.00	76.11	62.31	48.58	34.97	21.55	8.42	0.00
JUL.	02	0.00	7.72	20.99	34.54	48.27	62.11	76.01	89.00	76.01	62.11	48.27	34.54	20.99	7.72	0.00
JUL.	03	0.00	7.36	20.71	34.32	48.09	61.97	75.86	88.00	75.86	61.97	48.09	34.32	20.71	7.36	0.00
AGO.	01	0.00	6.29	19.82	33.56	47.43	61.33	75.01	85.00	75.01	61.33	47.43	33.56	19.82	6.29	0.00
AGO.	02	0.00	5.20	18.87	32.71	46.62	60.43	73.66	82.00	73.66	60.43	46.62	32.71	18.87	5.20	0.00
AGO.	03	0.00	4.10	17.88	31.77	45.65	59.28	71.92	79.00	71.92	59.28	45.65	31.77	17.88	4.10	0.00
SEP.	01	0.00	2.67	16.49	30.38	44.14	57.42	69.16	75.00	69.16	57.42	44.14	30.38	16.49	2.67	0.00
SEP.	02	0.00	1.12	15.03	28.86	42.40	55.23	66.08	71.00	66.08	55.23	42.40	28.86	15.03	1.12	0.00
SEP.	03	0.00	0.00	13.50	27.19	40.46	52.79	62.74	67.00	62.74	52.79	40.46	27.19	13.50	0.00	0.00
OCT.	01	0.00	0.00	11.91	25.42	38.35	50.11	59.26	63.00	59.26	50.11	38.35	25.42	11.91	0.00	0.00
OCT.	02	0.00	0.00	10.28	23.53	36.08	47.26	55.69	59.00	55.69	47.26	36.08	23.53	10.28	0.00	0.00
OCT.	03	0.00	0.00	9.02	22.06	34.29	45.03	52.95	56.00	52.95	45.03	34.29	22.06	9.02	0.00	0.00
NOV.	01	0.00	0.00	7.32	20.02	31.80	41.96	49.26	52.00	49.26	41.96	31.80	20.02	7.32	0.00	0.00
NOV.	02	0.00	0.00	6.46	18.97	30.52	40.38	47.39	50.00	47.39	40.38	30.52	18.97	6.46	0.00	0.00
NOV.	03	0.00	0.00	5.15	17.37	28.54	37.98	44.58	47.00	44.58	37.98	28.54	17.37	5.15	0.00	0.00
DIC.	01	0.00	0.00	4.71	16.93	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.93	4.71	0.00	0.00
DIC.	02	0.00	0.00	4.27	16.28	27.20	36.35	42.69	45.00	42.69	36.35	27.20	16.28	4.27	0.00	0.00
DIC.	03	0.00	0.00	4.27	16.28	27.20	36.35	42.69	45.00	42.69	36.35	27.20	16.28	4.27	0.00	0.00

LATITUD= 22.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.0	57.0	47.9	35.6	19.4	0.0	-19.4	-35.6	-47.9	-57.0	-64.0	******	******
ENE.	D2	******	******	64.9	57.9	49.7	36.3	19.8	0.0	-19.8	-36.3	-48.7	-57.9	-64.9	******	******
ENE.	D3	******	******	66.7	59.7	53.4	37.3	20.8	0.0	-20.8	-37.8	-50.4	-59.7	-66.7	******	******
FEB.	D1	******	******	69.4	62.4	53.1	40.3	22.4	0.0	-22.4	-40.3	-53.1	-62.4	-69.4	******	******
FEB.	D2	******	******	72.2	65.1	56.9	42.9	24.2	0.0	-24.2	-42.9	-56.9	-65.1	-72.2	******	******
FEB.	D3	******	******	75.8	68.9	59.8	46.7	27.0	0.0	-27.0	-46.7	-59.3	-68.9	-75.8	******	******
MAR.	D1	******	******	78.6	71.8	62.9	49.8	29.4	0.0	-29.4	-49.8	-62.9	-71.8	-78.6	******	******
MAR.	D2	******	******	82.4	75.8	67.2	54.5	33.3	0.0	-33.3	-54.5	-67.2	-75.8	-82.4	******	******
MAR.	D3	******	88.1	86.2	79.9	71.8	59.7	38.2	0.0	-38.2	-59.7	-71.8	-79.9	-86.2	-88.1	******
ABR.	D1	******	84.4	90.0	84.1	76.7	65.6	44.4	0.0	-44.4	-65.6	-76.7	-84.1	-90.0	-84.4	******
ABR.	D2	******	80.7	86.1	88.4	81.8	72.2	52.5	0.0	-52.5	-72.2	-81.8	-88.4	-86.1	-80.7	******
ABR.	D3	******	77.9	83.1	88.2	85.9	77.6	60.3	0.0	-60.3	-77.6	-85.9	-88.2	-83.1	-77.9	******
MAY.	D1	******	75.1	80.1	84.8	89.9	83.3	69.7	0.0	-69.7	-83.3	-89.9	-84.8	-80.1	-75.1	******
MAY.	D2	******	72.3	77.0	81.3	85.6	89.4	80.7	0.0	-80.7	-89.4	-85.6	-81.3	-77.0	-72.3	******
MAY.	D3	******	70.4	75.0	79.0	82.7	86.4	88.7	0.0	-88.7	-86.4	-82.7	-79.0	-75.0	-70.4	******
JUN.	D1	******	69.5	74.0	77.8	81.2	84.3	87.2	0.0	-87.2	-84.3	-81.2	-77.8	-74.0	-69.5	******
JUN.	D2	******	68.5	72.9	76.6	79.7	82.1	83.0	0.0	-83.0	-82.1	-79.7	-76.6	-72.9	-68.5	******
JUN.	D3	******	68.5	72.9	76.6	79.7	82.1	83.0	0.0	-83.0	-82.1	-79.7	-76.6	-72.9	-68.5	******
JUL.	D1	******	68.5	72.9	76.6	79.7	82.1	83.0	0.0	-83.0	-82.1	-79.7	-76.6	-72.9	-68.5	******
JUL.	D2	******	70.4	75.0	79.0	82.7	86.4	88.7	0.0	-88.7	-86.4	-82.7	-79.0	-75.0	-70.4	******
JUL.	D3	******	71.4	76.0	80.2	84.1	88.5	84.6	0.0	-84.6	-88.5	-84.1	-80.2	-76.0	-71.4	******
AGO.	D1	******	74.2	79.1	83.7	88.5	85.3	73.2	0.0	-73.2	-85.3	-88.5	-83.7	-79.1	-74.2	******
AGO.	D2	******	77.0	82.1	87.1	87.3	79.4	63.2	0.0	-63.2	-79.4	-87.3	-87.1	-82.1	-77.0	******
AGO.	D3	******	79.8	85.1	89.5	83.2	73.9	54.9	0.0	-54.9	-73.9	-83.2	-89.5	-85.1	-79.8	******
SEP.	D1	******	83.5	89.0	85.9	77.9	67.2	46.2	0.0	-46.2	-67.2	-77.9	-85.9	-89.0	-83.5	******
SEP.	D2	******	87.2	87.1	80.9	73.0	61.1	39.6	0.0	-39.6	-61.1	-73.0	-80.9	-87.1	-87.2	******
SEP.	D3	******	******	81.3	76.8	68.3	55.7	34.4	0.0	-34.4	-55.7	-68.3	-76.8	-83.3	******	******
OCT.	D1	******	******	79.6	72.8	63.9	51.0	30.3	0.0	-30.3	-51.0	-63.9	-72.8	-79.6	******	******
OCT.	D2	******	******	75.8	68.9	59.8	46.7	27.0	0.0	-27.0	-46.7	-59.8	-68.9	-75.8	******	******
OCT.	D3	******	******	73.1	66.1	56.8	43.8	24.8	0.0	-24.8	-43.8	-56.8	-66.1	-73.1	******	******
NOV.	D1	******	******	69.4	62.4	53.1	40.3	22.4	0.0	-22.4	-40.3	-53.1	-62.4	-69.4	******	******
NOV.	D2	******	******	67.6	60.8	51.3	38.6	21.3	0.0	-21.3	-38.6	-51.3	-60.8	-67.6	******	******
NOV.	D3	******	******	64.9	57.9	48.7	36.3	19.8	0.0	-19.8	-36.3	-48.7	-57.9	-64.9	******	******
DIC.	D1	******	******	64.0	57.0	47.9	35.6	19.4	0.0	-19.4	-35.6	-47.9	-57.0	-64.0	******	******
DIC.	D2	******	******	63.1	56.1	47.0	34.9	18.9	0.0	-18.9	-34.9	-47.0	-56.1	-63.1	******	******
DIC.	D3	******	******	63.1	56.1	47.0	34.9	18.9	0.0	-18.9	-34.9	-47.0	-56.1	-63.1	******	******

LATITUD=21.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	5.15	17.37	28.54	37.96	44.58	47.00	44.58	37.96	28.54	17.37	5.15	0.00	0.00
ENE.	02	0.00	0.00	5.58	17.90	29.20	38.78	45.52	48.00	45.52	38.78	29.20	17.90	5.58	0.00	0.00
ENE.	03	0.00	0.00	6.42	18.94	30.50	40.37	47.39	50.00	47.39	40.37	30.50	18.95	6.42	0.00	0.00
FEB.	01	0.00	0.00	7.67	20.48	32.40	42.72	50.18	53.00	50.18	42.72	32.40	20.48	7.67	0.00	0.00
FEB.	02	0.00	0.00	8.91	21.98	34.24	45.00	52.94	56.00	52.94	45.00	34.24	21.98	8.91	0.00	0.00
FEB.	03	0.00	0.00	10.52	23.49	36.58	47.94	56.57	60.00	56.57	47.94	36.58	23.49	10.52	0.00	0.00
MAR.	01	0.00	0.00	11.70	25.26	38.25	50.05	59.25	63.00	59.25	50.05	38.25	25.26	11.70	0.00	0.00
MAR.	02	0.00	0.00	13.24	27.00	40.33	52.70	62.71	67.00	62.71	52.70	40.33	27.00	13.24	0.00	0.00
MAR.	03	0.00	0.72	14.71	28.65	42.24	55.14	66.01	71.00	66.01	55.14	42.24	28.62	14.71	0.72	0.00
ABR.	01	0.00	2.15	16.13	30.11	43.95	57.30	69.11	75.00	69.11	57.30	43.95	30.11	16.13	2.15	0.00
ABR.	02	0.00	3.57	17.47	31.46	45.43	59.14	71.86	79.00	71.86	59.14	45.43	31.46	17.47	3.57	0.00
ABR.	03	0.00	4.62	18.42	32.37	46.37	60.27	73.59	82.00	73.59	60.27	46.37	32.37	18.42	4.62	0.00
MAY.	01	0.00	5.67	19.33	33.19	47.17	61.16	74.93	85.00	74.93	61.16	47.17	33.19	19.33	5.67	0.00
MAY.	02	0.00	6.70	20.19	33.92	47.80	61.78	75.77	88.00	75.77	61.78	47.80	33.92	20.19	6.70	0.00
MAY.	03	0.00	7.38	20.73	34.35	48.14	62.03	76.00	90.00	76.00	62.03	48.14	34.35	20.73	7.38	0.00
JUN.	01	0.00	7.72	20.99	34.54	48.27	62.11	76.01	89.00	76.01	62.11	48.27	34.54	20.99	7.72	0.00
JUN.	02	0.00	8.05	21.25	34.73	48.39	62.16	75.96	88.00	75.96	62.16	48.39	34.73	21.25	8.05	0.00
JUN.	03	0.00	8.05	21.25	34.73	48.39	62.16	75.96	88.00	75.96	62.16	48.39	34.73	21.25	8.05	0.00
JUL.	01	0.00	8.05	21.25	34.73	48.39	62.16	75.96	88.00	75.96	62.16	48.39	34.73	21.25	8.05	0.00
JUL.	02	0.00	7.38	20.73	34.35	48.14	62.03	76.00	90.00	76.00	62.03	48.14	34.35	20.73	7.38	0.00
JUL.	03	0.00	7.04	20.46	34.14	47.98	61.92	75.92	89.00	75.92	61.92	47.98	34.14	20.46	7.04	0.00
AGO.	01	0.00	6.01	19.62	33.45	47.40	61.40	75.27	86.00	75.27	61.40	47.40	33.45	19.62	6.01	0.00
AGO.	02	0.00	4.97	18.73	32.66	46.65	60.40	74.09	83.00	74.09	60.40	46.65	32.66	18.73	4.97	0.00
AGO.	03	0.00	3.92	17.79	31.78	45.76	59.55	72.47	80.00	72.47	59.55	45.76	31.78	17.79	3.92	0.00
SEP.	01	0.00	2.50	16.47	30.44	44.34	57.80	69.84	76.00	69.84	57.80	44.34	30.44	16.47	2.50	0.00
SEP.	02	0.00	1.07	15.07	29.01	42.69	55.71	66.02	72.00	66.02	55.71	42.69	29.01	15.07	1.97	0.00
SEP.	03	0.00	0.00	13.61	27.42	40.83	53.33	63.56	68.00	63.56	53.33	40.83	27.42	13.61	0.00	0.00
OCT.	01	0.00	0.00	12.09	25.71	38.78	50.73	60.12	64.00	60.12	50.73	38.78	25.71	12.09	0.00	0.00
OCT.	02	0.00	0.00	10.52	23.49	36.58	47.94	56.57	60.00	56.57	47.94	36.53	23.59	10.52	0.00	0.00
OCT.	03	0.00	0.00	9.31	22.46	34.83	45.75	53.86	57.00	53.86	45.75	34.83	22.46	9.31	0.00	0.00
NOV.	01	0.00	0.00	7.67	20.48	32.40	42.72	50.18	53.00	50.18	42.72	32.40	20.48	7.67	0.00	0.00
NOV.	02	0.00	0.00	6.84	19.46	31.14	41.16	48.32	51.00	48.32	41.16	31.14	19.46	6.84	0.00	0.00
NOV.	03	0.00	0.00	5.58	17.90	29.20	38.78	45.52	48.00	45.52	38.78	29.20	17.90	5.58	0.00	0.00
DIC.	01	0.00	0.00	5.15	17.37	28.54	37.95	44.58	47.00	44.58	37.98	28.54	17.37	5.15	0.00	0.00
DIC.	02	0.00	0.00	4.73	16.84	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.84	4.73	0.00	0.00
DIC.	03	0.00	0.00	4.73	16.84	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.84	4.73	0.00	0.00

LATITUD= 21.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	64.1	57.3	48.3	36.0	19.7	0.0	-19.7	-36.0	-48.3	-57.3	-64.1	******	******
ENE.	D2	******	******	65.0	58.2	49.1	36.8	20.2	0.0	-20.2	-36.8	-49.1	-58.2	-65.0	******	******
ENE.	D3	******	******	66.8	60.0	50.9	38.4	21.2	0.0	-21.2	-38.4	-50.9	-60.0	-66.8	******	******
FEB.	D1	******	******	69.5	62.7	53.6	40.9	22.9	0.0	-22.9	-40.9	-53.6	-62.7	-69.5	******	******
FEB.	D2	******	******	72.3	65.5	56.4	43.6	24.7	0.0	-24.7	-43.6	-56.4	-65.5	-72.3	******	******
FEB.	D3	******	******	76.0	69.3	60.4	47.5	27.7	0.0	-27.7	-47.5	-60.4	-69.3	-76.0	******	******
MAR.	D1	******	******	78.8	72.2	63.6	50.8	30.2	0.0	-30.2	-50.8	-63.6	-72.2	-78.8	******	******
MAR.	D2	******	******	82.6	76.3	68.0	55.6	34.3	0.0	-34.3	-55.6	-68.0	-76.3	-82.6	******	******
MAR.	D3	******	88.1	86.4	80.4	72.7	60.9	39.5	0.0	-39.5	-60.9	-72.7	-80.4	-86.4	-88.1	******
ABR.	D1	******	84.4	89.7	84.7	77.6	67.0	46.2	0.0	-46.2	-67.0	-77.6	-84.7	-89.7	-84.4	******
ABR.	D2	******	80.7	85.7	89.0	82.8	73.7	55.0	0.0	-55.0	-73.7	-82.8	-89.0	-85.7	-80.7	******
ABR.	D3	******	77.8	82.8	87.6	86.9	79.3	63.2	0.0	-63.2	-79.3	-86.9	-87.6	-82.8	-77.8	******
MAY.	D1	******	75.0	79.7	84.2	88.8	85.1	73.1	0.0	-73.1	-85.1	-88.8	-84.2	-79.7	-75.0	******
MAY.	D2	******	72.2	76.7	80.7	84.5	88.7	84.5	0.0	-84.5	-88.7	-84.5	-80.7	-76.7	-72.2	******
MAY.	D3	******	70.3	74.6	78.3	81.6	84.5	87.3	0.0	-87.3	-84.5	-81.6	-78.3	-74.6	-70.3	******
JUN.	D1	******	69.3	73.6	77.1	80.1	82.4	83.2	0.0	-83.2	-82.4	-80.1	-77.1	-73.6	-69.3	******
JUN.	D2	******	68.4	72.6	75.9	78.6	80.2	79.0	0.0	-79.0	-80.2	-78.6	-75.9	-72.6	-68.4	******
JUN.	D3	******	68.4	72.6	75.9	78.6	80.2	79.0	0.0	-79.0	-80.2	-78.6	-75.9	-72.6	-68.4	******
JUL.	D1	******	68.4	72.6	75.9	78.6	80.2	79.0	0.0	-79.0	-80.2	-78.6	-75.9	-72.6	-68.4	******
JUL.	D2	******	70.3	74.6	78.3	81.6	84.5	87.3	0.0	-87.3	-84.5	-81.6	-78.3	-74.6	-70.3	******
JUL.	D3	******	71.2	75.7	79.5	83.0	86.6	88.6	0.0	-88.6	-86.6	-83.0	-79.5	-75.7	-71.2	******
AGO.	D1	******	74.1	78.7	83.0	87.4	87.1	76.8	0.0	-76.8	-87.1	-87.4	-83.0	-78.7	-74.1	******
AGO.	D2	******	76.9	81.8	86.5	88.3	81.2	66.3	0.0	-66.3	-81.2	-88.3	-86.5	-81.8	-76.9	******
AGO.	D3	******	79.7	84.8	89.8	84.2	75.5	57.5	0.0	-57.5	-75.5	-84.2	-89.8	-84.8	-79.7	******
SEP.	D1	******	83.5	88.7	85.7	75.9	68.6	48.2	0.0	-48.2	-68.6	-75.9	-85.7	-88.7	-83.5	******
SEP.	D2	******	87.2	87.4	81.4	73.9	62.4	41.0	0.0	-41.0	-62.4	-73.9	-81.4	-87.4	-87.2	******
SEP.	D3	******	******	83.6	77.3	69.1	56.8	35.5	0.0	-35.5	-56.8	-69.1	-77.3	-83.6	******	******
OCT.	D1	******	******	79.8	73.2	64.6	51.9	31.2	0.0	-31.2	-51.9	-64.6	-73.2	-79.8	******	******
OCT.	D2	******	******	76.0	69.3	60.4	47.5	27.7	0.0	-27.7	-47.5	-60.4	-69.3	-76.0	******	******
OCT.	D3	******	******	73.2	66.4	57.4	44.5	25.4	0.0	-25.4	-44.5	-57.4	-66.4	-73.2	******	******
NOV.	D1	******	******	69.5	62.7	53.6	40.9	22.9	0.0	-22.9	-40.9	-53.6	-62.7	-69.5	******	******
NOV.	D2	******	******	67.7	60.9	51.8	39.2	21.7	0.0	-21.7	-39.2	-51.8	-60.9	-67.7	******	******
NOV.	D3	******	******	65.0	58.2	49.1	36.8	20.2	0.0	-20.2	-36.8	-49.1	-58.2	-65.0	******	******
DIC.	D1	******	******	64.1	57.3	48.3	36.0	19.7	0.0	-19.7	-36.0	-48.3	-57.3	-64.1	******	******
DIC.	D2	******	******	63.1	56.4	47.4	35.3	19.2	0.0	-19.2	-35.3	-47.4	-56.4	-63.1	******	******
DIC.	D3	******	******	63.1	56.4	47.4	35.3	19.2	0.0	-19.2	-35.3	-47.4	-56.4	-63.1	******	******

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LATITUD=23.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	4.27	16.28	27.20	36.35	42.69	45.00	42.69	36.35	27.20	16.28	4.27	0.00	0.00
ENE.	D2	0.00	0.00	4.73	16.84	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.84	4.73	0.00	0.00
ENE.	D3	0.00	0.00	5.63	17.94	29.22	38.80	45.52	48.00	45.52	38.80	29.22	17.94	5.63	0.00	0.00
FEB.	D1	0.00	0.00	6.97	19.56	31.20	41.19	48.33	51.00	48.33	41.19	31.20	19.56	6.97	0.00	0.00
FEB.	D2	0.00	0.00	8.29	21.13	33.11	43.54	51.12	54.00	51.12	43.54	33.11	21.13	8.29	0.00	0.00
FEB.	D3	0.00	0.00	10.03	23.17	35.57	46.57	54.79	58.00	54.79	46.57	35.57	23.17	10.03	0.00	0.00
MAR.	D1	0.00	0.00	11.31	24.64	37.34	48.76	57.50	61.00	57.50	48.76	37.34	24.64	11.31	0.00	0.00
MAR.	D2	0.00	0.00	12.97	26.51	39.56	51.54	61.04	65.00	61.04	51.54	39.56	26.51	12.97	0.00	0.00
MAR.	D3	0.00	0.78	14.58	28.27	41.62	54.13	64.45	69.00	64.45	54.13	41.62	28.27	14.58	0.78	0.00
ABR.	D1	0.00	2.34	16.13	29.91	43.49	56.48	67.09	73.00	67.09	56.48	43.49	29.91	16.13	2.34	0.00
ABR.	D2	0.00	3.89	17.61	31.41	45.14	58.53	70.64	77.00	70.64	58.53	45.14	31.41	17.61	3.89	0.00
ABR.	D3	0.00	5.04	18.66	32.44	46.23	59.84	72.60	80.00	72.60	59.84	46.23	32.44	18.66	5.04	0.00
MAY.	D1	0.00	6.18	19.68	33.38	47.17	60.93	74.24	83.00	74.24	60.93	47.17	33.38	19.68	6.18	0.00
MAY.	D2	0.00	7.31	20.64	34.22	47.96	61.76	75.45	86.00	75.45	61.76	47.96	34.22	20.64	7.31	0.00
MAY.	D3	0.00	8.05	21.25	34.73	48.39	62.16	75.96	88.00	75.96	62.16	48.39	34.73	21.25	8.05	0.00
JUN.	D1	0.00	8.42	21.55	34.97	48.58	62.31	76.11	89.00	76.11	62.31	48.58	34.97	21.55	8.42	0.00
JUN.	D2	0.00	8.78	21.84	35.19	48.75	62.43	76.20	90.00	76.20	62.43	48.75	35.19	21.84	8.78	0.00
JUN.	D3	0.00	8.78	21.84	35.19	48.75	62.43	76.20	90.00	76.20	62.43	48.75	35.19	21.84	8.78	0.00
JUL.	D1	0.00	8.78	21.84	35.19	48.75	62.43	76.20	90.00	76.20	62.43	48.75	35.19	21.84	8.78	0.00
JUL.	D2	0.00	8.05	21.25	34.73	48.39	62.16	75.96	88.00	75.96	62.16	48.39	34.73	21.25	8.05	0.00
JUL.	D3	0.00	7.68	20.95	34.48	48.18	61.98	75.73	87.00	75.73	61.98	48.18	34.48	20.95	7.68	0.00
AGO.	D1	0.00	6.56	20.00	33.67	47.45	61.23	74.69	84.00	74.69	61.23	47.45	33.67	20.00	6.56	0.00
AGO.	D2	0.00	5.42	19.01	32.76	46.56	60.23	73.19	81.00	73.19	60.23	46.56	32.76	19.01	5.42	0.00
AGO.	D3	0.00	4.28	17.96	31.76	45.52	58.99	71.33	78.00	71.33	58.99	45.52	31.76	17.96	4.28	0.00
SEP.	D1	0.00	2.73	16.50	30.29	43.92	57.02	68.46	74.00	68.46	57.02	43.92	30.29	16.50	2.73	0.00
SEP.	D2	0.00	1.17	14.97	28.49	42.10	54.74	65.28	70.00	65.28	54.74	42.10	28.49	14.97	1.17	0.00
SEP.	D3	0.00	0.00	13.38	26.96	40.09	52.21	61.91	66.00	61.91	52.21	40.09	26.96	13.38	0.00	0.00
OCT.	D1	0.00	0.00	11.73	25.12	37.91	49.47	58.40	62.00	58.40	49.47	37.91	25.12	11.73	0.00	0.00
OCT.	D2	0.00	0.00	10.03	23.17	35.57	46.57	54.79	58.00	54.79	46.57	35.57	23.17	10.03	0.00	0.00
OCT.	D3	0.00	0.00	8.73	21.65	33.74	44.31	52.04	55.00	52.04	44.31	33.74	21.65	8.73	0.00	0.00
NOV.	D1	0.00	0.00	6.97	19.56	31.20	41.19	48.33	51.00	48.33	41.19	31.20	19.56	6.97	0.00	0.00
NOV.	D2	0.00	0.00	6.08	18.48	29.89	39.60	46.46	49.00	46.46	39.60	29.89	18.48	6.08	0.00	0.00
NOV.	D3	0.00	0.00	4.73	16.84	27.88	37.17	43.63	46.00	43.63	37.17	27.88	16.84	4.73	0.00	0.00
DIC.	D1	0.00	0.00	4.27	16.28	27.20	36.35	42.69	45.00	42.69	36.35	27.20	16.28	4.27	0.00	0.00
DIC.	D2	0.00	0.00	3.82	15.72	26.52	35.53	41.74	44.00	41.74	35.53	26.52	15.72	3.82	0.00	0.00
DIC.	D3	0.00	0.00	3.82	15.72	26.52	35.53	41.74	44.00	41.74	35.53	26.52	15.72	3.82	0.00	0.00

LATITUD= 23.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.9	56.8	47.5	35.1	19.1	0.0	-19.1	-35.1	-47.5	-56.8	-63.9	******	******
ENE.	D2	******	******	64.8	57.6	47.3	35.9	19.5	0.0	-19.5	-35.9	-48.3	-57.6	-64.8	******	******
ENE.	D3	******	******	66.6	59.4	50.0	37.3	20.4	0.0	-20.4	-37.3	-50.0	-59.4	-66.6	******	******
FEB.	D1	******	******	69.3	62.3	52.6	39.7	22.0	0.0	-22.0	-39.7	-52.6	-62.1	-69.3	******	******
FEB.	D2	******	******	72.0	64.8	55.3	42.2	23.7	0.0	-23.7	-42.2	-55.3	-64.8	-72.0	******	******
FEB.	D3	******	******	75.7	68.5	59.2	45.9	26.3	0.0	-26.3	-45.9	-59.2	-68.5	-75.7	******	******
MAR.	D1	******	******	77.4	71.6	62.2	49.0	28.6	0.0	-28.6	-49.0	-62.2	-71.4	-78.4	******	******
MAR.	D2	******	******	82.1	75.3	66.4	53.5	32.3	0.0	-32.3	-53.5	-66.4	-75.3	-82.1	******	******
MAR.	D3	******	88.2	85.9	79.6	71.0	58.5	36.9	0.0	-36.9	-58.5	-71.0	-79.3	-85.9	-88.2	******
ABR.	D1	******	84.3	89.7	83.5	75.8	64.2	42.7	0.0	-42.7	-64.2	-75.8	-83.5	-89.7	-84.5	******
ABR.	D2	******	80.6	86.4	87.8	80.8	70.6	50.3	0.0	-50.3	-70.6	-80.8	-87.8	-86.4	-80.5	******
ABR.	D3	******	78.9	83.4	88.9	84.8	75.9	57.5	0.0	-57.5	-75.9	-84.8	-88.9	-83.4	-78.7	******
MAY.	D1	******	75.2	80.4	85.5	89.6	81.5	66.3	0.0	-66.3	-81.5	-89.6	-85.5	-80.4	-75.2	******
MAY.	D2	******	72.4	77.4	82.0	86.7	87.5	76.9	0.0	-76.9	-87.5	-86.7	-82.0	-77.4	-72.4	******
MAY.	D3	******	70.5	75.4	79.7	83.8	88.3	84.7	0.0	-84.7	-88.3	-83.8	-79.7	-75.4	-70.5	******
JUN.	D1	******	69.6	74.3	78.5	82.3	86.2	89.8	0.0	-89.8	-86.2	-82.3	-78.5	-74.3	-69.6	******
JUN.	D2	******	68.7	73.3	77.1	80.8	84.0	87.1	0.0	-87.1	-84.0	-80.8	-77.3	-73.3	-68.7	******
JUN.	D3	******	68.7	73.3	77.3	80.8	84.0	87.1	0.0	-87.1	-84.0	-80.8	-77.3	-73.3	-68.7	******
JUL.	D1	******	68.7	73.3	77.3	80.8	84.0	87.1	0.0	-87.1	-84.0	-80.8	-77.3	-73.3	-68.7	******
JUL.	D2	******	70.5	75.4	79.7	83.8	88.3	84.7	0.0	-84.7	-88.3	-83.8	-79.7	-75.4	-70.5	******
JUL.	D3	******	71.5	76.4	80.8	85.3	89.6	80.7	0.0	-80.7	-89.6	-85.3	-80.8	-76.4	-71.5	******
AGO.	D1	******	74.3	79.4	84.3	89.6	83.5	69.7	0.0	-69.7	-83.5	-89.6	-84.3	-79.4	-74.3	******
AGO.	D2	******	77.1	82.4	87.7	86.2	77.7	60.3	0.0	-60.3	-77.7	-86.2	-87.7	-82.4	-77.1	******
AGO.	D3	******	79.9	85.4	88.9	82.2	72.3	52.5	0.0	-52.5	-72.3	-82.2	-88.0	-85.4	-79.9	******
SEP.	D1	******	83.6	89.3	84.6	77.0	65.7	44.4	0.0	-44.4	-65.7	-77.0	-84.6	-89.3	-83.6	******
SEP.	D2	******	87.2	86.9	80.4	73.1	54.9	38.2	0.0	-38.2	-54.9	-72.1	-80.4	-86.9	-87.2	******
SEP.	D3	******	******	83.1	76.3	67.5	54.7	33.3	0.0	-33.3	-54.7	-67.5	-76.3	-83.1	******	******
OCT.	D1	******	******	79.3	72.3	63.2	50.0	29.5	0.0	-29.5	-50.0	-63.2	-72.3	-79.3	******	******
OCT.	D2	******	******	75.7	68.5	59.2	45.9	26.3	0.0	-26.3	-45.9	-59.2	-68.5	-75.7	******	******
OCT.	D3	******	******	72.9	65.7	56.3	43.1	24.3	0.0	-24.3	-43.1	-56.3	-65.7	-72.9	******	******
NOV.	D1	******	******	69.3	62.1	52.6	39.7	22.0	0.0	-22.0	-39.7	-52.6	-62.1	-69.3	******	******
NOV.	D2	******	******	67.5	60.3	50.9	38.1	20.9	0.0	-20.9	-38.1	-50.9	-60.3	-67.5	******	******
NOV.	D3	******	******	64.8	57.6	48.3	35.9	19.5	0.0	-19.5	-35.9	-48.3	-57.6	-64.8	******	******
DIC.	D1	******	******	63.9	56.8	47.5	35.1	19.1	0.0	-19.1	-35.1	-47.5	-56.8	-63.9	******	******
DIC.	D2	******	******	63.0	55.9	46.7	34.4	18.6	0.0	-18.6	-34.4	-46.7	-55.9	-63.0	******	******
DIC.	D3	******	******	63.0	55.9	46.7	34.4	18.6	0.0	-18.6	-34.4	-46.7	-55.9	-63.0	******	******

LATITUD=24.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	3.83	15.73	26.52	35.53	41.74	44.00	41.74	35.53	26.52	15.73	3.83	0.00	0.00
ENE.	02	0.00	0.00	4.30	16.30	27.21	36.16	42.69	45.00	42.69	36.36	27.21	16.30	4.30	0.00	0.00
ENE.	03	0.00	0.00	5.23	17.43	28.58	38.00	44.58	47.00	44.58	38.00	28.58	17.43	5.23	0.00	0.00
FEB.	01	0.00	0.00	6.61	19.08	30.59	40.42	47.40	50.00	47.40	40.42	30.59	19.08	6.61	0.00	0.00
FEB.	02	0.00	0.00	7.98	20.71	32.54	42.80	50.20	53.00	50.20	42.80	32.54	20.71	7.98	0.00	0.00
FEB.	03	0.00	0.00	9.78	22.80	35.06	45.87	53.89	57.00	53.89	45.87	35.06	22.80	9.78	0.00	0.00
MAR.	01	0.00	0.00	11.11	24.32	36.86	48.10	56.62	60.00	56.62	48.10	36.86	24.32	11.11	0.00	0.00
MAR.	02	0.00	0.00	12.83	26.25	39.15	50.94	60.19	64.00	60.19	50.94	39.15	26.25	12.83	0.00	0.00
MAR.	03	0.00	0.61	14.51	28.00	41.28	53.60	63.65	68.00	63.65	53.60	41.28	28.00	14.51	0.61	0.00
ABR.	01	0.00	2.44	16.12	29.79	43.23	56.03	66.94	72.00	66.94	56.03	43.23	29.79	16.12	2.44	0.00
ABR.	02	0.00	4.05	17.47	31.36	44.97	58.19	69.99	76.00	69.99	58.19	44.97	31.36	17.47	4.05	0.00
ABR.	03	0.00	5.25	18.78	32.45	46.13	59.58	72.74	79.00	72.74	59.58	46.13	32.45	18.78	5.25	0.00
MAY.	01	0.00	6.44	19.84	33.45	47.14	60.76	73.81	82.00	73.81	60.76	47.14	33.45	19.84	6.44	0.00
MAY.	02	0.00	7.61	20.85	34.35	48.00	61.70	75.19	85.00	75.19	61.73	48.00	34.35	20.85	7.61	0.00
MAY.	03	0.00	8.38	21.50	34.90	48.49	62.17	75.83	87.00	75.83	62.17	48.49	34.90	21.50	8.38	0.00
JUN.	01	0.00	8.76	21.81	35.16	48.70	62.36	76.06	88.00	76.06	62.36	48.70	35.16	21.81	8.76	0.00
JUN.	02	0.00	9.14	22.12	35.41	48.90	62.52	76.21	89.00	76.21	62.52	48.90	35.41	22.12	9.14	0.00
JUN.	03	0.00	9.14	22.12	35.41	48.90	62.52	76.21	89.00	76.21	62.52	48.90	35.41	22.12	9.14	0.00
JUL.	01	0.00	9.14	22.12	35.41	48.90	62.52	76.21	89.00	76.21	62.52	48.90	35.41	22.12	9.14	0.00
JUL.	02	0.00	8.38	21.50	34.90	48.49	62.17	75.83	87.00	75.83	62.17	48.49	34.90	21.50	8.38	0.00
JUL.	03	0.00	8.00	21.18	34.63	48.26	61.95	75.54	86.00	75.54	61.95	48.26	34.63	21.18	8.00	0.00
AGO.	01	0.00	6.83	20.18	33.76	47.45	61.10	74.32	83.00	74.32	61.10	47.45	33.76	20.18	6.83	0.00
AGO.	02	0.00	5.65	19.14	32.79	46.48	60.00	72.67	80.00	72.67	60.00	46.48	32.79	19.14	5.65	0.00
AGO.	03	0.00	4.45	18.04	31.71	45.37	58.67	70.70	77.00	70.70	58.67	45.37	31.71	18.04	4.45	0.00
SEP.	01	0.00	2.84	16.51	30.19	43.69	56.60	67.73	73.00	67.73	56.60	43.69	30.19	16.51	2.84	0.00
SEP.	02	0.00	1.22	14.92	28.52	41.79	54.23	64.49	69.00	64.49	54.23	41.79	28.52	14.92	1.22	0.00
SEP.	03	0.00	0.00	13.26	26.72	39.70	51.62	61.07	65.00	61.07	51.62	39.70	26.72	13.26	0.00	0.00
OCT.	01	0.00	0.00	11.54	24.81	37.45	48.82	57.52	61.00	57.52	48.82	37.45	24.81	11.54	0.00	0.00
OCT.	02	0.00	0.00	9.78	22.80	35.06	45.87	53.89	57.00	53.89	45.87	35.06	22.80	9.78	0.00	0.00
OCT.	03	0.00	0.00	8.44	21.24	33.18	43.57	51.13	54.00	51.13	43.57	33.13	21.24	8.44	0.00	0.00
NOV.	01	0.00	0.00	6.61	19.08	30.59	40.42	47.40	50.00	47.40	40.42	30.59	19.08	6.61	0.00	0.00
NOV.	02	0.00	0.00	5.69	17.98	29.25	38.81	45.52	48.00	45.52	38.81	29.25	17.98	5.69	0.00	0.00
NOV.	03	0.00	0.00	4.30	16.30	27.21	35.16	42.69	45.00	42.69	36.36	27.21	16.30	4.30	0.00	0.00
DIC.	01	0.00	0.00	3.83	15.73	26.52	35.53	41.74	44.00	41.74	35.53	26.52	15.73	3.83	0.00	0.00
DIC.	02	0.00	0.00	3.37	15.16	25.83	34.70	40.79	43.00	40.79	34.70	25.83	15.16	3.37	0.00	0.00
DIC.	03	0.00	0.00	3.37	15.16	25.83	34.70	40.79	43.00	40.79	34.70	25.83	15.16	3.37	0.00	0.00

LATITUD= 24.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	******	******	63.4	58.5	47.1	34.7	18.8	0.0	-15.8	-34.7	-47.1	-56.5	-63.8	******	******
ENE.	02	******	******	64.7	57.4	47.9	35.4	19.2	0.0	-19.2	-35.4	-47.?	-57.4	-64.7	******	******
ENE.	03	******	******	67.5	59.1	49.6	36.9	20.1	0.0	-20.1	-36.9	-49.6	-59.1	-66.5	******	******
FEB.	01	******	******	69.2	61.8	52.1	39.1	21.?	0.0	-21.6	-39.1	-52.1	-61.9	-6?.7	******	******
FEB.	02	******	******	71.?	64.?	54.8	41.6	23.7	0.0	-23.2	-41.6	-54.5	-64.4	-71.9	******	******
FEB.	03	******	******	75.5	68.1	58.6	45.7	25.7	0.0	-25.7	-45.2	-58.6	-68.1	-75.5	******	******
MAR.	01	******	******	73.2	77.?	61.5	48.1	27.9	0.0	-27.9	-48.1	-61.7	-70.9	-78.2	******	******
MAR.	02	******	******	81.9	74.8	65.7	52.7	31.4	0.0	-31.4	-52.5	-65.7	-74.8	-81.9	******	******
MAR.	03	******	57.2	85.7	78.8	70.1	57.4	35.6	0.0	-35.6	-57.4	-70.1	-78.4	-85.7	-58.2	******
ABR.	01	******	32.5	89.5	72.?	74.8	62.9	41.1	0.0	-41.1	-62.9	-74.8	-82.9	-89.5	-44.5	******
ABR.	02	******	37.?	81.7	17.?	79.9	69.1	48.2	0.0	-48.2	-69.1	-79.9	-87.2	[illegible]	-80.8	******
ABR.	03	******	73.1	33.3	-9.?	13.8	74.2	54.9	0.0	-54.9	-74.2	-83.8	-69.5	-?3.8	-78.1	******
MAY.	01	******	75.3	8?.d	56.1	87.9	79.8	63.2	0.0	-63.2	-79.9	-87.9	-36.4	[illegible]	-75.3	******
MAY.	02	******	77.5	77.6	32.7	87.?	85.7	73.2	0.0	-73.2	-85.7	-37.8	-82.7	-77.8	-77.5	******
MAY.	03	******	77.7	75.7	89.2	84.9	89.8	80.7	0.0	-80.7	-89.8	-84.9	-80.3	-75.7	-70.7	******
JUN.	01	******	59.?	73.7	79.?	63.4	98.1	84.8	0.1	-84.8	-88.1	-83.4	-74.7	-74.7	-69.7	******
JUN.	02	******	6?.?	?1.7	78.?	81.9	85.9	88.9	0.0	-88.9	-85.9	-81.9	-78.0	-73.7	-68.8	******
JUN.	03	******	[illegible]	71.7	74.?	41.9	85.9	88.9	0.0	-88.9	-85.9	-81.9	-78.0	-73.7	-69.8	******
JUL.	01	******	69.6	73.7	78.0	81.9	85.9	88.9	0.0	-89.9	-85.9	-81.9	-78.0	-73.7	-69.8	******
JUL.	02	******	77.7	75.7	80.3	84.9	89.8	80.7	0.0	-80.7	-89.3	-84.9	-80.3	-75.7	-70.7	******
JUL.	03	******	71.6	75.d	61.4	86.4	87.7	76.9	0.0	-76.9	-87.7	-36.4	-81.5	-76.8	-71.6	******
AGO.	01	******	73.8	79.8	25.0	89.3	81.7	66.3	0.0	-66.3	-81.7	-89.3	-85.0	-79.?	-74.4	******
AGO.	02	******	77.2	82.d	88.?	85.2	76.0	57.5	0.0	-57.5	-76.0	-85.2	-88.4	-?2.8	-77.2	******
AGO.	03	******	79.9	85.7	63.3	81.2	70.7	50.2	0.0	-50.2	-70.7	-81.2	-88.1	-?5.7	-79.9	******
SEP.	01	******	83.6	29.6	84.0	76.1	64.4	42.7	0.0	-42.7	-64.4	-76.1	-84.0	-59.6	-83.6	******
SEP.	02	******	97.3	9?.?	79.8	71.3	58.7	38.9	0.0	-36.9	-58.7	-71.3	-79.8	-86.4	-87.3	******
SEP.	03	******	******	87.8	75.8	66.8	53.6	32.3	0.0	-32.3	-53.6	-66.5	-75.8	-82.?	******	******
OCT.	01	******	******	79.1	71.9	62.5	49.2	28.7	0.0	-28.7	-49.2	-62.5	-71.9	-79.1	******	******
OCT.	02	******	******	75.5	68.1	58.6	45.2	25.7	0.0	-27.7	-45.2	-58.6	-68.1	-75.5	******	******
OCT.	03	******	******	72.8	65.3	55.7	42.5	23.8	0.1	-23.8	-42.5	-55.7	-65.3	-72.8	******	******
NOV.	01	******	******	69.2	61.8	52.1	39.1	21.6	0.0	-21.6	-39.1	-52.1	-61.8	-69.2	******	******
NOV.	02	******	******	67.4	60.0	50.4	37.6	20.6	0.0	-20.6	-37.6	-50.4	-60.0	-67.4	******	******
NOV.	03	******	******	64.7	57.4	47.9	35.4	19.2	0.0	-19.2	-35.4	-47.9	-57.4	-64.7	******	******
DIC.	01	******	******	63.d	56.5	47.1	34.7	18.8	0.0	-18.8	-34.7	-47.1	-56.5	-63.8	******	******
DIC.	02	******	******	63.0	55.7	46.3	34.0	18.3	0.0	-18.3	-34.0	-46.3	-55.7	-63.0	******	******
DIC.	03	******	******	63.0	55.7	46.3	34.0	18.3	0.0	-18.3	-34.0	-46.3	-55.7	-63.0	******	******

LATITUD=25.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	3.39	15.18	25.84	34.71	40.80	43.00	40.80	34.71	25.84	15.18	3.39	0.00	0.00
ENE.	D2	0.00	0.00	3.87	15.76	26.54	35.54	41.75	44.00	41.75	35.54	26.54	15.76	3.87	0.00	0.00
ENE.	D3	0.00	0.00	4.83	16.91	27.93	37.23	43.54	46.00	43.54	37.23	27.93	16.91	4.83	0.00	0.00
FEB.	D1	0.00	0.00	6.26	18.61	29.97	39.64	46.47	49.00	46.47	39.64	29.97	18.61	6.26	0.00	0.00
FEB.	D2	0.00	0.00	7.67	20.27	31.96	42.06	49.26	52.00	49.26	42.06	31.96	20.27	7.67	0.00	0.00
FEB.	D3	0.00	0.00	9.53	22.45	34.53	45.16	52.99	56.00	52.99	45.16	34.53	22.45	9.53	0.00	0.00
MAR.	D1	0.00	0.00	10.90	23.98	36.38	47.43	55.74	59.00	55.74	47.43	36.38	23.98	10.90	0.00	0.00
MAR.	D2	0.00	0.00	12.69	25.98	38.73	50.32	59.33	63.00	59.33	50.32	38.73	25.98	12.69	0.00	0.00
MAR.	D3	0.00	0.85	14.43	27.88	40.94	53.05	62.73	67.00	62.73	53.05	40.94	27.88	14.43	0.85	0.00
ABR.	D1	0.00	2.53	16.11	29.66	42.96	55.56	66.18	71.00	66.18	55.56	42.96	29.66	16.11	2.53	0.00
ABR.	D2	0.00	4.21	17.72	31.31	44.77	57.82	69.31	75.00	69.31	57.82	44.77	31.31	17.72	4.21	0.00
ABR.	D3	0.00	5.46	18.90	32.45	46.01	59.30	71.45	78.00	71.45	59.30	46.01	32.45	18.90	5.46	0.00
MAY.	D1	0.00	6.69	20.00	33.51	47.10	60.57	73.34	81.00	73.34	60.57	47.10	33.51	20.00	6.69	0.00
MAY.	D2	0.00	7.91	21.06	34.48	48.03	61.61	74.87	84.00	74.87	61.61	48.03	34.48	21.06	7.91	0.00
MAY.	D3	0.00	8.71	21.74	35.07	48.57	62.15	75.63	86.00	75.63	62.15	48.57	35.07	21.74	8.71	0.00
JUN.	D1	0.00	9.11	22.07	35.34	48.81	62.38	75.93	87.00	75.93	62.38	48.81	35.34	22.07	9.11	0.00
JUN.	D2	0.00	9.50	22.40	35.61	49.03	62.58	76.16	88.00	76.16	62.58	49.03	35.61	22.40	9.50	0.00
JUN.	D3	0.00	9.50	22.40	35.61	49.03	62.58	76.16	88.00	76.16	62.58	49.03	35.61	22.40	9.50	0.00
JUL.	D1	0.00	9.50	22.40	35.61	49.03	62.58	76.16	88.00	76.16	62.58	49.03	35.61	22.40	9.50	0.00
JUL.	D2	0.00	8.71	21.74	35.07	48.57	62.15	75.63	86.00	75.63	62.15	48.57	35.07	21.74	8.71	0.00
JUL.	D3	0.00	8.31	21.41	34.78	48.31	61.90	75.28	85.00	75.28	61.90	48.31	34.78	21.41	8.31	0.00
AGO.	D1	0.00	7.10	20.36	33.84	47.43	60.94	73.89	82.00	73.89	60.94	47.43	33.84	20.36	7.10	0.00
AGO.	D2	0.00	5.97	19.26	32.82	46.39	59.75	72.11	79.00	72.11	59.75	46.39	32.82	19.26	5.97	0.00
AGO.	D3	0.00	4.63	18.11	31.70	45.21	58.33	70.05	76.00	70.05	58.33	45.21	31.70	18.11	4.63	0.00
SEP.	D1	0.00	2.95	16.52	30.08	43.44	56.15	66.79	72.00	66.79	56.15	43.44	30.08	16.52	2.95	0.00
SEP.	D2	0.00	1.27	14.85	28.34	41.46	53.70	63.68	68.00	63.68	53.70	41.46	28.34	14.85	1.27	0.00
SEP.	D3	0.00	0.00	13.13	26.47	39.30	51.02	60.22	64.00	60.22	51.02	39.30	26.47	13.13	0.00	0.00
OCT.	D1	0.00	0.00	11.35	24.49	36.98	48.16	56.64	60.00	56.64	48.16	36.98	24.49	11.35	0.00	0.00
OCT.	D2	0.00	0.00	9.53	22.42	34.53	45.16	52.99	56.00	52.99	45.16	34.53	22.42	9.53	0.00	0.00
OCT.	D3	0.00	0.00	8.14	20.82	32.61	42.83	50.21	53.00	50.21	42.83	32.61	20.82	8.14	0.00	0.00
NOV.	D1	0.00	0.00	6.26	18.61	29.97	39.64	46.47	49.00	46.47	39.64	29.97	18.61	6.26	0.00	0.00
NOV.	D2	0.00	0.00	5.11	17.48	28.61	38.02	44.59	47.00	44.59	38.02	28.61	17.48	5.11	0.00	0.00
NOV.	D3	0.00	0.00	3.87	15.76	26.54	35.54	41.75	44.00	41.75	35.54	26.54	15.76	3.87	0.00	0.00
DIC.	D1	0.00	0.00	3.39	15.18	25.84	34.71	40.80	43.00	40.80	34.71	25.84	15.18	3.39	0.00	0.00
DIC.	D2	0.00	0.00	2.91	14.60	25.14	33.87	39.84	42.00	39.84	33.87	25.14	14.60	2.91	0.00	0.00
DIC.	D3	0.00	0.00	2.91	14.60	25.14	33.87	39.84	42.00	39.84	33.87	25.14	14.60	2.91	0.00	0.00

LATITUD= 25.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.8	56.3	46.8	34.3	18.5	[illegible]	-18.5	-34.3	-46.3	-56.3	-63.8	******	******
ENE.	D2	******	******	64.7	57.1	47.6	35.0	18.9	[illegible]	-18.9	-35.0	-47.6	-57.1	-64.7	******	******
ENE.	D3	******	******	66.4	58.0	49.2	36.4	19.6	[illegible]	-19.6	-36.4	-49.2	-58.0	-66.4	******	******
FEB.	D1	******	******	69.1	61.5	51.7	38.6	21.2	[illegible]	-21.2	-38.6	-51.7	-61.5	-69.1	******	******
FEB.	D2	******	******	71.7	64.1	54.3	41.7	22.7	[illegible]	-22.7	-41.7	-54.3	-64.3	-71.7	******	******
FEB.	D3	******	******	75.3	67.7	57.0	44.5	25.1	[illegible]	-25.1	-44.5	-58.0	-67.7	-75.3	******	******
MAR.	D1	******	******	78.0	70.5	60.9	47.3	27.7	[illegible]	-27.2	-47.3	-60.9	-70.5	-78.0	******	******
MAR.	D2	******	******	81.7	74.3	64.9	51.5	30.5	[illegible]	-30.5	-51.5	-64.9	-74.3	-81.7	******	******
MAR.	D3	******	[illegible]	85.4	78.3	69.3	56.2	34.5	[illegible]	-34.5	-56.2	-69.3	-78.3	-85.4	-88.2	******
ABR.	D1	******	[illegible]	89.2	82.4	73.9	61.6	39.4	[illegible]	-39.6	-61.6	-73.9	-82.4	-89.2	-84.6	******
ABR.	D2	******	[illegible]	87.0	86.6	78.9	67.6	46.2	[illegible]	-46.2	-67.6	-78.9	-86.6	-87.0	-80.9	******
ABR.	D3	******	[illegible]	84.1	89.9	82.8	72.6	52.4	0.0	-52.4	-72.6	-82.8	-89.9	-84.1	-78.2	******
MAY.	D1	******	[illegible]	81.1	86.8	86.6	78.0	60.2	[illegible]	-60.2	-78.0	-86.8	-86.8	-81.1	-75.4	******
MAY.	D2	******	[illegible]	78.1	83.4	88.9	83.5	69.6	[illegible]	-69.6	-83.8	-88.9	-83.4	-78.1	-72.7	******
MAY.	D3	******	[illegible]	76.1	81.6	86.0	87.9	76.9	[illegible]	-76.9	-87.9	-86.0	-81.0	-76.1	-70.8	******
JUN.	D1	******	[illegible]	75.1	79.9	84.6	90.0	80.8	[illegible]	-80.8	-90.0	-84.6	-79.9	-75.1	-69.9	******
JUN.	D2	******	[illegible]	74.1	78.7	83.1	87.9	84.8	[illegible]	-84.8	-87.0	-83.1	-78.7	-74.1	-69.0	******
JUN.	D3	******	[illegible]	74.1	78.7	83.1	87.9	84.8	[illegible]	-84.8	-87.9	-83.1	-78.7	-74.1	-69.0	******
JUL.	D1	******	[illegible]	74.1	78.7	83.1	87.9	84.8	[illegible]	-84.8	-87.9	-83.1	-78.7	-74.1	-69.0	******
JUL.	D2	******	[illegible]	76.1	81.0	86.0	87.7	76.9	0.0	-76.9	-87.7	-86.0	-81.0	-76.1	-70.0	******
JUL.	D3	******	[illegible]	77.1	82.2	87.5	85.9	73.2	0.0	-73.2	-85.9	-87.5	-82.2	-77.1	-71.7	******
AGO.	D1	******	[illegible]	80.2	85.7	88.2	79.9	63.1	0.0	-63.1	-79.9	-88.2	-85.7	-80.2	-74.5	******
AGO.	D2	******	[illegible]	83.1	89.0	88.1	74.4	54.8	0.0	-54.8	-74.4	-88.1	-89.0	-83.1	-77.3	******
AGO.	D3	******	[illegible]	85.0	87.7	80.2	69.2	48.1	[illegible]	-48.1	-69.2	-80.2	-87.7	-86.0	-80.3	******
SEP.	D1	******	[illegible]	89.9	83.4	75.1	63.0	41.1	0.0	-41.1	-63.0	-75.1	-83.4	-89.9	-83.7	******
SEP.	D2	******	[illegible]	86.3	79.1	72.4	57.5	35.7	0.0	-35.7	-57.5	-72.4	-79.3	-86.3	-87.3	******
SEP.	D3	******	******	82.6	75.1	66.3	52.6	31.4	0.0	-31.4	-52.6	-66.6	-75.3	-82.6	******	******
OCT.	D1	******	******	79.9	71.5	61.9	48.3	28.0	[illegible]	-28.0	-48.3	-61.9	-71.5	-78.9	******	******
OCT.	D2	******	******	75.3	67.7	58.0	44.5	25.1	[illegible]	-25.1	-44.5	-58.0	-67.7	-75.3	******	******
OCT.	D3	******	******	72.6	65.0	55.2	41.8	23.3	[illegible]	-23.3	-41.8	-55.2	-65.0	-72.6	******	******
NOV.	D1	******	******	69.1	61.5	51.7	38.6	21.2	0.0	-21.2	-38.6	-51.7	-61.5	-69.1	******	******
NOV.	D2	******	******	67.3	59.7	50.0	37.1	20.2	0.0	-20.2	-37.1	-50.0	-59.7	-67.3	******	******
NOV.	D3	******	******	64.7	57.1	47.6	35.0	18.9	0.0	-18.9	-35.0	-47.6	-57.1	-64.7	******	******
DIC.	D1	******	******	63.8	56.3	46.8	34.3	18.5	0.0	-18.5	-34.3	-46.3	-56.3	-63.8	******	******
DIC.	D2	******	******	62.9	55.5	46.0	33.7	18.1	0.0	-18.1	-33.7	-46.0	-55.5	-62.9	******	******
DIC.	D3	******	******	62.9	55.5	46.0	33.7	18.1	[illegible]	-18.1	-33.7	-46.0	-55.5	-62.9	******	******

LATITUD=26.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	2.95	14.62	25.15	33.88	39.85	42.00	39.85	33.88	25.15	14.62	2.95	0.00	0.00
ENE.	02	0.00	0.00	3.44	15.22	25.86	34.72	40.80	43.00	40.80	34.72	25.86	15.22	3.44	0.00	0.00
ENE.	03	0.00	0.00	4.13	16.39	27.27	36.39	42.70	45.00	42.70	36.39	27.27	16.39	4.13	0.00	0.00
FEB.	01	0.00	0.00	5.90	18.13	29.35	38.86	45.54	48.00	45.54	38.86	29.35	18.13	5.90	0.00	0.00
FEB.	02	0.00	0.60	7.36	19.83	31.38	41.27	48.36	51.00	48.36	41.27	31.38	19.83	7.36	0.00	0.00
FEB.	03	0.00	0.00	9.28	22.04	34.00	44.44	52.08	55.00	52.08	44.44	34.00	22.04	9.28	0.00	0.00
MAR.	01	0.00	0.20	10.59	23.45	35.49	46.78	54.84	58.00	54.84	46.78	35.49	23.45	10.59	0.20	0.00
MAR.	02	0.00	0.33	12.54	25.71	38.11	49.69	58.47	62.00	58.47	49.69	38.11	25.71	12.54	0.33	0.00
MAR.	03	0.00	1.89	14.35	27.67	40.58	52.49	62.30	66.00	62.30	52.49	40.58	27.67	14.35	1.89	0.00
ABR.	01	0.00	2.63	16.09	29.59	42.69	55.08	65.40	70.00	65.40	55.08	42.69	29.59	16.09	2.63	0.00
ABR.	02	0.00	4.37	17.77	31.24	44.59	57.47	68.61	74.00	68.61	57.47	44.59	31.24	17.77	4.37	0.00
ABR.	03	0.00	5.66	18.96	32.45	45.88	58.99	70.83	77.00	70.83	58.99	45.88	32.45	18.96	5.66	0.00
MAY.	01	0.00	6.94	20.15	33.56	47.03	60.35	72.82	80.00	72.82	60.35	47.03	33.56	20.15	6.94	0.00
MAY.	02	0.00	8.21	21.26	34.59	48.04	61.48	74.49	83.00	74.49	61.48	48.04	34.59	21.26	8.21	0.00
MAY.	03	0.00	9.04	21.98	35.22	48.63	62.10	75.38	85.00	75.38	62.10	48.63	35.22	21.98	9.04	0.00
JUN.	01	0.00	9.45	22.33	35.51	48.89	62.36	75.74	86.00	75.74	62.36	48.89	35.51	22.33	9.45	0.00
JUN.	02	0.00	9.86	22.67	35.80	49.14	62.60	76.03	87.00	76.03	62.60	49.14	35.80	22.67	9.86	0.00
JUN.	03	0.00	9.86	22.67	35.80	49.14	62.60	76.03	87.00	76.03	62.60	49.14	35.80	22.67	9.86	0.00
JUL.	01	0.00	9.86	22.67	35.80	49.14	62.60	76.03	87.00	76.03	62.60	49.14	35.80	22.67	9.86	0.00
JUL.	02	0.00	9.04	21.98	35.22	48.63	62.10	75.38	85.00	75.38	62.10	48.63	35.22	21.98	9.04	0.00
JUL.	03	0.00	8.62	21.62	34.91	48.34	61.81	74.96	84.00	74.96	61.81	48.34	34.91	21.62	8.62	0.00
AGO.	01	0.00	7.36	20.53	33.91	47.39	60.75	73.42	81.00	73.42	60.75	47.39	33.91	20.53	7.36	0.00
AGO.	02	0.00	6.09	19.38	32.83	46.29	59.46	71.52	78.00	71.52	59.46	46.29	32.83	19.38	6.09	0.00
AGO.	03	0.00	4.80	18.15	31.65	45.03	57.96	69.37	75.00	69.37	57.96	45.03	31.65	18.15	4.80	0.00
SEP.	01	0.00	3.06	16.52	29.97	43.18	55.69	66.22	71.00	66.22	55.69	43.18	29.97	16.52	3.06	0.00
SEP.	02	0.00	1.31	14.79	28.15	41.12	53.15	62.76	67.00	62.76	53.15	41.12	28.15	14.79	1.31	0.00
SEP.	03	0.00	0.00	13.00	26.21	38.89	50.41	59.36	63.00	59.36	50.41	38.89	26.21	13.00	0.00	0.00
OCT.	01	0.00	0.00	11.16	24.17	36.51	47.49	55.76	59.00	55.76	47.49	36.51	24.17	11.16	0.00	0.00
OCT.	02	0.00	0.00	9.28	22.04	34.00	44.44	52.08	55.00	52.08	44.44	34.00	22.04	9.28	0.00	0.00
OCT.	03	0.00	0.00	7.84	20.39	32.04	42.08	49.29	52.00	49.29	42.08	32.04	20.39	7.84	0.00	0.00
NOV.	01	0.00	0.00	5.90	18.13	29.35	38.86	45.54	48.00	45.54	38.86	29.35	18.13	5.90	0.00	0.00
NOV.	02	0.00	0.00	4.92	16.97	27.97	37.22	43.65	46.00	43.65	37.22	27.97	16.97	4.92	0.00	0.00
NOV.	03	0.00	0.00	3.44	15.22	25.86	34.72	40.80	43.00	40.80	34.72	25.86	15.22	3.44	0.00	0.00
DIC.	01	0.00	0.00	2.95	14.62	25.15	33.88	39.85	42.00	39.85	33.88	25.15	14.62	2.95	0.00	0.00
DIC.	02	0.00	0.00	2.46	14.03	24.44	33.04	38.89	41.00	38.89	33.04	24.44	14.03	2.46	0.00	0.00
DIC.	03	0.00	0.00	2.46	14.03	24.44	33.04	38.89	41.00	38.89	33.04	24.44	14.03	2.46	0.00	0.00

LATITUD= 26.

AZIMUTO HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.7	54.1	46.4	33.9	18.2	0.0	-19.2	-33.9	-46.4	-56.1	-63.7	******	******
ENE.	D2	******	******	64.6	56.9	47.2	34.6	18.6	0.0	-18.6	-34.6	-47.2	-56.9	-64.6	******	******
ENE.	D3	******	******	66.4	58.4	49.3	36.0	19.5	0.0	-19.5	-36.0	-48.3	-58.4	-66.4	******	******
FEB.	D1	******	******	69.0	61.2	51.2	38.1	20.8	0.0	-20.8	-38.1	-51.2	-61.2	-69.0	******	******
FEB.	D2	******	******	71.6	63.8	53.5	40.4	22.3	0.0	-22.3	-40.4	-53.8	-63.8	-71.6	******	******
FEB.	D3	******	******	75.2	67.3	57.4	43.8	24.6	0.0	-24.6	-43.8	-57.4	-67.3	-75.2	******	******
MAR.	D1	******	******	77.9	70.1	60.2	46.5	26.6	0.0	-26.6	-46.5	-60.2	-70.1	-77.9	******	******
MAR.	D2	******	******	81.1	73.9	64.2	50.6	29.6	0.0	-29.6	-50.6	-64.2	-73.9	-81.5	******	******
MAR.	D3	******	[illegible]	85.1	77.8	69.5	55.1	33.4	0.0	-33.4	-55.1	-69.5	-77.8	-85.1	-88.2	******
ABR.	D1	******	[illegible]	88.9	81.8	73.1	60.3	38.2	0.0	-38.2	-60.3	-73.1	-81.8	-88.9	-84.6	******
ABR.	D2	******	[illegible]	87.3	86.0	77.9	66.1	44.3	0.0	-44.3	-66.1	-77.9	-86.0	-87.3	-81.0	******
ABR.	D3	******	[illegible]	84.4	89.2	81.8	71.0	50.2	0.0	-50.2	-71.0	-81.0	-89.2	-84.4	-79.3	******
MAY.	D1	******	75.5	81.5	87.5	85.8	76.3	57.4	0.0	-57.4	-76.3	-85.8	-87.5	-81.5	-75.5	******
MAY.	D2	******	72.8	78.5	84.0	90.0	82.0	66.2	0.0	-66.2	-82.0	-90.0	-84.0	-78.5	-72.8	******
MAY.	D3	******	71.0	76.5	81.7	87.2	86.0	73.1	0.0	-73.1	-86.0	-87.2	-81.7	-76.5	-71.0	******
JUN.	D1	******	70.0	75.5	80.6	85.7	88.1	76.9	0.0	-76.9	-88.1	-85.7	-80.6	-75.5	-70.0	******
JUN.	D2	******	69.1	74.5	79.4	84.2	89.8	80.8	0.0	-80.8	-89.8	-84.2	-79.4	-74.5	-69.1	******
JUN.	D3	******	69.1	74.5	79.4	84.2	89.8	80.8	0.0	-80.8	-89.9	-84.2	-79.4	-74.5	-69.1	******
JUL.	D1	******	[illegible]	74.5	79.4	[illegible]	89.9	80.8	0.0	-80.8	-89.9	-84.2	-79.4	-74.5	-69.1	******
JUL.	D2	******	71.0	76.5	81.7	87.2	86.0	73.1	0.0	-73.1	-86.0	-87.2	-81.7	-76.5	-71.0	******
JUL.	D3	******	[illegible]	77.5	82.9	88.6	84.0	69.6	0.0	-69.6	-84.0	-88.6	-82.9	-77.5	-71.9	******
AGO.	D1	******	[illegible]	79.5	86.3	87.2	78.2	60.1	0.0	-60.1	-78.2	-87.2	-86.3	-79.5	-74.6	******
AGO.	D2	******	77.4	83.5	89.7	83.1	72.7	52.4	0.0	-52.4	-72.7	-83.1	-89.7	-83.5	-77.4	******
AGO.	D3	******	[illegible]	86.4	87.5	79.2	67.7	46.1	0.0	-46.1	-67.7	-79.2	-87.1	-86.4	-80.1	******
SEP.	D1	******	83.7	89.8	82.8	74.2	61.7	39.6	0.0	-39.6	-61.7	-74.2	-82.8	-89.8	-83.7	******
SEP.	D2	******	87.3	86.1	78.8	69.6	56.9	34.5	0.0	-34.5	-56.4	-69.6	-78.8	-86.1	-87.3	******
SEP.	D3	******	******	82.4	74.8	65.3	51.7	30.5	0.0	-30.5	-51.7	-65.3	-74.8	-82.4	******	******
OCT.	D1	******	******	79.8	71.0	61.2	47.5	27.3	0.0	-27.3	-47.5	-61.2	-71.0	-78.8	******	******
OCT.	D2	******	******	75.2	67.3	57.4	43.9	24.6	0.0	-24.6	-43.8	-57.4	-67.3	-75.2	******	******
OCT.	D3	******	******	72.5	64.7	54.7	41.2	22.8	0.0	-22.8	-41.2	-54.7	-64.7	-72.5	******	******
NOV.	D1	******	******	69.0	61.7	51.2	38.1	20.8	0.0	-20.8	-38.1	-51.2	-61.7	-69.0	******	******
NOV.	D2	******	******	67.2	59.4	49.6	36.7	19.9	0.0	-19.9	-36.7	-49.6	-59.4	-67.2	******	******
NOV.	D3	******	******	64.6	56.9	47.2	34.6	18.6	0.0	-18.6	-34.6	-47.2	-56.9	-64.6	******	******
DIC.	D1	******	******	63.7	56.1	46.4	33.9	18.2	0.0	-18.2	-33.9	-46.4	-56.1	-63.7	******	******
DIC.	D2	******	******	62.9	55.1	45.6	33.3	17.8	0.0	-17.8	-33.3	-45.6	-55.1	-62.9	******	******
DIC.	D3	******	******	62.9	55.1	45.6	33.3	17.8	0.0	-17.8	-33.3	-45.6	-55.1	-62.9	******	******

LATITUD=27.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	2.51	14.06	24.46	33.05	38.90	41.00	38.90	33.05	24.46	14.06	2.51	0.00	0.00
ENE.	D2	0.00	0.00	3.01	14.67	25.18	33.90	39.85	42.00	39.85	33.90	25.18	14.67	3.01	0.00	0.00
ENE.	D3	0.00	0.00	4.03	15.87	26.61	35.58	41.76	44.00	41.76	35.58	26.61	15.87	4.03	0.00	0.00
FEB.	D1	0.00	0.00	5.54	17.64	28.72	38.07	14.60	47.00	44.60	38.07	28.72	17.64	5.54	0.00	0.00
FEB.	D2	0.00	0.00	7.24	19.39	30.78	40.52	47.43	50.00	47.43	40.52	30.78	19.39	7.24	0.00	0.00
FEB.	D3	0.00	0.00	9.02	21.65	33.45	43.72	51.17	54.00	51.17	43.72	33.45	21.65	9.02	0.00	0.00
MAR.	D1	0.00	0.00	10.49	23.30	35.39	46.05	53.95	57.00	53.95	46.05	35.39	23.30	10.49	0.00	0.00
MAR.	D2	0.00	0.00	12.39	25.43	37.67	49.05	57.59	61.00	57.59	49.05	37.67	25.43	12.39	0.00	0.00
MAR.	D3	0.00	0.91	14.26	27.46	40.20	51.91	61.16	65.00	61.16	51.91	40.20	27.46	14.26	0.91	0.00
ABR.	D1	0.00	2.72	16.07	29.37	42.38	54.57	64.61	69.00	64.61	54.57	42.33	29.37	16.07	2.72	0.00
ABR.	D2	0.00	4.52	17.81	31.17	44.37	57.01	67.90	73.00	67.90	57.01	44.37	31.17	17.81	4.52	0.00
ABR.	D3	0.00	5.86	19.38	32.43	45.73	59.65	70.17	76.00	70.17	59.65	45.73	32.43	19.38	5.86	0.00
MAY.	D1	0.00	7.17	20.29	33.60	46.95	60.10	72.26	79.00	72.26	60.10	46.95	33.60	20.29	7.17	0.00
MAY.	D2	0.00	8.50	21.46	34.68	48.03	61.33	74.06	82.00	74.06	61.33	48.03	34.68	21.46	8.50	0.00
MAY.	D3	0.00	9.36	22.21	35.35	48.67	62.02	75.06	84.00	75.06	62.02	48.67	35.35	22.21	9.36	0.00
JUN.	D1	0.00	9.79	22.57	35.67	48.96	62.31	75.48	85.00	75.48	62.31	48.96	35.67	22.57	9.79	0.00
JUN.	D2	0.00	10.22	22.93	35.98	49.23	62.59	75.84	86.00	75.84	62.59	49.23	35.98	22.93	10.22	0.00
JUN.	D3	0.00	10.22	22.93	35.98	49.23	62.59	75.84	86.00	75.84	62.59	49.23	35.98	22.93	10.22	0.00
JUL.	D1	0.00	10.22	22.93	35.98	49.23	62.58	75.84	86.00	75.84	62.59	49.23	35.98	22.93	10.22	0.00
JUL.	D2	0.00	9.36	22.21	35.35	48.67	62.02	75.06	84.00	75.06	62.02	48.67	35.35	22.21	9.36	0.00
JUL.	D3	0.00	8.93	21.84	35.02	48.36	61.69	74.58	83.00	74.58	61.69	48.30	35.02	21.84	8.93	0.00
AGO.	D1	0.00	7.63	20.69	33.97	47.33	60.53	72.90	80.00	72.90	60.53	47.33	33.97	20.69	7.63	0.00
AGO.	D2	0.00	6.31	19.49	32.83	46.15	59.15	70.89	77.00	70.89	59.15	46.15	32.83	19.49	6.31	0.00
AGO.	D3	0.00	4.97	18.24	31.60	44.84	57.57	68.66	74.00	68.66	57.57	44.84	31.60	18.24	4.97	0.00
SEP.	D1	0.00	3.17	16.51	29.88	42.90	55.21	65.48	70.00	65.48	55.21	42.90	29.88	16.51	3.17	0.00
SEP.	D2	0.00	1.35	14.72	27.95	40.76	52.59	62.03	66.00	62.03	52.59	40.76	27.95	14.72	1.35	0.00
SEP.	D3	0.00	0.00	12.86	25.96	38.46	49.78	58.49	62.00	58.49	49.78	38.46	25.96	12.86	0.00	0.00
OCT.	D1	0.00	0.00	10.96	23.84	36.02	46.81	54.97	58.00	54.97	46.81	36.02	23.84	10.96	0.00	0.00
OCT.	D2	0.00	0.00	9.02	21.65	33.45	43.72	51.17	54.00	51.17	43.72	33.45	21.65	9.02	0.00	0.00
OCT.	D3	0.00	0.00	7.54	19.96	31.40	41.13	48.37	51.00	48.37	41.33	31.40	19.96	7.54	0.00	0.00
NOV.	D1	0.00	0.00	5.54	17.64	28.72	38.07	44.60	47.00	44.60	38.07	28.72	17.60	5.54	0.00	0.00
NOV.	D2	0.00	0.00	4.53	16.44	27.32	36.41	42.71	45.00	42.71	36.41	27.32	16.44	4.53	0.00	0.00
NOV.	D3	0.00	0.00	3.01	14.67	25.18	33.90	39.95	42.00	39.95	33.90	25.13	14.67	3.01	0.00	0.00
DIC.	D1	0.00	0.00	2.51	14.06	24.46	33.05	38.90	41.00	38.70	33.05	24.46	14.06	2.51	0.00	0.00
DIC.	D2	0.00	0.00	2.00	13.46	23.74	32.20	37.94	40.00	37.94	32.20	23.74	13.46	2.00	0.00	0.00
DIC.	D3	0.00	0.00	2.00	13.46	23.74	32.20	37.94	40.00	37.94	32.20	23.74	13.46	2.00	0.00	0.00

LATITUD= 28.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.7	55.9	46.1	33.6	18.0	0.0	-18.0	-33.6	-46.1	-55.9	-63.7	******	******
ENE.	D2	******	******	64.6	56.7	46.3	34.2	17.3	0.0	-17.3	-34.2	-46.3	-56.7	-64.6	******	******
ENE.	D3	******	******	66.3	58.4	48.4	35.5	19.2	0.0	-19.2	-35.5	-48.4	-58.4	-66.3	******	******
FEB.	D1	******	******	68.9	60.9	50.8	37.6	20.5	0.0	-20.5	-37.6	-50.8	-60.9	-68.9	******	******
FEB.	D2	******	******	71.5	63.5	53.3	39.9	21.9	0.0	-21.9	-39.9	-53.3	-63.5	-71.5	******	******
FEB.	D3	******	******	75.0	67.0	56.4	43.1	24.1	0.0	-24.1	-43.1	-56.8	-67.0	-75.0	******	******
MAR.	D1	******	******	77.7	69.7	59.6	45.8	25.9	0.0	-25.9	-45.8	-59.6	-69.7	-77.7	******	******
MAR.	D2	******	******	81.3	73.4	63.5	49.7	28.9	0.0	-28.9	-49.7	-63.5	-73.4	-81.3	******	******
MAR.	D3	******	88.2	84.9	77.3	67.7	54.1	32.6	0.0	-32.6	-54.1	-67.7	-77.3	-84.9	-88.2	******
ABR.	D1	******	88.6	87.2	81.2	72.2	59.1	36.9	0.0	-36.9	-59.1	-72.2	-81.2	-88.6	-88.6	******
ABR.	D2	******	81.1	87.7	85.4	76.4	64.7	42.6	0.0	-42.6	-64.7	-76.4	-85.4	-87.7	-81.1	******
ABR.	D3	******	78.4	88.2	89.4	80.7	69.4	48.0	0.0	-48.0	-69.4	-80.7	-89.4	-88.8	-78.4	******
MAY.	D1	******	75.7	81.9	88.1	84.7	74.6	54.7	0.0	-54.7	-74.6	-84.7	-86.1	-81.9	-75.7	******
MAY.	D2	******	72.9	78.9	88.7	88.3	81.2	63.0	0.0	-63.0	-81.2	-88.3	-88.7	-78.9	-72.9	******
MAY.	D3	******	71.1	76.9	82.4	88.3	84.2	69.6	0.0	-69.6	-84.2	-88.3	-82.4	-76.9	-71.1	******
JUN.	D1	******	70.2	75.9	81.3	86.6	86.2	73.1	0.0	-73.1	-86.2	-86.3	-81.3	-75.9	-70.2	******
JUN.	D2	******	69.3	74.9	80.1	85.4	88.3	76.9	0.0	-76.9	-88.3	-85.4	-80.1	-74.9	-69.3	******
JUN.	D3	******	69.3	74.9	80.1	85.4	88.3	76.9	0.0	-76.9	-88.3	-85.4	-80.1	-74.9	-69.3	******
JUL.	D1	******	69.3	74.9	80.1	85.4	88.3	76.9	0.0	-76.9	-88.3	-85.4	-80.1	-74.9	-69.3	******
JUL.	D2	******	71.1	76.9	82.4	88.3	84.2	69.6	0.0	-69.6	-84.2	-88.3	-82.4	-76.9	-71.1	******
JUL.	D3	******	72.0	77.9	83.6	89.7	82.2	66.2	0.0	-66.2	-82.2	-89.7	-83.6	-77.9	-72.0	******
AGO.	D1	******	74.8	80.9	87.0	86.1	76.4	57.3	0.0	-57.3	-76.4	-86.1	-87.0	-80.9	-74.8	******
AGO.	D2	******	77.5	83.9	89.7	82.0	71.1	50.1	0.0	-50.1	-71.1	-82.0	-89.7	-83.8	-77.5	******
AGO.	D3	******	80.2	86.7	86.4	78.2	66.3	44.3	0.0	-44.3	-66.3	-78.2	-86.4	-86.7	-80.2	******
SEP.	D1	******	83.8	89.5	82.3	73.3	60.4	38.2	0.0	-38.2	-60.4	-73.3	-82.3	-89.5	-83.8	******
SEP.	D2	******	87.3	85.8	79.2	68.8	55.3	33.4	0.0	-33.4	-55.3	-68.8	-79.2	-85.8	-87.3	******
SEP.	D3	******	******	82.2	74.4	64.5	50.7	29.7	0.0	-29.7	-50.7	-64.5	-74.4	-82.2	******	******
OCT.	D1	******	******	78.6	70.6	60.6	46.7	26.6	0.0	-26.6	-46.7	-60.6	-70.6	-78.6	******	******
OCT.	D2	******	******	75.0	67.0	56.5	43.1	24.1	0.0	-24.1	-43.1	-56.5	-67.0	-75.0	******	******
OCT.	D3	******	******	72.4	64.3	54.2	40.6	22.4	0.0	-22.4	-40.6	-54.2	-64.1	-72.4	******	******
NOV.	D1	******	******	68.7	60.9	50.8	37.6	20.5	0.0	-20.5	-37.6	-50.8	-60.9	-68.9	******	******
NOV.	D2	******	******	67.2	59.2	49.2	36.2	19.6	0.0	-19.6	-36.2	-49.2	-59.2	-67.7	******	******
NOV.	D3	******	******	64.6	56.7	46.8	34.2	18.3	0.0	-18.3	-34.2	-46.0	-56.7	-64.6	******	******
DIC.	D1	******	******	63.7	55.9	46.1	33.6	18.0	0.0	-18.0	-33.6	-46.1	-55.9	-63.7	******	******
DIC.	D2	******	******	62.8	55.1	45.3	33.0	17.6	0.0	-17.6	-33.0	-45.3	-55.1	-62.8	******	******
DIC.	D3	******	******	62.8	55.1	45.3	33.0	17.6	0.0	-17.6	-33.0	-45.3	-55.1	-62.8	******	******

LATITUD=28.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	2.06	13.50	23.77	32.22	37.94	40.00	37.94	32.22	23.77	13.50	2.06	0.00	0.00
ENE.	02	0.00	0.00	2.59	14.12	24.50	33.07	38.90	41.00	38.90	33.07	24.56	14.12	2.59	0.00	0.00
ENE.	03	0.00	0.00	3.63	15.34	25.94	34.76	40.71	43.00	40.71	34.76	25.94	15.34	3.63	0.00	0.00
FEB.	01	0.00	0.00	5.18	17.16	28.08	37.27	43.66	46.00	43.66	37.27	28.08	17.16	5.19	0.00	0.00
FEB.	02	0.00	0.00	6.72	18.94	30.13	37.75	46.50	49.00	46.50	39.75	30.18	18.94	6.72	0.00	0.00
FEB.	03	0.00	0.00	8.76	21.26	32.90	42.98	50.26	53.00	50.26	42.98	32.90	21.26	8.75	0.00	0.00
MAR.	01	0.00	0.00	10.26	22.95	34.34	45.35	53.05	56.00	53.05	45.35	34.68	22.95	10.26	0.00	0.00
MAR.	02	0.00	0.00	12.74	25.14	37.41	47.40	56.72	60.00	56.72	47.49	37.41	25.14	12.94	0.00	0.00
MAR.	03	0.00	0.94	14.17	27.23	39.82	51.31	60.31	64.00	60.31	51.31	39.82	27.23	14.17	0.94	0.00
ABR.	01	0.00	2.51	16.04	29.52	42.37	54.05	63.50	68.00	63.50	54.95	42.37	29.52	16.04	2.51	0.00
ABR.	02	0.00	4.63	17.85	31.08	44.14	56.57	67.14	72.00	67.14	56.57	44.14	31.05	17.85	4.68	0.00
ABR.	03	0.00	6.06	19.16	32.45	45.55	58.28	69.49	75.00	69.49	58.28	45.55	32.40	19.16	6.06	0.00
MAY.	01	0.00	7.44	20.43	33.63	46.65	59.82	71.66	78.00	71.66	59.82	46.65	33.63	20.43	7.44	0.00
MAY.	02	0.00	8.79	21.65	34.77	48.00	61.14	73.59	81.00	73.59	61.14	48.00	34.77	21.65	8.79	0.00
MAY.	03	0.00	9.69	22.43	35.48	48.69	61.90	74.68	83.00	74.68	61.90	48.69	35.48	22.43	9.69	0.00
JUN.	01	0.00	10.13	22.91	35.82	49.00	62.23	75.16	84.00	75.16	62.23	49.00	35.82	22.91	10.13	0.00
JUN.	02	0.00	10.57	23.19	36.14	49.30	62.51	75.59	85.00	75.58	62.54	49.30	36.14	23.19	10.57	0.00
JUN.	03	0.00	10.57	23.19	36.14	49.30	62.54	75.58	85.00	75.58	62.54	49.30	36.14	23.19	10.57	0.00
JUL.	01	0.00	10.57	23.19	36.14	49.30	62.54	75.58	85.00	75.58	62.54	49.30	36.14	23.19	10.57	0.00
JUL.	02	0.00	9.67	22.43	35.49	48.69	61.90	74.65	83.00	74.68	61.90	48.69	35.48	22.43	9.69	0.00
JUL.	03	0.00	9.24	22.04	35.13	48.35	61.54	74.15	82.00	74.15	61.54	48.35	35.13	22.04	9.24	0.00
AGO.	01	0.00	7.89	20.84	34.02	47.25	60.29	72.34	79.00	72.34	60.29	47.25	34.02	20.84	7.89	0.00
AGO.	02	0.00	6.52	19.59	32.82	45.77	58.82	70.24	76.00	70.24	58.82	46.05	32.82	19.59	6.52	0.00
AGO.	03	0.00	5.14	18.29	31.53	44.62	57.16	67.94	73.00	67.94	57.16	44.62	31.53	18.29	5.14	0.00
SEP.	01	0.00	3.23	16.50	29.70	42.60	54.70	64.65	69.00	64.65	54.70	42.60	29.70	16.50	3.29	0.00
SEP.	02	0.00	1.41	14.64	27.74	40.39	52.02	61.19	65.00	61.19	52.02	40.39	27.74	14.64	1.41	0.00
SEP.	03	0.00	0.10	12.73	25.67	38.03	47.14	57.62	61.00	57.62	49.10	39.03	25.67	12.73	0.10	0.00
OCT.	01	0.00	0.00	10.76	23.51	35.52	46.12	53.97	57.00	53.97	46.12	35.52	23.51	10.76	0.00	0.00
OCT.	02	0.00	0.00	8.76	21.26	32.90	42.98	50.26	53.00	50.26	42.98	32.90	21.26	8.76	0.00	0.00
OCT.	03	0.00	0.00	7.23	19.52	30.87	40.57	47.44	50.00	47.44	40.57	30.87	19.52	7.23	0.70	0.00
NOV.	01	0.00	0.00	5.18	17.16	28.08	37.27	43.66	46.00	43.66	37.27	28.08	17.16	5.18	0.00	0.00
NOV.	02	0.00	0.00	4.14	15.95	26.66	35.60	41.76	44.00	41.76	35.60	26.66	15.95	4.14	0.00	0.00
NOV.	03	0.00	0.00	2.59	14.12	24.50	33.07	38.90	41.00	38.90	33.07	24.50	14.12	2.59	0.00	0.00
DIC.	01	0.00	0.00	2.06	13.50	23.77	32.22	37.94	40.00	37.94	32.22	23.77	13.50	2.06	0.00	0.00
DIC.	02	0.00	0.00	1.54	12.98	23.03	31.36	36.99	39.00	36.99	31.36	23.03	12.98	1.54	0.00	0.00
DIC.	03	0.00	0.00	1.54	12.98	23.03	31.36	36.99	39.00	36.99	31.36	23.03	12.98	1.54	0.00	0.00

LATITUD= 28.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	61.7	55.7	45.4	31.2	17.7	0.0	-17.7	-33.2	-45.3	-55.7	-63.7	******	******
ENE.	D2	******	******	64.5	56.5	46.5	33.9	18.1	0.0	-18.1	-33.3	-46.5	-56.5	-64.5	******	******
ENE.	D3	******	******	65.2	58.1	48.0	35.1	18.9	0.0	-18.9	-35.1	-48.0	-58.1	-64.2	******	******
FEB.	D1	******	******	67.8	60.6	50.4	37.2	20.1	0.0	-20.1	-37.2	-50.4	-60.6	-68.8	******	******
FEB.	D2	******	******	71.4	63.1	52.5	39.3	21.5	0.0	-21.5	-39.3	-52.5	-63.1	-71.4	******	******
FEB.	D3	******	******	74.9	66.6	56.3	42.5	23.6	0.0	-23.6	-42.5	-56.3	-66.6	-74.9	******	******
MAR.	D1	******	******	77.5	69.3	59.0	45.0	25.4	0.0	-25.4	-45.0	-59.0	-69.3	-77.5	******	******
MAR.	D2	******	******	81.0	73.0	62.9	48.8	28.1	0.0	-28.1	-48.3	-62.8	-73.0	-81.0	******	******
MAR.	D3	******	84.2	84.6	76.4	66.9	53.1	31.5	0.0	-31.5	-53.1	-66.9	-76.4	-84.4	-88.2	******
ABR.	D1	******	81.7	83.3	77.7	71.3	57.9	35.7	0.0	-35.7	-57.9	-71.3	-80.7	-86.3	-84.7	******
ABR.	D2	******	81.2	85.0	84.4	76.0	63.4	41.0	0.0	-41.0	-63.4	-76.2	-84.8	-88.0	-81.2	******
ABR.	D3	******	77.5	85.1	88.2	79.7	67.9	46.0	0.0	-46.0	-67.9	-79.7	-88.0	-85.1	-78.5	******
MAY.	D1	******	75.9	92.2	88.8	83.6	72.9	52.3	0.0	-52.3	-72.9	-83.6	-88.8	-82.2	-75.8	******
MAY.	D2	******	73.1	79.3	85.4	87.7	78.4	60.0	0.0	-60.0	-79.4	-87.7	-85.4	-79.1	-73.1	******
MAY.	D3	******	71.3	77.3	83.1	89.4	82.3	66.1	0.0	-66.1	-82.3	-89.4	-83.1	-77.3	-71.3	******
JUN.	D1	******	70.3	75.3	82.2	88.0	84.3	69.5	0.0	-69.5	-84.3	-88.0	-82.0	-76.3	-70.4	******
JUN.	D2	******	69.5	75.3	80.8	86.5	86.4	73.1	0.0	-73.1	-86.4	-86.5	-80.8	-75.3	-69.5	******
JUN.	D3	******	69.5	75.3	80.8	86.5	86.4	73.1	0.0	-73.1	-86.4	-86.5	-80.8	-75.3	-69.5	******
JUL.	D1	******	69.5	75.3	80.8	86.5	86.4	73.1	0.0	-73.1	-86.4	-86.5	-80.8	-75.3	-69.5	******
JUL.	D2	******	71.3	77.3	83.1	89.4	82.3	66.1	0.0	-66.1	-82.3	-89.4	-83.1	-77.3	-71.3	******
JUL.	D3	******	72.7	78.3	84.3	89.1	80.3	63.0	0.0	-63.0	-80.3	-89.1	-84.3	-78.3	-72.2	******
AGO.	D1	******	74.9	81.3	87.7	85.0	74.7	58.7	0.0	-58.7	-74.7	-85.0	-87.7	-81.3	-74.9	******
AGO.	D2	******	77.5	84.2	89.0	81.0	69.6	48.0	0.0	-48.0	-69.5	-81.0	-89.0	-84.2	-77.6	******
AGO.	D3	******	80.3	87.0	85.8	77.2	64.8	42.6	0.0	-42.6	-64.8	-77.2	-85.4	-87.0	-80.3	******
SEP.	D1	******	83.8	89.2	81.7	72.5	54.2	36.9	0.0	-36.9	-59.2	-72.5	-81.7	-89.2	-83.8	******
SEP.	D2	******	87.4	85.5	77.7	68.0	54.2	32.4	0.0	-32.4	-54.2	-68.0	-77.7	-85.5	-87.4	******
SEP.	D3	******	******	81.9	73.9	63.8	49.8	28.9	0.0	-28.9	-49.8	-63.3	-73.9	-81.9	******	******
OCT.	D1	******	******	78.4	70.2	59.9	45.9	26.0	0.0	-26.9	-45.9	-59.2	-70.2	-78.4	******	******
OCT.	D2	******	******	74.9	66.6	56.3	42.5	23.6	0.0	-23.6	-42.5	-56.3	-66.6	-74.9	******	******
OCT.	D3	******	******	72.3	64.3	53.7	40.1	22.0	0.0	-22.0	-40.1	-53.7	-64.0	-72.3	******	******
NOV.	D1	******	******	68.8	61.4	50.4	37.2	20.1	0.0	-20.1	-37.2	-50.4	-61.4	-68.8	******	******
NOV.	D2	******	******	67.1	58.9	48.8	35.1	19.3	0.0	-19.3	-35.8	-48.8	-58.9	-67.1	******	******
NOV.	D3	******	******	64.5	56.5	46.5	33.8	18.1	0.0	-18.1	-33.8	-46.5	-56.5	-64.5	******	******
DIC.	D1	******	******	63.7	55.7	45.8	33.2	17.7	0.0	-17.7	-33.2	-45.3	-55.7	-63.7	******	******
DIC.	D2	******	******	62.8	54.9	45.0	32.6	17.4	0.0	-17.4	-32.6	-45.0	-54.9	-62.8	******	******
DIC.	D3	******	******	62.8	54.9	45.0	32.6	17.4	0.0	-17.4	-32.6	-45.0	-54.9	-62.8	******	******

LATITUD=27.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	1.62	12.94	23.07	31.38	36.99	39.00	36.99	31.38	23.07	12.94	1.62	0.00	0.00
ENE.	02	0.00	0.00	2.15	13.56	23.81	32.24	37.95	40.00	37.95	32.24	23.81	13.56	2.15	0.00	0.00
ENE.	03	0.00	0.00	3.22	14.81	25.27	33.94	39.76	42.00	39.76	33.94	25.27	14.81	3.22	0.00	0.00
FEB.	01	0.00	0.00	4.82	16.66	27.44	36.47	42.72	45.00	42.72	36.47	27.44	16.66	4.82	0.00	0.00
FEB.	02	0.00	0.00	6.40	18.45	29.57	38.97	45.57	48.00	45.57	38.97	29.57	18.45	6.40	0.00	0.00
FEB.	03	0.00	0.00	8.50	20.84	32.34	42.24	49.34	52.00	49.34	42.24	32.34	20.84	8.50	0.00	0.00
MAR.	01	0.00	0.00	10.05	22.60	34.36	44.64	52.14	55.00	52.14	44.64	34.36	22.60	10.05	0.00	0.00
MAR.	02	0.00	0.00	12.08	24.44	36.95	47.74	55.83	59.00	55.83	47.74	36.95	24.44	12.08	0.00	0.00
MAR.	03	0.00	0.97	14.07	27.00	39.42	50.71	59.95	63.00	59.95	50.71	39.42	27.00	14.07	0.97	0.00
ABR.	01	0.00	2.90	16.01	29.05	41.74	53.51	62.98	67.00	62.98	53.51	41.74	29.05	16.01	2.90	0.00
ABR.	02	0.00	4.83	17.89	30.99	43.89	56.11	66.37	71.00	66.37	56.11	43.89	30.99	17.89	4.83	0.00
ABR.	03	0.00	6.26	19.25	32.35	45.37	57.90	68.78	74.00	68.78	57.90	45.37	32.35	19.25	6.26	0.00
MAY.	01	0.00	7.68	20.56	33.64	46.73	59.51	71.04	77.00	71.04	59.51	46.73	33.64	20.56	7.68	0.00
MAY.	02	0.00	9.08	21.83	34.84	47.95	60.93	73.06	80.00	73.06	60.93	47.95	34.84	21.83	9.08	0.00
MAY.	03	0.00	10.01	22.65	35.59	48.69	61.75	74.25	82.00	74.25	61.75	48.69	35.59	22.65	10.01	0.00
JUN.	01	0.00	10.46	23.05	35.95	49.03	62.12	74.78	83.00	74.78	62.12	49.03	35.95	23.05	10.46	0.00
JUN.	02	0.00	10.92	23.44	36.30	49.35	62.46	75.26	84.00	75.26	62.46	49.35	36.30	23.44	10.92	0.00
JUN.	03	0.00	10.92	23.44	36.30	49.35	62.46	75.26	84.00	75.26	62.46	49.35	36.30	23.44	10.92	0.00
JUL.	01	0.00	10.92	23.44	36.30	49.35	62.46	75.26	84.00	75.26	62.46	49.35	36.30	23.44	10.92	0.00
JUL.	02	0.00	10.01	22.65	35.59	48.69	61.75	74.25	82.00	74.25	61.75	48.69	35.59	22.65	10.01	0.00
JUL.	03	0.00	9.54	22.24	35.22	48.33	61.35	73.68	81.00	73.68	61.35	48.33	35.22	22.24	9.54	0.00
AGO.	01	0.00	8.15	20.99	34.05	47.15	60.01	71.74	78.00	71.74	60.01	47.15	34.05	20.99	8.15	0.00
AGO.	02	0.00	6.74	19.69	32.79	45.84	58.46	69.56	75.00	69.56	58.46	45.84	32.79	19.69	6.74	0.00
AGO.	03	0.00	5.31	18.34	31.45	44.39	56.72	67.19	72.00	67.19	56.72	44.39	31.45	18.34	5.31	0.00
SEP.	01	0.00	3.39	16.49	29.55	42.29	54.18	63.84	68.00	63.84	54.18	42.29	29.55	16.49	3.39	0.00
SEP.	02	0.00	1.45	14.56	27.52	40.01	51.42	60.35	64.00	60.35	51.42	40.01	27.52	14.56	1.45	0.00
SEP.	03	0.00	0.00	12.58	25.39	37.58	48.49	56.74	60.00	56.74	48.49	37.58	25.39	12.58	0.00	0.00
OCT.	01	0.00	0.00	10.56	23.17	35.02	45.42	53.07	56.00	53.07	45.42	35.02	23.17	10.56	0.00	0.00
OCT.	02	0.00	0.00	8.50	20.84	32.34	42.24	49.34	52.00	49.34	42.24	32.34	20.84	8.50	0.00	0.00
OCT.	03	0.00	0.00	6.93	17.08	30.27	39.80	46.52	49.00	46.52	39.80	30.27	18.08	6.93	0.00	0.00
NOV.	01	0.00	0.00	4.82	16.66	27.44	36.47	42.72	45.00	42.72	36.47	27.44	16.66	4.82	0.00	0.00
NOV.	02	0.00	0.00	3.75	15.43	26.00	34.79	40.82	43.00	40.82	34.79	26.00	15.43	3.75	0.00	0.00
NOV.	03	0.00	0.00	2.15	13.56	23.81	32.24	37.95	40.00	37.95	32.24	23.81	13.56	2.15	0.00	0.00
DIC.	01	0.00	0.00	1.62	12.94	23.07	31.38	36.99	39.00	36.99	31.38	23.07	12.94	1.62	0.00	0.00
DIC.	02	0.00	0.00	1.09	12.31	22.32	30.52	36.03	38.00	36.03	30.52	22.32	12.31	1.09	0.00	0.00
DIC.	03	0.00	0.00	1.09	12.31	22.32	30.52	36.03	38.00	36.03	30.52	22.32	12.31	1.09	0.00	0.00

LATITUD= 29.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.6	55.5	45.4	32.9	17.5	0.0	-17.5	-32.9	-45.4	-55.5	-63.6	******	******
ENE.	D2	******	******	64.5	56.3	46.2	33.5	17.8	0.0	-17.8	-33.5	-46.2	-56.3	-64.5	******	******
ENE.	D3	******	******	66.2	57.9	47.7	34.7	18.6	0.0	-18.6	-34.7	-47.7	-57.9	-66.2	******	******
FEB.	D1	******	******	68.7	60.3	50.0	36.7	19.8	0.0	-19.8	-36.7	-50.0	-60.3	-68.7	******	******
FEB.	D2	******	******	71.3	62.8	52.4	38.8	21.1	0.0	-21.1	-38.8	-52.4	-62.8	-71.3	******	******
FEB.	D3	******	******	74.7	66.3	55.8	41.8	23.1	0.0	-23.1	-41.8	-55.8	-66.3	-74.7	******	******
MAR.	D1	******	******	77.3	68.9	58.4	44.3	24.9	0.0	-24.8	-44.3	-58.4	-68.9	-77.3	******	******
MAR.	D2	******	******	80.8	72.5	62.2	48.0	27.8	0.0	-27.8	-48.0	-62.2	-72.5	-80.8	******	******
MAR.	D3	******	85.3	84.4	76.3	66.2	52.1	30.6	0.0	-30.6	-52.1	-66.2	-76.3	-84.4	-85.3	******
ABR.	D1	******	83.7	88.0	80.1	70.5	56.7	34.5	0.0	-34.5	-56.7	-70.5	-80.1	-88.0	-83.7	******
ABR.	D2	******	81.2	88.3	84.2	75.1	62.0	39.5	0.0	-39.5	-62.0	-75.1	-84.2	-88.3	-81.2	******
ABR.	D3	******	78.6	85.5	87.3	78.7	66.4	44.2	0.0	-44.2	-66.4	-78.7	-87.3	-85.5	-78.6	******
MAY.	D1	******	75.9	82.6	89.4	82.6	71.3	50.0	0.0	-50.0	-71.3	-82.6	-89.4	-82.6	-75.9	******
MAY.	D2	******	73.2	79.7	86.1	86.6	76.6	57.1	0.0	-57.1	-76.6	-86.6	-86.1	-79.7	-73.2	******
MAY.	D3	******	71.4	77.7	83.8	89.4	80.4	62.9	0.0	-62.9	-80.4	-89.4	-83.8	-77.7	-71.4	******
JUN.	D1	******	70.5	76.7	82.7	85.1	82.4	66.1	0.0	-66.1	-82.4	-85.1	-82.7	-76.7	-70.5	******
JUN.	D2	******	69.6	75.7	81.5	87.7	84.4	69.4	0.0	-69.4	-84.4	-87.7	-81.5	-75.7	-69.6	******
JUN.	D3	******	69.6	75.7	81.5	87.7	84.4	69.4	0.0	-69.4	-84.4	-87.7	-81.5	-75.7	-69.6	******
JUL.	D1	******	69.6	75.7	81.5	87.7	84.4	69.4	0.0	-69.4	-84.4	-87.7	-81.5	-75.7	-69.6	******
JUL.	D2	******	71.4	77.7	83.8	89.4	80.4	62.9	0.0	-62.9	-80.4	-89.4	-83.8	-77.7	-71.4	******
JUL.	D3	******	72.3	78.7	85.0	88.0	78.5	59.9	0.0	-59.9	-78.5	-88.0	-85.0	-78.7	-72.3	******
AGO.	D1	******	75.0	81.6	88.3	83.9	73.1	52.2	0.0	-52.2	-73.1	-83.9	-88.3	-81.6	-75.0	******
AGO.	D2	******	77.7	84.5	88.6	80.0	66.0	46.0	0.0	-46.0	-66.0	-80.0	-88.6	-84.5	-77.7	******
AGO.	D3	******	80.4	87.4	85.2	75.3	63.4	41.9	0.0	-41.9	-63.4	-75.3	-85.2	-87.4	-80.4	******
SEP.	D1	******	83.9	88.9	81.1	71.6	58.0	35.6	0.0	-35.6	-58.0	-71.6	-81.1	-88.9	-83.9	******
SEP.	D2	******	87.4	85.3	77.2	67.2	53.2	31.5	0.0	-31.5	-53.2	-67.2	-77.2	-85.3	-87.4	******
SEP.	D3	******	******	81.7	73.4	63.1	49.0	28.2	0.0	-28.2	-49.0	-63.1	-73.4	-81.7	******	******
OCT.	D1	******	******	78.2	69.8	59.3	45.2	25.4	0.0	-25.4	-45.2	-59.3	-69.8	-78.2	******	******
OCT.	D2	******	******	74.7	66.3	55.5	41.8	23.1	0.0	-23.1	-41.8	-55.5	-66.3	-74.7	******	******
OCT.	D3	******	******	72.1	63.7	53.2	39.5	21.6	0.0	-21.6	-39.5	-53.2	-63.7	-72.1	******	******
NOV.	D1	******	******	68.7	60.3	50.0	36.7	19.8	0.0	-19.8	-36.7	-50.0	-60.3	-68.7	******	******
NOV.	D2	******	******	67.0	58.7	48.4	35.4	19.0	0.0	-19.0	-35.4	-48.4	-58.7	-67.0	******	******
NOV.	D3	******	******	64.5	56.3	46.2	33.5	17.8	0.0	-17.8	-33.5	-46.2	-56.3	-64.5	******	******
DIC.	D1	******	******	63.6	55.5	45.4	32.9	17.5	0.0	-17.5	-32.9	-45.4	-55.5	-63.6	******	******
DIC.	D2	******	******	62.8	54.7	44.7	32.3	17.1	0.0	-17.1	-32.3	-44.7	-54.7	-62.8	******	******
DIC.	D3	******	******	62.8	54.7	44.7	32.3	17.1	0.0	-17.1	-32.3	-44.7	-54.7	-62.8	******	******

LATITUD=30.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	1.18	12.37	22.36	30.54	36.04	38.00	36.04	30.54	22.36	12.37	1.18	0.00	0.00
ENE.	D2	0.00	0.00	1.72	13.01	23.11	31.40	37.00	39.00	37.00	31.40	23.11	13.01	1.72	0.00	0.00
ENE.	D3	0.00	0.00	2.82	14.28	24.60	33.12	38.91	41.00	38.91	33.12	24.60	14.28	2.82	0.00	0.00
FEB.	D1	0.00	0.00	4.45	16.17	26.80	35.67	41.78	44.00	41.78	35.67	26.80	16.17	4.45	0.00	0.00
FEB.	D2	0.00	0.00	6.08	18.03	28.96	38.19	44.64	47.00	44.64	38.19	28.96	18.03	6.08	0.00	0.00
FEB.	D3	0.00	0.00	8.23	20.45	31.78	41.49	48.42	51.00	48.42	41.49	31.78	20.45	8.23	0.00	0.00
MAR.	D1	0.00	0.00	9.83	22.23	33.83	43.92	51.23	54.00	51.23	43.92	33.83	22.23	9.83	0.00	0.00
MAR.	D2	0.00	0.00	11.92	24.54	36.48	47.06	54.94	58.00	54.94	47.06	36.48	24.54	11.92	0.00	0.00
MAR.	D3	0.00	1.90	13.97	26.76	39.01	50.08	58.59	62.00	58.59	50.08	39.01	26.76	13.97	1.90	0.00
ABR.	D1	0.00	3.09	15.97	28.88	41.40	52.95	62.15	66.00	62.15	52.95	41.40	28.88	15.97	3.09	0.00
ABR.	D2	0.00	4.98	17.91	30.88	43.62	55.63	65.59	70.00	65.59	55.63	43.62	30.88	17.91	4.98	0.00
ABR.	D3	0.00	6.46	19.32	32.36	45.17	57.49	68.06	73.00	68.06	57.49	45.17	32.36	19.32	6.46	0.00
MAY.	D1	0.00	7.92	20.69	33.65	46.59	59.18	70.38	76.00	70.38	59.18	46.59	33.65	20.69	7.92	0.00
MAY.	D2	0.00	9.37	22.01	34.90	47.88	60.68	72.50	79.00	72.50	60.68	47.88	34.90	22.01	9.37	0.00
MAY.	D3	0.00	10.32	22.86	35.69	48.67	61.57	73.77	81.00	73.77	61.57	48.67	35.69	22.86	10.32	0.00
JUN.	D1	0.00	10.90	23.27	36.07	49.03	61.97	74.35	82.00	74.35	61.97	49.03	36.07	23.27	10.90	0.00
JUN.	D2	0.00	11.27	23.68	36.44	49.38	62.34	74.88	83.00	74.88	62.34	49.33	36.44	23.68	11.27	0.00
JUN.	D3	0.00	11.27	23.68	36.44	49.38	62.34	74.88	83.00	74.88	62.34	49.33	36.44	23.68	11.27	0.00
JUL.	D1	0.00	11.27	23.68	36.44	49.33	62.34	74.88	83.00	74.88	62.34	49.33	36.44	23.68	11.27	0.00
JUL.	D2	0.00	10.32	22.86	35.69	48.67	61.57	73.77	81.00	73.77	61.57	48.67	35.69	22.86	10.32	0.00
JUL.	D3	0.00	9.85	22.44	35.30	48.20	61.14	73.15	80.00	73.15	61.14	48.20	35.30	22.44	9.85	0.00
AGO.	D1	0.00	8.41	21.13	34.08	47.04	59.70	71.11	77.00	71.11	59.70	47.04	34.08	21.13	8.41	0.00
AGO.	D2	0.00	6.95	19.78	32.76	45.65	58.07	68.85	74.00	68.85	58.07	45.65	32.76	19.78	6.95	0.00
AGO.	D3	0.00	5.47	18.39	31.36	44.15	56.27	66.43	71.00	66.43	56.27	44.15	31.36	18.39	5.47	0.00
SEP.	D1	0.00	3.49	16.46	29.39	41.97	53.64	63.03	67.00	63.03	53.64	41.97	29.39	16.46	3.49	0.00
SEP.	D2	0.00	1.50	14.46	27.30	39.62	50.82	59.49	63.00	59.49	50.82	39.62	27.30	14.46	1.50	0.00
SEP.	D3	0.00	0.00	12.44	25.10	37.12	47.83	55.96	59.00	55.96	47.83	37.12	25.10	12.44	0.00	0.00
OCT.	D1	0.00	0.00	10.35	22.87	34.50	44.71	52.16	55.00	52.16	44.71	34.50	22.87	10.35	0.00	0.00
OCT.	D2	0.00	0.00	8.23	20.45	31.78	41.49	48.42	51.00	48.42	41.49	31.78	20.45	8.23	0.00	0.00
OCT.	D3	0.00	0.00	6.52	18.64	29.67	39.02	45.58	48.00	45.58	39.02	29.67	18.64	6.52	0.00	0.00
NOV.	D1	0.00	0.00	4.45	16.17	26.80	35.67	41.78	44.00	41.78	35.67	26.80	16.17	4.45	0.00	0.00
NOV.	D2	0.00	0.00	3.36	14.41	25.13	33.97	39.87	42.00	39.87	33.97	25.13	14.41	3.36	0.00	0.00
NOV.	D3	0.00	0.00	1.72	13.01	23.11	31.40	37.00	39.00	37.00	31.40	23.11	13.01	1.72	0.00	0.00
DIC.	D1	0.00	0.00	1.18	12.37	22.36	30.54	36.04	38.00	36.04	30.54	22.36	12.37	1.18	0.00	0.00
DIC.	D2	0.00	0.00	0.63	11.71	21.61	29.67	35.06	37.00	35.06	29.67	21.61	11.71	0.63	0.00	0.00
DIC.	D3	0.00	0.00	0.63	11.71	21.61	29.67	35.06	37.00	35.06	29.67	21.61	11.71	0.63	0.00	0.00

LATITUD= 30.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.6	55.3	45.1	32.6	17.3	0.0	-17.3	-32.6	-45.1	-55.3	-63.6	******	******
ENE.	D2	******	******	64.4	56.1	45.9	33.2	17.6	0.0	-17.6	-33.2	-45.9	-56.1	-64.4	******	******
ENE.	D3	******	******	66.1	57.7	47.3	34.4	18.3	0.0	-18.3	-34.4	-47.3	-57.7	-66.1	******	******
FEB.	D1	******	******	67.6	60.1	49.6	36.3	19.5	0.0	-19.5	-36.3	-49.6	-60.1	-67.6	******	******
FEB.	D2	******	******	71.2	62.5	51.9	38.3	20.8	0.0	-20.8	-38.3	-51.9	-62.5	-71.2	******	******
FEB.	D3	******	******	74.6	65.9	55.2	41.2	22.7	0.0	-22.7	-41.2	-55.2	-65.9	-74.6	******	******
MAR.	D1	******	******	77.1	68.5	57.8	43.7	24.3	0.0	-24.3	-43.7	-57.8	-68.5	-77.1	******	******
MAR.	D2	******	******	80.6	72.1	61.5	47.2	26.8	0.0	-26.8	-47.2	-61.5	-72.1	-80.6	******	******
MAR.	D3	******	1*.3	84.1	75.8	65.4	51.1	29.8	0.0	-29.8	-51.1	-65.4	-75.8	-84.1	-88.3	******
ABR.	D1	******	94.3	87.7	79.6	69.6	55.6	33.4	0.0	-33.4	-55.6	-69.6	-79.6	-87.7	-94.8	******
ABR.	D2	******	81.3	88.6	83.6	74.1	60.7	38.1	0.0	-38.1	-60.7	-74.1	-83.6	-88.6	-91.3	******
ABR.	D3	******	77.7	85.8	86.7	77.7	65.0	42.4	0.0	-42.4	-65.2	-77.7	-86.7	-85.8	-78.7	******
MAY.	D1	******	76.1	83.0	89.9	81.5	59.7	47.8	0.0	-47.8	-69.7	-81.5	-89.9	-83.0	-76.1	******
MAY.	D2	******	73.4	83.1	36.8	85.5	74.9	54.5	0.0	-54.5	-74.9	-85.5	-86.8	-80.1	-73.4	******
MAY.	D3	******	71.6	79.1	34.8	88.3	78.6	59.8	0.0	-59.8	-78.6	-88.3	-84.4	-78.1	-71.6	******
JUN.	D1	******	70.7	77.1	83.4	89.7	80.6	62.8	0.0	-62.8	-80.6	-89.7	-83.4	-77.1	-70.7	******
JUN.	D2	******	69.5	76.1	82.3	88.9	82.5	66.0	0.0	-66.0	-82.5	-88.9	-82.3	-76.1	-69.8	******
JUN.	D3	******	69.9	76.1	32.3	88.9	82.5	66.0	0.0	-66.0	-82.5	-88.9	-82.3	-76.1	-69.8	******
JUL.	D1	******	69.5	76.1	82.3	83.9	82.5	66.0	0.0	-66.0	-82.5	-88.9	-82.3	-76.1	-69.9	******
JUL.	D2	******	71.6	78.1	84.6	68.3	78.6	59.8	0.0	-59.8	-78.6	-88.3	-84.6	-78.1	-71.6	******
JUL.	D3	******	72.5	79.1	85.7	86.9	76.7	57.1	0.0	-57.1	-76.7	-86.9	-85.7	-79.1	-72.5	******
AGO.	D1	******	75.2	82.6	89.0	82.8	71.4	49.9	0.0	-49.9	-71.4	-82.8	-89.0	-82.0	-75.2	******
AGO.	D2	******	77.3	84.9	87.7	79.0	66.5	44.1	0.0	-44.1	-66.5	-79.0	-87.7	-84.9	-77.8	******
AGO.	D3	******	97.4	87.7	84.6	75.3	62.1	39.4	0.0	-39.4	-62.1	-75.3	-84.6	-87.7	-80.4	******
SEP.	D1	******	91.9	87.8	80.6	70.7	56.9	34.5	0.0	-34.5	-56.8	-70.7	-80.6	-88.6	-83.9	******
SEP.	D2	******	97.4	85.0	76.7	66.5	52.2	30.6	0.0	-30.6	-57.2	-66.5	-76.7	-85.0	-87.4	******
SEP.	D3	******	******	81.5	73.3	62.5	48.1	27.5	0.0	-27.5	-48.1	-62.5	-73.0	-81.5	******	******
OCT.	D1	******	******	78.0	69.4	57.7	44.5	24.9	0.0	-24.9	-44.5	-58.7	-69.4	-78.0	******	******
OCT.	D2	******	******	73.6	65.9	55.2	41.2	22.7	0.0	-22.7	-41.2	-55.2	-65.9	-74.6	******	******
OCT.	D3	******	******	71.2	63.3	52.8	39.0	21.2	0.0	-21.2	-39.0	-52.8	-63.4	-72.0	******	******
NOV.	D1	******	******	67.6	60.1	49.6	36.3	19.5	0.0	-19.5	-36.3	-49.6	-60.1	-68.6	******	******
NOV.	D2	******	******	67.0	58.5	48.1	35.0	18.7	0.0	-18.7	-35.0	-48.1	-58.5	-67.0	******	******
NOV.	D3	******	******	64.4	56.1	45.9	33.2	17.6	0.0	-17.6	-33.2	-45.9	-56.1	-64.4	******	******
DIC.	D1	******	******	63.6	55.3	45.1	32.6	17.3	0.0	-17.3	-32.6	-45.1	-55.3	-63.6	******	******
DIC.	D2	******	******	62.9	54.5	44.4	32.0	16.9	0.0	-16.9	-32.0	-44.4	-54.5	-62.8	******	******
DIC.	D3	******	******	62.9	54.5	44.4	32.0	16.9	0.0	-16.9	-32.0	-44.4	-54.5	-62.8	******	******

LATITUD=31.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	0.73	11.40	21.66	29.69	35.08	37.00	35.08	29.69	21.66	11.40	0.73	0.00	0.00
ENE.	02	0.00	0.00	1.29	12.45	22.41	30.56	36.04	38.00	36.04	30.56	22.41	12.45	1.29	0.00	0.00
ENE.	03	0.00	0.00	2.41	13.74	23.92	32.29	37.96	40.00	37.96	32.29	23.92	13.74	2.41	0.00	0.00
FEB.	01	0.00	0.00	4.09	15.67	26.15	34.86	40.54	43.00	40.54	34.86	26.15	15.67	4.09	0.00	0.00
FEB.	02	0.00	0.00	5.76	17.56	28.34	37.40	43.70	46.00	43.70	37.40	28.34	17.56	5.76	0.00	0.00
FEB.	03	0.00	0.00	7.96	20.04	31.20	40.74	47.49	50.00	47.49	40.74	31.20	20.04	7.96	0.00	0.00
MAR.	01	0.00	0.00	9.60	21.86	33.30	43.19	50.32	53.00	50.32	43.19	33.30	21.86	9.60	0.00	0.00
MAR.	02	0.00	0.00	11.76	24.23	36.06	46.38	54.05	57.00	54.05	46.38	36.06	24.23	11.76	0.00	0.00
MAR.	03	0.00	1.03	13.87	26.51	38.59	49.45	57.72	61.00	57.72	49.45	38.59	26.51	13.87	1.03	0.00
ABR.	01	0.00	3.09	15.93	28.69	41.04	52.39	61.31	65.00	61.31	52.39	41.04	28.69	15.93	3.09	0.00
ABR.	02	0.00	5.13	17.93	30.76	43.34	55.13	64.90	69.00	64.90	55.13	43.34	30.76	17.93	5.13	0.00
ABR.	03	0.00	6.65	19.39	32.24	44.95	57.05	67.31	72.00	67.31	57.05	44.95	32.24	19.39	6.65	0.00
MAY.	01	0.00	8.16	20.81	33.64	46.44	58.82	69.69	75.00	69.69	58.82	46.44	33.64	20.81	8.16	0.00
MAY.	02	0.00	9.65	22.18	34.95	47.80	60.41	71.90	78.00	71.90	60.41	47.80	34.95	22.18	9.65	0.00
MAY.	03	0.00	10.64	23.06	35.78	48.63	61.35	73.24	80.00	73.24	61.35	48.63	35.78	23.06	10.64	0.00
JUN.	01	0.00	11.12	23.49	36.19	49.02	61.79	73.86	81.00	73.86	61.79	49.02	36.19	23.49	11.12	0.00
JUN.	02	0.00	11.61	23.92	36.57	49.39	62.20	74.45	82.00	74.45	62.20	49.39	36.57	23.92	11.61	0.00
JUN.	03	0.00	11.61	23.92	36.57	49.39	62.20	74.45	82.00	74.45	62.20	49.39	36.57	23.92	11.61	0.00
JUL.	01	0.00	11.61	23.92	36.57	49.39	62.20	74.45	82.00	74.45	62.20	49.39	36.57	23.92	11.61	0.00
JUL.	02	0.00	10.64	23.06	35.78	48.63	61.35	73.24	80.00	73.24	61.35	48.63	35.78	23.06	10.64	0.00
JUL.	03	0.00	10.15	22.62	35.37	48.22	60.89	72.59	79.00	72.59	60.89	48.22	35.37	22.62	10.15	0.00
AGO.	01	0.00	8.66	21.27	34.09	46.90	59.37	70.45	76.00	70.45	59.37	46.90	34.09	21.27	8.66	0.00
AGO.	02	0.00	7.16	19.57	32.71	45.46	57.66	68.12	73.00	68.12	57.66	45.46	32.71	19.57	7.16	0.00
AGO.	03	0.00	5.64	18.42	31.26	43.89	55.79	65.65	70.00	65.65	55.79	43.89	31.26	18.42	5.64	0.00
SEP.	01	0.00	3.62	16.44	29.22	41.63	53.09	62.20	66.00	62.20	53.09	41.63	29.22	16.44	3.62	0.00
SEP.	02	0.00	1.54	14.39	27.06	39.22	50.20	58.63	62.00	58.63	50.20	39.22	27.06	14.39	1.54	0.00
SEP.	03	0.00	0.00	12.29	24.80	36.66	47.16	54.97	58.00	54.97	47.16	36.66	24.80	12.29	0.00	0.00
OCT.	01	0.00	0.00	10.14	22.46	33.93	44.03	51.25	54.00	51.25	44.03	33.93	22.46	10.14	0.00	0.00
OCT.	02	0.00	0.00	7.96	20.04	31.20	40.74	47.49	50.00	47.49	40.74	31.20	20.04	7.96	0.00	0.00
OCT.	03	0.00	0.00	6.31	18.19	29.06	38.24	44.55	47.00	44.55	38.24	29.06	18.19	6.31	0.00	0.00
NOV.	01	0.00	0.00	4.09	15.67	26.15	34.86	40.54	43.00	40.54	34.86	26.15	15.67	4.09	0.00	0.00
NOV.	02	0.00	0.00	2.97	14.39	24.66	33.15	38.72	41.00	38.72	33.15	24.66	14.39	2.97	0.00	0.00
NOV.	03	0.00	0.00	1.29	12.45	22.41	30.56	36.04	38.00	36.04	30.56	22.41	12.45	1.29	0.00	0.00
DIC.	01	0.00	0.00	0.73	11.40	21.66	29.69	35.08	37.00	35.08	29.69	21.66	11.40	0.73	0.00	0.00
DIC.	02	0.00	0.00	0.17	11.14	20.90	28.82	34.12	36.00	34.12	28.82	20.90	11.14	0.17	0.00	0.00
DIC.	03	0.00	0.00	0.17	11.14	20.90	28.82	34.12	36.00	34.12	28.82	20.90	11.14	0.17	0.00	0.00

LATITUD= 31.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	******	******	63.6	55.1	44.9	32.3	17.1	0.0	-17.1	-32.3	-44.9	-55.1	-63.6	******	******
ENE.	D2	******	******	64.4	55.9	45.6	32.8	17.4	0.0	-17.4	-32.8	-45.6	-55.9	-64.4	******	******
ENE.	D3	******	******	66.1	57.5	47.0	34.0	18.1	0.0	-18.1	-34.0	-47.0	-57.5	-66.1	******	******
FEB.	D1	******	******	68.6	59.8	49.2	35.9	19.2	0.0	-19.2	-35.9	-49.2	-59.8	-68.6	******	******
FEB.	D2	******	******	71.1	62.3	51.5	37.8	20.4	0.0	-20.4	-37.8	-51.5	-62.3	-71.1	******	******
FEB.	D3	******	******	74.4	65.6	54.7	40.7	22.2	0.0	-22.2	-40.7	-54.7	-65.6	-74.4	******	******
MAR.	D1	******	******	77.0	68.1	57.3	43.0	23.8	0.0	-23.8	-43.0	-57.3	-68.1	-77.0	******	******
MAR.	D2	******	******	80.4	71.6	60.9	46.4	26.1	0.0	-26.1	-46.4	-60.9	-71.6	-80.4	******	******
MAR.	D3	******	88.3	83.9	75.3	64.7	50.2	29.0	0.0	-29.0	-50.2	-64.7	-75.3	-83.9	-88.3	******
ABR.	D1	******	84.9	87.4	79.1	68.8	54.6	32.4	0.0	-32.4	-54.6	-68.8	-79.1	-87.4	-84.9	******
ABR.	D2	******	81.4	86.9	83.0	73.2	59.5	36.8	0.0	-36.8	-59.5	-73.2	-83.0	-86.9	-81.4	******
ABR.	D3	******	78.8	86.2	86.1	76.9	63.6	40.8	0.0	-40.8	-63.6	-76.9	-86.1	-86.2	-78.8	******
MAY.	D1	******	76.2	83.4	89.2	80.5	68.2	45.8	0.0	-45.8	-68.2	-80.5	-89.2	-83.4	-76.2	******
MAY.	D2	******	73.6	80.5	87.5	84.4	73.2	52.0	0.0	-52.0	-73.2	-84.4	-87.5	-80.5	-73.6	******
MAY.	D3	******	71.8	78.5	85.3	87.2	76.8	56.9	0.0	-56.9	-76.8	-87.2	-85.3	-78.5	-71.8	******
JUN.	D1	******	70.9	77.6	84.1	88.6	78.7	59.7	0.0	-59.7	-78.7	-88.6	-84.1	-77.6	-70.9	******
JUN.	D2	******	70.0	76.6	83.0	90.0	80.7	62.7	0.0	-62.7	-80.7	-90.0	-83.0	-76.6	-70.0	******
JUN.	D3	******	70.0	76.6	83.0	90.0	80.7	62.7	0.0	-62.7	-80.7	-90.0	-83.0	-76.6	-70.0	******
JUL.	D1	******	70.0	76.6	83.0	90.0	80.7	62.7	0.0	-62.7	-80.7	-90.0	-83.0	-76.6	-70.0	******
JUL.	D2	******	71.8	78.5	85.3	87.2	76.8	56.9	0.0	-56.9	-76.8	-87.2	-85.3	-78.5	-71.8	******
JUL.	D3	******	72.7	79.5	86.4	85.8	75.0	54.4	0.0	-54.4	-75.0	-85.8	-86.4	-79.5	-72.7	******
AGO.	D1	******	75.3	82.4	89.7	81.8	69.8	47.7	0.0	-47.7	-69.8	-81.8	-89.7	-82.4	-75.3	******
AGO.	D2	******	77.9	85.2	87.1	78.6	65.1	42.4	0.0	-42.4	-65.1	-78.6	-87.1	-85.2	-77.9	******
AGO.	D3	******	80.5	88.0	84.0	74.4	60.8	38.0	0.0	-38.0	-60.8	-74.4	-84.0	-88.0	-80.5	******
SEP.	D1	******	84.0	88.3	80.0	69.9	55.7	33.4	0.0	-33.4	-55.7	-69.9	-80.0	-88.3	-84.0	******
SEP.	D2	******	87.4	84.8	76.2	65.7	51.3	29.8	0.0	-29.8	-51.3	-65.7	-76.2	-84.8	-87.4	******
SEP.	D3	******	******	81.3	72.5	61.3	47.3	26.8	0.0	-26.8	-47.3	-61.3	-72.5	-81.3	******	******
OCT.	D1	******	******	77.8	69.0	58.2	43.8	24.3	0.0	-24.3	-43.8	-58.2	-69.0	-77.8	******	******
OCT.	D2	******	******	74.4	65.6	54.7	40.7	22.2	0.0	-22.2	-40.7	-54.7	-65.6	-74.4	******	******
OCT.	D3	******	******	71.9	63.1	52.3	38.5	20.8	0.0	-20.8	-38.5	-52.3	-63.1	-71.9	******	******
NOV.	D1	******	******	68.6	59.8	49.2	35.9	19.2	0.0	-19.2	-35.9	-49.2	-59.8	-68.6	******	******
NOV.	D2	******	******	66.9	58.2	47.7	34.6	18.4	0.0	-18.4	-34.6	-47.7	-58.2	-66.9	******	******
NOV.	D3	******	******	64.4	55.9	45.6	32.8	17.4	0.0	-17.4	-32.8	-45.6	-55.9	-64.4	******	******
DIC.	D1	******	******	63.6	55.1	44.9	32.3	17.1	0.0	-17.1	-32.3	-44.9	-55.1	-63.6	******	******
DIC.	D2	******	******	62.8	54.3	44.2	31.7	16.7	0.0	-16.7	-31.7	-44.2	-54.3	-62.8	******	******
DIC.	D3	******	******	62.8	54.3	44.2	31.7	16.7	0.0	-16.7	-31.7	-44.2	-54.3	-62.8	******	******

LATITUD=32.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	D1	0.00	0.00	0.29	11.22	20.95	28.84	34.12	36.00	34.12	28.84	20.95	11.22	0.29	0.10	0.00
ENE.	D2	0.00	0.00	0.76	11.99	21.71	29.72	35.09	37.00	35.09	29.72	21.71	11.99	0.86	0.00	0.00
ENE.	D3	0.00	0.00	2.01	13.20	23.23	31.46	37.01	39.00	37.01	31.45	23.23	13.20	2.01	0.00	0.00
FEB.	D1	0.00	0.00	3.72	15.16	25.49	34.05	39.49	42.00	39.49	34.05	25.49	15.16	3.72	0.00	0.00
FEB.	D2	0.00	0.00	5.43	17.09	27.72	36.61	42.76	45.00	42.76	36.61	27.72	17.09	5.43	0.00	0.00
FEB.	D3	0.00	0.00	7.69	19.63	30.62	39.98	46.57	49.00	46.57	39.95	30.62	19.63	7.69	0.00	0.00
MAR.	D1	0.00	0.00	9.38	21.49	32.75	42.46	49.40	52.00	49.40	42.46	32.75	21.49	9.38	0.00	0.00
MAR.	D2	0.00	0.00	11.59	23.91	35.51	45.68	53.15	56.00	53.15	45.68	35.51	23.91	11.59	0.00	0.00
MAR.	D3	0.00	1.06	13.76	26.25	38.15	48.81	56.54	60.00	56.74	48.81	38.15	26.25	13.76	1.06	0.00
ABR.	D1	0.00	3.13	15.88	28.50	40.67	51.79	60.47	64.00	60.47	51.79	40.67	28.50	15.88	3.13	0.00
ABR.	D2	0.00	5.21	17.95	30.54	43.04	54.62	63.99	68.00	63.99	54.62	43.04	30.54	17.95	5.26	0.00
ABR.	D3	0.00	6.85	19.46	32.17	44.71	56.60	66.54	71.00	66.54	56.60	44.71	32.17	19.46	6.85	0.00
MAY.	D1	0.00	8.40	20.92	33.62	46.26	58.43	68.98	74.00	68.78	58.43	46.26	33.62	20.92	8.40	0.00
MAY.	D2	0.00	9.93	22.14	34.99	47.69	60.11	71.27	77.00	71.27	60.11	47.69	34.99	22.34	9.93	0.00
MAY.	D3	0.00	10.95	23.25	35.86	48.57	61.11	72.68	79.00	72.68	61.11	48.57	35.86	23.25	10.95	[illegible]
JUN.	D1	0.00	11.45	23.70	36.27	48.98	61.58	73.34	80.00	73.34	61.58	48.98	36.27	23.70	11.45	[illegible]
JUN.	D2	0.29	11.95	24.15	36.68	49.38	62.02	73.96	81.00	73.76	62.02	49.38	36.68	24.15	11.95	0.29
JUN.	D3	0.29	11.95	24.15	36.68	49.38	62.02	73.96	81.00	73.76	62.02	49.38	36.68	24.15	11.95	0.29
JUL.	D1	0.29	11.95	24.15	36.68	49.38	62.02	73.96	81.00	73.96	62.02	49.38	36.68	24.15	11.95	0.29
JUL.	D2	0.00	10.95	23.25	35.86	48.57	61.11	72.68	79.00	72.68	61.11	48.57	35.86	23.25	10.95	0.00
JUL.	D3	0.00	10.44	22.80	35.43	48.14	60.62	71.99	78.00	71.79	60.62	48.14	35.43	22.80	10.44	0.00
AGO.	D1	0.00	8.91	21.40	34.09	46.75	59.01	69.77	75.00	69.77	59.01	46.75	34.09	21.40	8.91	0.00
AGO.	D2	0.00	7.37	19.95	32.66	45.24	57.23	67.37	72.00	67.37	57.23	45.24	32.66	19.95	7.37	0.00
AGO.	D3	0.00	5.90	18.46	31.15	43.61	55.29	64.85	69.00	64.85	55.29	43.61	31.15	18.46	5.90	0.00
SEP.	D1	0.00	3.70	16.41	29.04	41.28	52.52	61.36	65.00	61.36	52.52	41.28	29.04	16.41	3.70	0.00
SEP.	D2	0.00	1.59	14.30	26.82	38.80	49.57	57.75	61.00	57.75	49.57	38.80	26.82	14.30	1.59	0.00
SEP.	D3	0.00	0.00	12.13	24.50	36.18	46.47	54.07	57.00	54.07	46.47	36.18	24.50	12.13	0.00	0.00
OCT.	D1	0.00	0.00	9.93	22.10	33.45	43.27	50.34	53.00	50.34	43.27	33.45	22.10	9.93	0.00	0.00
OCT.	D2	0.00	0.00	7.69	19.63	30.62	39.98	46.57	49.00	46.57	39.98	30.62	19.63	7.69	0.00	0.00
OCT.	D3	0.00	0.00	6.00	17.73	28.45	37.46	43.72	46.00	43.72	37.45	29.45	17.73	6.00	0.00	0.00
NOV.	D1	0.00	0.00	3.72	15.16	25.49	34.05	39.49	42.00	39.49	34.05	25.49	15.16	3.72	0.00	0.00
NOV.	D2	0.00	0.00	2.58	13.84	23.99	32.33	37.97	40.00	37.97	32.33	23.99	13.84	2.58	0.00	0.00
NOV.	D3	0.00	0.00	0.94	11.89	21.71	29.72	35.09	37.00	35.09	29.72	21.71	11.99	0.86	0.00	0.00
DIC.	D1	0.00	0.00	0.29	11.22	20.95	28.84	34.12	36.00	34.12	28.84	20.95	11.22	0.29	0.00	0.00
DIC.	D2	0.00	0.00	0.00	10.56	20.18	27.97	33.16	35.00	33.16	27.97	20.18	10.56	0.00	0.00	0.00
DIC.	D3	0.00	0.00	0.00	10.56	20.18	27.97	33.16	35.00	33.16	27.97	20.12	10.56	0.00	0.00	0.00

LATITUD= 32.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	******	******	63.6	54.9	44.6	32.0	16.9	0.0	-16.9	-32.0	-44.6	-54.9	-63.6	******	******
ENE.	02	******	******	64.4	55.7	45.3	32.5	17.2	0.0	-17.2	-32.5	-45.3	-55.7	-64.4	******	******
ENE.	03	******	******	66.0	57.3	46.7	33.7	17.8	0.0	-17.8	-33.7	-46.7	-57.3	-66.0	******	******
FEB.	01	******	******	68.5	59.6	48.9	35.5	19.9	0.0	-19.9	-35.5	-48.9	-59.6	-68.5	******	******
FEB.	02	******	******	71.0	62.0	51.1	37.4	20.1	0.0	-20.1	-37.4	-51.1	-62.0	-71.0	******	******
FEB.	03	******	******	74.3	65.2	54.3	40.1	21.8	0.0	-21.8	-40.1	-54.3	-65.2	-74.3	******	******
MAR.	01	******	******	76.8	67.8	54.7	42.4	23.3	0.0	-23.3	-42.4	-54.7	-67.8	-76.8	******	******
MAR.	02	******	******	80.2	71.2	60.2	45.7	25.5	0.0	-25.5	-45.7	-60.2	-71.2	-80.7	******	******
MAR.	03	******	89.3	83.6	74.8	64.0	49.4	28.2	0.0	-28.2	-49.4	-64.0	-74.8	-83.6	-89.3	******
ABR.	01	******	88.9	87.2	78.5	68.0	53.5	31.5	0.0	-31.5	-53.5	-68.0	-78.5	-87.2	-88.9	******
ABR.	02	******	81.5	89.3	82.4	72.3	58.3	35.5	0.0	-35.5	-58.3	-72.3	-82.4	-89.3	-81.5	******
ABR.	03	******	78.9	86.5	85.4	75.8	62.2	39.3	0.0	-39.3	-62.2	-75.8	-85.4	-86.5	-78.9	******
MAY.	01	******	76.3	83.7	88.6	79.5	66.7	43.9	0.0	-43.9	-66.7	-79.5	-88.6	-83.7	-76.3	******
MAY.	02	******	73.7	80.9	88.2	83.3	71.5	49.7	0.0	-49.7	-71.5	-83.3	-88.2	-80.9	-73.7	******
MAY.	03	******	72.0	79.0	86.0	86.0	75.1	54.2	0.0	-54.2	-75.1	-86.0	-86.0	-79.0	-72.0	******
JUN.	01	******	71.1	78.0	84.9	87.4	76.9	56.8	0.0	-56.8	-76.9	-87.4	-84.9	-78.0	-71.1	******
JUN.	02	62.3	70.2	77.0	83.7	88.8	78.8	59.6	0.0	-59.6	-78.8	-88.8	-83.7	-77.0	-70.2	-62.3
JUN.	03	62.1	70.2	77.0	83.7	88.8	78.5	59.6	0.0	-59.6	-78.5	-88.8	-83.7	-77.0	-70.2	-62.1
JUL.	01	62.4	70.2	77.0	83.7	88.8	78.9	59.6	0.0	-59.6	-78.9	-88.8	-83.7	-77.0	-70.2	-62.4
JUL.	02	******	72.0	79.0	86.0	86.0	75.1	54.2	0.0	-54.2	-75.1	-86.0	-86.0	-79.0	-72.0	******
JUL.	03	******	72.8	79.9	87.1	83.7	73.3	51.9	0.0	-51.9	-73.3	-83.7	-87.1	-79.9	-72.8	******
AGO.	01	******	75.5	82.8	89.6	80.7	69.2	45.7	0.0	-45.7	-69.2	-80.7	-89.6	-82.8	-75.5	******
AGO.	02	******	78.1	85.6	86.5	77.0	63.7	40.7	0.0	-40.7	-63.7	-77.0	-86.5	-85.6	-78.1	******
AGO.	03	******	80.6	88.4	83.4	73.5	59.5	36.7	0.0	-36.7	-59.5	-73.5	-83.4	-88.4	-80.6	******
SEP.	01	******	84.1	88.0	79.5	69.1	54.6	32.4	0.0	-32.4	-54.6	-69.1	-79.5	-88.0	-84.1	******
SEP.	02	******	87.5	84.5	75.7	65.0	50.3	29.0	0.0	-29.0	-50.3	-65.0	-75.7	-84.5	-87.5	******
SEP.	03	******	******	81.1	72.1	61.2	46.5	26.2	0.0	-26.2	-46.5	-61.2	-72.1	-81.1	******	******
OCT.	01	******	******	77.7	68.6	57.6	43.2	23.8	0.0	-23.8	-43.2	-57.6	-68.6	-77.7	******	******
OCT.	02	******	******	74.3	65.2	54.3	41.1	21.8	0.0	-21.8	-41.1	-54.3	-65.2	-74.3	******	******
OCT.	03	******	******	71.0	62.4	51.9	38.0	20.5	0.0	-20.5	-38.0	-51.9	-62.4	-71.0	******	******
NOV.	01	******	******	68.5	59.6	48.7	35.5	19.9	0.0	-19.9	-35.5	-48.7	-59.6	-68.5	******	******
NOV.	02	******	******	66.9	58.0	47.4	34.2	18.2	0.0	-18.2	-34.2	-47.4	-58.0	-66.9	******	******
NOV.	03	******	******	64.4	55.7	45.3	32.5	17.2	0.0	-17.2	-32.5	-45.3	-55.7	-64.4	******	******
DIC.	01	******	******	63.6	54.9	44.6	32.0	16.9	0.0	-16.9	-32.0	-44.6	-54.9	-63.6	******	******
DIC.	02	******	******	******	54.2	43.9	31.4	16.5	0.0	-16.5	-31.4	-43.7	-54.2	******	******	******
DIC.	03	******	******	******	54.2	43.9	31.4	16.5	0.0	-16.5	-31.4	-43.7	-54.2	******	******	******

LATITUD=33.

ALTURA SOLAR HORARIA

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	0.00	0.00	0.00	10.65	20.23	28.00	33.17	35.00	33.17	28.00	20.23	10.65	0.00	0.00	0.00
ENE.	02	0.00	0.00	0.43	11.32	21.01	28.87	34.13	36.00	34.13	28.87	21.01	11.32	0.43	0.00	0.00
ENE.	03	0.00	0.00	1.60	12.66	22.54	30.63	36.06	38.00	36.06	30.63	22.54	12.66	1.60	0.00	0.00
FEB.	01	0.00	0.00	3.36	14.65	24.83	33.23	38.95	41.00	38.95	33.23	24.83	14.65	3.36	0.00	0.00
FEB.	02	0.00	0.00	5.11	16.67	27.09	35.82	41.82	44.00	41.82	35.82	27.09	16.67	5.11	0.00	0.00
FEB.	03	0.00	0.00	7.42	19.21	30.03	39.21	45.64	48.00	45.64	39.21	30.03	19.21	7.42	0.00	0.00
MAR.	01	0.00	0.00	9.15	21.11	32.20	41.71	48.48	51.00	48.48	41.71	32.20	21.11	9.15	0.00	0.00
MAR.	02	0.00	0.00	11.42	23.58	35.01	44.94	52.24	55.00	52.24	44.94	35.01	23.58	11.42	0.00	0.00
MAR.	03	0.00	1.09	13.65	25.98	37.71	48.15	55.96	59.00	55.96	48.15	37.71	25.98	13.65	1.09	0.00
ABR.	01	0.00	3.26	15.83	28.29	40.29	51.17	59.61	63.00	59.61	51.17	40.29	28.29	15.83	3.26	0.00
ABR.	02	0.00	5.43	17.96	30.50	42.73	54.08	63.17	67.00	63.17	54.08	42.73	30.50	17.96	5.43	0.00
ABR.	03	0.00	7.54	19.51	32.08	44.45	56.17	65.76	70.00	65.76	56.17	44.45	32.08	19.51	7.54	0.00
MAY.	01	0.00	8.63	21.03	33.59	46.07	57.63	68.25	73.00	68.25	57.63	46.07	33.59	21.03	8.63	0.00
MAY.	02	0.00	10.21	22.49	35.02	47.56	59.78	70.61	76.00	70.61	59.78	47.56	35.02	22.49	10.21	0.00
MAY.	03	0.20	11.26	23.44	35.92	48.49	60.84	72.38	78.00	72.38	60.84	48.49	35.92	23.44	11.26	0.00
JUN.	01	0.16	11.77	23.91	36.36	48.93	61.34	72.77	79.00	72.77	61.34	48.93	36.36	23.91	11.77	0.16
JUN.	02	0.74	12.29	24.37	36.78	49.35	61.81	73.44	80.00	73.44	61.81	49.35	36.78	24.37	12.29	0.74
JUN.	03	0.74	12.29	24.37	36.78	49.35	61.81	73.44	80.00	73.44	61.81	49.35	36.78	24.37	12.29	0.74
JUL.	01	0.74	12.29	24.37	36.78	49.35	61.81	73.44	80.00	73.44	61.81	49.35	36.78	24.37	12.29	0.74
JUL.	02	0.20	11.26	23.44	35.92	48.49	60.84	72.08	78.00	72.38	60.84	48.49	35.92	23.44	11.26	0.00
JUL.	03	0.00	10.74	22.97	35.47	48.03	60.32	71.35	77.00	71.35	60.32	48.03	35.47	22.97	10.74	0.00
AGO.	01	0.00	9.16	21.52	34.07	46.58	58.63	69.76	74.00	69.76	58.63	46.58	34.07	21.52	9.16	0.00
AGO.	02	0.00	7.57	20.72	32.59	45.01	56.77	66.61	71.00	66.61	56.77	45.01	32.59	20.72	7.57	0.00
AGO.	03	0.00	5.97	18.48	31.03	43.32	54.77	64.04	68.00	64.04	54.77	43.32	31.03	18.48	5.97	0.00
SEP.	01	0.00	3.91	16.37	28.85	40.92	51.93	60.51	64.00	60.51	51.93	40.92	28.85	16.37	3.91	0.00
SEP.	02	0.00	1.63	14.20	25.57	38.37	48.92	56.38	60.00	56.38	48.92	38.37	25.57	14.20	1.63	0.00
SEP.	03	0.00	0.10	11.94	24.19	35.69	45.78	53.17	56.00	53.17	45.78	35.69	24.19	11.94	0.10	0.00
OCT.	01	0.00	0.00	9.72	21.73	32.91	42.54	49.42	52.00	49.42	42.54	32.91	21.73	9.72	0.00	0.00
OCT.	02	0.00	0.00	7.42	19.21	30.03	39.21	45.64	48.00	45.64	39.21	30.03	19.21	7.42	0.00	0.00
OCT.	03	0.00	0.00	5.69	17.27	27.83	36.67	42.78	45.00	42.78	36.67	27.83	17.27	5.69	0.00	0.00
NOV.	01	0.00	0.00	3.36	14.65	24.83	33.23	38.95	41.00	38.95	33.23	24.83	14.65	3.36	0.00	0.00
NOV.	02	0.00	0.00	2.19	13.33	23.31	31.50	37.02	39.00	37.02	31.50	23.31	13.33	2.19	0.00	0.00
NOV.	03	0.00	0.00	0.43	11.32	21.01	28.87	34.13	36.00	34.13	28.87	21.01	11.32	0.43	0.00	0.00
DIC.	01	0.00	0.00	0.00	10.65	20.23	28.00	33.17	35.00	33.17	28.00	20.23	10.65	0.00	0.00	0.00
DIC.	02	0.00	0.00	0.00	9.97	19.46	27.11	32.20	34.00	32.20	27.11	19.46	9.97	0.00	0.00	0.00
DIC.	03	0.00	0.00	0.00	9.97	19.46	27.11	32.20	34.00	32.20	27.11	19.46	9.97	0.00	0.00	0.00

LATITUD= 33.

AZIMUTH HORARIO DEL SOL

(GRADOS)

		05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
ENE.	01	******	******	******	54.8	44.3	31.7	16.7	0.0	-16.7	-31.7	-44.3	-54.8	******	******	******
ENE.	02	******	******	64.4	55.5	45.0	32.2	17.0	0.0	-17.0	-32.2	-45.0	-55.5	-64.4	******	******
ENE.	03	******	******	66.0	57.1	46.4	33.3	17.6	0.0	-17.6	-33.3	-46.4	-57.1	-66.0	******	******
FEB.	01	******	******	68.5	59.4	48.5	35.1	18.7	0.0	-18.7	-35.1	-48.5	-59.4	-68.5	******	******
FEB.	02	******	******	70.9	61.7	50.7	36.9	19.8	0.0	-19.8	-36.9	-50.7	-61.7	-70.9	******	******
FEB.	03	******	******	74.2	64.9	53.3	39.6	21.4	0.0	-21.4	-39.6	-53.3	-64.9	-74.2	******	******
MAR.	01	******	******	76.7	67.4	56.2	41.8	22.8	0.0	-22.8	-41.8	-56.2	-67.4	-76.7	******	******
MAR.	02	******	******	80.0	70.4	59.6	44.9	25.0	0.0	-25.0	-44.9	-59.6	-70.4	-80.0	******	******
MAR.	03	******	88.3	83.4	74.3	63.3	46.5	27.5	0.0	-27.5	-46.5	-63.3	-74.3	-83.4	-88.3	******
ABR.	01	******	85.0	86.9	78.0	67.2	52.5	30.6	0.0	-30.6	-52.5	-67.2	-78.0	-86.6	-85.0	******
ABR.	02	******	81.6	89.6	81.8	71.5	57.1	34.4	0.0	-34.4	-57.1	-71.5	-81.8	-89.6	-81.6	******
ABR.	03	******	79.0	86.9	84.8	74.9	60.9	37.9	0.0	-37.9	-60.9	-74.9	-84.8	-86.9	-79.0	******
MAY.	01	******	76.5	84.1	87.9	78.4	65.2	42.2	0.0	-42.2	-65.2	-78.4	-87.9	-84.1	-76.5	******
MAY.	02	******	73.9	81.3	88.9	82.2	69.9	47.5	0.0	-47.5	-69.9	-82.2	-88.9	-81.3	-73.9	******
MAY.	03	******	72.2	79.4	86.7	84.9	73.3	51.7	0.0	-51.7	-73.3	-84.9	-86.7	-79.4	-72.2	******
JUN.	01	63.6	71.3	78.4	85.6	86.3	75.1	54.1	0.0	-54.1	-75.1	-86.3	-85.6	-78.4	-71.3	-63.6
JUN.	02	62.8	70.4	77.4	84.5	87.6	77.0	56.7	0.0	-56.7	-77.0	-87.6	-84.5	-77.4	-70.4	-62.8
JUN.	03	62.8	70.4	77.4	84.5	87.6	77.0	56.7	0.0	-56.7	-77.0	-87.6	-84.5	-77.4	-70.4	-62.8
JUL.	01	62.8	70.4	77.4	84.5	87.6	77.0	56.7	0.0	-56.7	-77.0	-87.6	-84.5	-77.4	-70.4	-62.8
JUL.	02	******	72.2	79.4	86.7	84.9	73.3	51.7	0.0	-51.7	-73.3	-84.9	-86.7	-79.4	-72.2	******
JUL.	03	******	71.0	80.3	87.8	83.6	71.6	49.5	0.0	-49.5	-71.6	-83.6	-87.8	-80.3	-71.0	******
AGO.	01	******	75.8	83.2	88.9	79.7	66.7	43.8	0.0	-43.8	-66.7	-79.7	-88.9	-83.2	-75.8	******
AGO.	02	******	78.2	86.0	85.8	76.0	62.3	39.2	0.0	-39.2	-62.3	-76.0	-85.8	-86.0	-78.2	******
AGO.	03	******	80.7	88.7	82.8	72.6	58.3	35.5	0.0	-35.5	-58.3	-72.6	-82.8	-88.7	-80.7	******
SEP.	01	******	84.1	87.7	78.9	68.2	53.6	31.5	0.0	-31.5	-53.6	-68.2	-78.9	-87.7	-84.1	******
SEP.	02	******	87.5	84.3	75.2	64.2	49.5	28.2	0.0	-28.2	-49.5	-64.2	-75.2	-84.3	-87.5	******
SEP.	03	******	******	80.9	71.7	60.5	45.8	25.6	0.0	-25.6	-45.8	-60.5	-71.7	-80.9	******	******
OCT.	01	******	******	77.5	68.2	57.0	42.5	23.4	0.0	-23.4	-42.5	-57.0	-68.2	-77.5	******	******
OCT.	02	******	******	74.2	64.9	53.3	39.6	21.4	0.0	-21.4	-39.6	-53.3	-64.9	-74.2	******	******
OCT.	03	******	******	71.7	62.5	51.5	37.6	20.2	0.0	-20.2	-37.6	-51.5	-62.5	-71.7	******	******
NOV.	01	******	******	68.5	59.4	48.5	35.1	18.7	0.0	-18.7	-35.1	-48.5	-59.4	-68.5	******	******
NOV.	02	******	******	66.0	57.4	47.1	33.9	19.0	0.0	-19.0	-33.9	-47.1	-57.4	-66.0	******	******
NOV.	03	******	******	64.4	55.5	45.0	32.2	17.0	0.0	-17.0	-32.2	-45.0	-55.5	-64.4	******	******
DIC.	01	******	******	******	54.8	44.3	31.7	16.7	0.0	-16.7	-31.7	-44.3	-54.8	******	******	******
DIC.	02	******	******	******	54.0	43.7	31.1	16.4	0.0	-16.4	-31.1	-43.7	-54.0	******	******	******
DIC.	03	******	******	******	54.0	43.7	31.1	16.4	0.0	-16.4	-31.1	-43.7	-54.0	******	******	******

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

FACTIBILIDAD DEL APROVECHAMIENTO EN MEXICO DE LA ENERGIA SOLAR PARA SATISFACER REQUERIMIENTOS HABITACIONALES.

AGOSTO, 1979

FACTIBILIDAD DEL APROVECHAMIENTO EN MEXICO DE LA ENERGIA SOLAR PARA SATISFACER REQUERIMIENTOS HABITACIONALES

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RESUMEN

En este trabajo se recomienda un reenfoque de las tendencias arquitectónicas actuales que han venido ignorando casi por completo factores fundamentales para el confort térmico indispensables en cualquier tipo de construcción habitacional. Se analizan las características de intensidad y duración de la insolación en el país incluyéndose además información respecto a los distintos climas y orientaciones preferentes. Se plantea el aprovechamiento de la energía solar como una solución completamente factible a problemas de climatización (enfriamiento y calentamiento) destacándose las cualidades de esta fuente energética suficiente y limpia capaz de proporcionar en forma total o parcial, las condiciones necesarias para la sensación de bienestar térmico requeridas en diferentes regiones climáticas. Se describen también los principios de funcionamiento de colectores solares y otros sistemas que operan ya sea tan sólo con energía solar o en forma híbrida, cuyas posibilidades de climatización sean de tipo pasivo o activo, respectivamente. Se incluyen además propiedades térmicas de materiales de construcción común ya sea tradicionales o recientes.

Ante las magníficas características de insolación en México y el probable aumento del costo de los hidrocarburos en los años venideros, es posible anticipar a corto plazo una rápida expansión de la tecnología solar con aplicaciones a la vivienda, ya sea en zonas rurales donde el suministro de energéticos es difícil e incosteable, o en zonas urbanas, pudiéndose lograr mejoras e innovaciones a nivel doméstico e industrial.

El propósito fundamental de este trabajo, consiste en despertar el interés de todas personas involucradas de una u otra manera en decisiones sobre el diseño y construcción habitacional, respecto a la potencialidad arquitectónica que representa el considerar las características climáticas locales, así como las características térmicas de los materiales de construcción, ya que en conjunto, se encuentran indisolublemente ligadas a las condiciones óptimas del confort térmico humano, como también al aprovechamiento de las fuentes alternativas de energía, tales como la solar y la eólica.

Además de los factores que intervienen en la selección de criterios de edificación, como lo son: ubicación, estética, costo, finalidad de la construcción, etc., resulta por demás aconsejable y conveniente que, arquitectos, ingenieros y urbanistas, reconsideren los factores fundamentales que motivaron al hombre desde tiempos remotos a diseñar su vivienda. Estos pueden concretarse en un sólo propósito: lograr el bienestar humano en el interior de la vivienda protegiéndola de las inclemencias del intemperismo.

Desde la antigüedad, el hombre se ha visto forzado a disponer de una vivienda cuyos materiales de construcción y características de diseño (orientación, forma, etc.) le brinden una protección y abrigo contra el impacto de los elementos meteorológicos reguladores del clima local.

Inicialmente cuando el hombre no disponía de los conocimientos suficientes para construir su albergue, tuvo que limitarse al abrigo natural de las cavernas, las cuales además de brindarles protección contra los animales salvajes, le permitían disfrutar de un clima más benigno sensiblemente distinto del reinante a la intemperie.

Evolucionando a través de los tiempos, fueron surgiendo un sinnúmero de viviendas, que en nuestros días hemos considerado como regionalmente típicas y que fueron construídas, en muchos de los casos, con los pocos materiales disponibles de la localidad, sino es que con los únicos; tal es el caso de los iglús, cuyo elemento único de construcción lo es el hielo y sin embargo, sus geniales características de diseño y construcción, aseguran la supervivencia del hombre a tan bajas temperaturas.

Podemos decir que desde el punto de vista, respuesta al medio ambiente, el constructor primitivo mostró un agudo conocimiento de su habitat, basado en la experiencia de la problemática climatológica, local, así como de las propiedades térmicas de los materiales involucrados.

Dentro del rango de condiciones higrotérmicas indispensables para la supervivencia humana, el hombre primitivo realmente tuvo escaso margen de equivocación en lo que respecta al diseño y aprovechamiento de los generalmente escasos materiales de construcción. Un error de cuantificación de sus limitados recursos, quiza hubiese causado su aniquilamiento a causa de los severos y en ocasiones implacables fenómenos meteorológicos, sobre todo en regiones de climas extremosos.

Los efectos actuales de urbanización e industrialización del mundo, así como la tendençia al uso excesivo de combustibles (hasta hace poco baratos) para fines de calefacción y enfriamiento artificial, han ignorado, casi por completo, la importancia de los elementos bio-climáticos que entran en juego en el diseño arquitectónico. En consecuencia, el enfoque original con el cual fué diseñada la vivienda durante milenios, ha sido drásticamente modificada principalmente en lo que va de este siglo. Muchos problemas de salud causados por un habitat inadecuadamente climatizado, pueden ser evitados al considerar factores tan simples como lo puede ser el conocimiento de las características térmicas de los materialès de construcción. Urge entonces reenfocar las actuales tendencias arquitéctonicas, que aunque disponen de recursos tecnológicos mucho más avanzados, tienden a edificar construcciones cada vez menos confortables, subestimando inconscientemente, la mayoría de las veces, otro factor tan prioritario como la orientación. Al mismo tiempo, el hombre ha venido sobrestimando su capacidad tecnológica de construcción, la cual como puede constatarse, ha sacrificado el bienestar de sus ocupantes por la estética. Estas tendencias, como la que ha venido abusando del uso del vidrio como elemento estructural, ha llegado a crear situaciones climáticas internas desagradables e incomódas, quedando totalmente fuera del polígono del confort térmico. Para evacuar la energía calorífica en exceso acumulada por efecto del vidrio, este tipo de construcciones precisan del consumo de enormes cantidades de energía, que anualmente se destinan a complejos sistemas de ventilación y aire acondicionado; en algunos casos, aún en época de invierno. Lo anterior no significa de ninguna manera que el vidrio sea incompatible con los materiales idóneos de construcción, sino al contrario; el vidrio ha mostrado ser insustituíble en los sitemas pasivos de climatización solar, mediante los cuales se logra la circulación natural de importantes volúmenes de aire caliente o frío dentro de las habitaciones sin ninguna otra fuerza motriz, que la conversión de energía solar en calor.

Hay que recordar que toda vivienda es un sistema en continuo contacto con el medio ambiente, y en consecuencia, atravezado por numerosos flujos: de aire , agua, substancias orgánicas, substancias minerales, y primordialmente, de energía; la cual, directa o indirectamente proviene del sol. La permeabilidad o impermeabilidad de paredes ventanas y pisos, es decir, de las barreras físicas del sistema, regulan la magnitud y dirección de los intercambios de calor (radiación, convección y conducción) y de masa(convección), determinando así las condiciones internas del confort térmico.

Para precisar los requerimientos arquitectónicos, a los que las viviendas deberán estar sujetas para tener la capacidad de responder como un todo a estos flujos de intercambio y así poder alcanzar las condiciones confortables de vida y de trabajo, deben tenerse en consideración los siguientes elementos meteorológicos:temperatura, duración e intensidad de la insolación, húmedad, viento y precipitación pluvial.

El análisis local de las condiciones de asoleamiento y de la frecuencia e intensidad con que se presentan estos elementos, constituyen la base para encuadrar un diseño arquitectónico científico.

el cual será tan compatible con otros factores como puede serlo estético, en la medida de la habilidad con que el diseñador reuna eficientemente éstos y los demás factores que determinan los criterios de construcción antes mencionados.

De ésta manera, el planteamiento arquitectónico basado en la orientación óptima de la vivienda; intercambio masa-energía de los ocupantes con su medio ambiente; así como las propiedades térmicas de los materiales, es posible aprovechar racionalmente las aportaciones energéticas que el sol suministra día con día, de tal forma que la estructura misma de la vivienda actúe como una envolvente autoreguladora de las condiciones internas del confort térmico. El simple efecto de proveer una iluminación suficiente, repercutirá positivamente en el ánimo de sus ocupantes.

DISPONIBILIDAD DE LA ENERGIA SOLAR EN MEXICO

Dado que la disponibilidad de la energía solar en un lugar de la tierra depende fundamentalmente de su latitud geográfica y de sus características climatológicas (principalmente la nubosidad porcentual), la energía solar disponible en la República

Mexicana es cuantiosa por encontrarse dentro de la zona mundial de máximo asoleamiento anual.

En la figura 1 puede apreciarse su ubicación latitudinal observándose claramente como el trópico de Cáncer divide al país en dos regiones de elevada insolación, donde se presentan climas cálidos extremosos, ya sea secos (zonas áridas) ó húmedas (selvas tropicales).

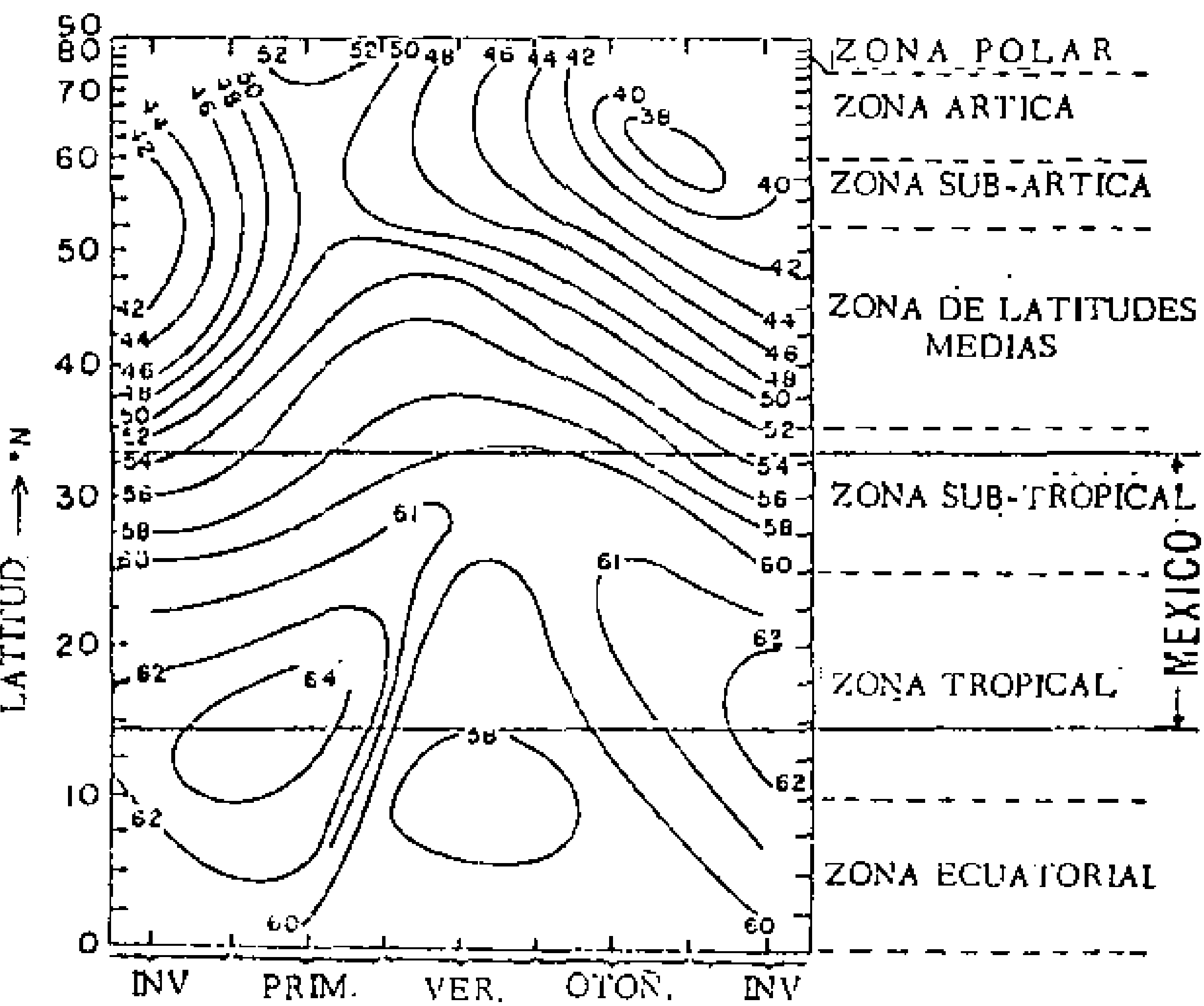
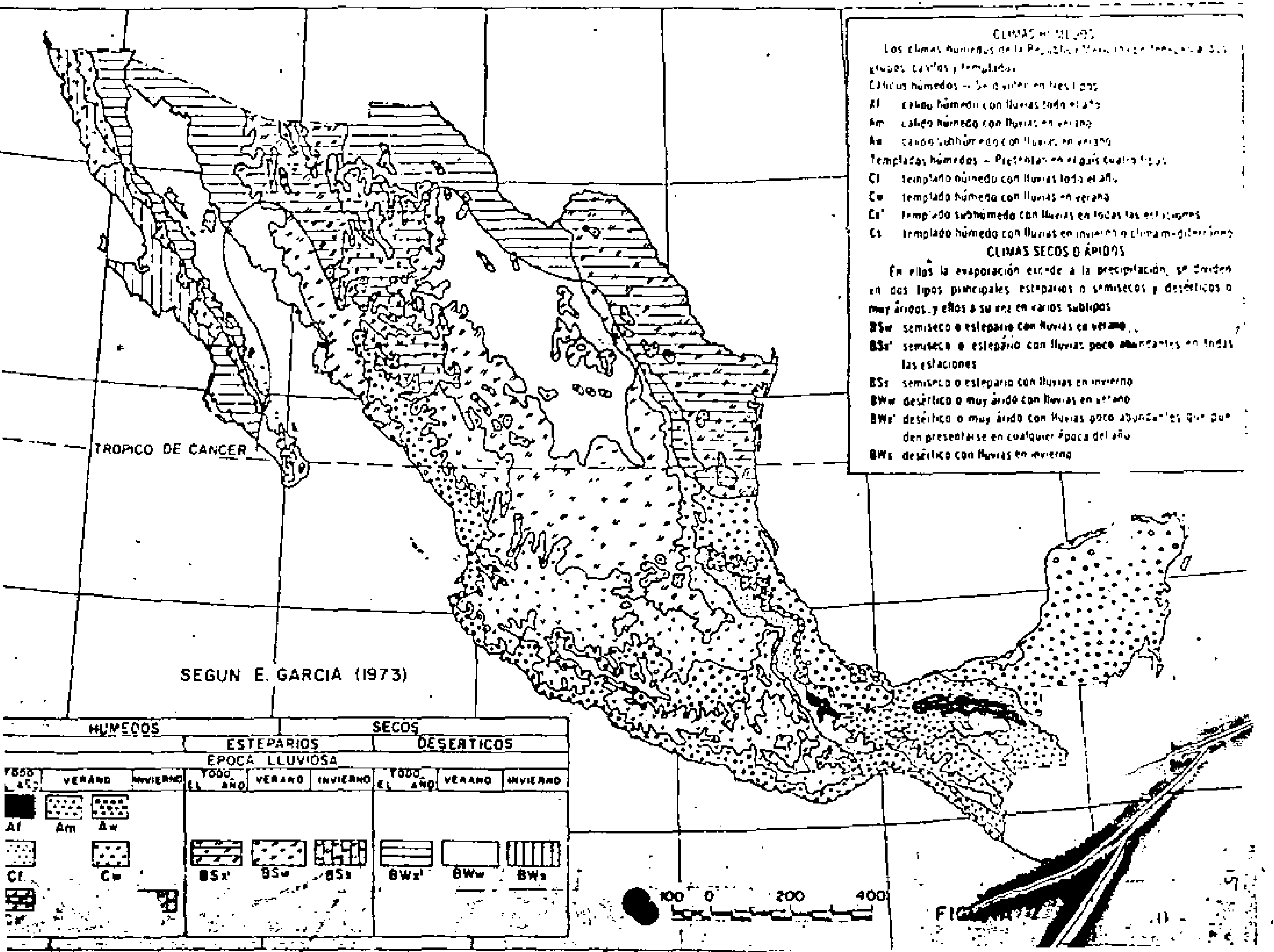


Fig. 1. Líneas que muestran los porcentajes de la radiación solar extraterrestre que alcanza a llegar al suelo respecto a las diferentes latitudes geográficas (1).


CLIMAS SECOS O ÁRIDOS
Af cálido húmedo con lluvias todo el año
Am cálido húmedo con lluvias en verano
Aw cálido subhúmedo con lluvias en verano
Cf templado húmedo con lluvias todo el año
Cw templado húmedo con lluvias en verano
Cx' templado subhúmedo con lluvias en todas las estaciones
Cs templado húmedo con lluvias en invierno o clima mediterráneo
BSw semiseco o estepario con lluvias en verano
BSx' semiseco o estepario con lluvias poco abundantes en todas las estaciones
BSs semiseco o estepario con lluvias en invierno
BWw desértico o muy árido con lluvias en verano
BWx' desértico o muy árido con lluvias poco abundantes que pueden presentarse en cualquier época del año
BWs desértico con lluvias en invierno
TROPICO DE CANCER
SEGUN E. GARCIA (1973)
HUMEDOS
SECOS
ESTEPARIOS
DESERTICOS
EPOCA LLUVIOSA
TODO EL AÑO
VERANO
INVIERNO
Af
Am
Aw
Cf
Cw
BSx'
BSw
BSs
BWx'
BWw
BWs
100
0
200
400

La figura 2 muestra los tipos de clima imperantes en nuestro país según la modificación al sistema de Köpen adaptada a nuestro país por E. García. Dentro del contexto mundial, México está clasificado como un país privilegiado en cuanto a intensidad, duración y calidad de la insolación. En particular el noroeste de México junto con otras regiones del planeta, como lo son: el norte y sur de Africa, la península Arábiga, la zona central de Australia y la parte norte de Chile, son regiones que gozan de espléndidas características anuales de insolación.

La radiación recibida sobre una superficie horizontal ya sea en forma directa o difusa, forma en conjunto la radiación global (figura 3). La intensidad de ésta, depende de las atenuaciones que sufra en su trayecto atmosférico debido a los fenómenos de absorción, reflexión y dispersión por los gases atmosféricos y partículas suspendidas. En sí, las nubes son las causantes principales de la disminución de la energía solar que alcanza a llegar a nivel del suelo, ya que su presencia contribuye a obstaculizar la radiación directa proveniente directamente del disco solar y a su vez incrementa el e-

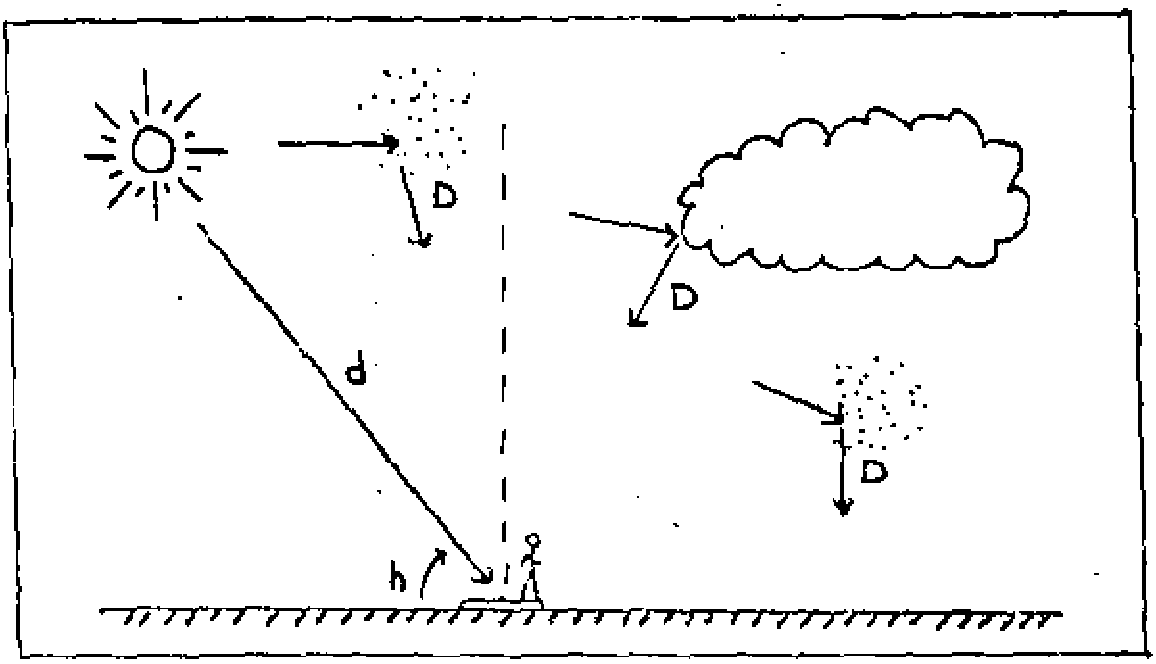


FIG. 3. RADIACION SOLAR GLOBAL

(DIRECTA + DIFUSA)

radiación directa (d) :

proveniente directamente del disco solar

radiación difusa (D) :

proveniente de la atmósfera y las nubes

(reflejada y dispersada)

fecto de los tres fenómenos atenuadores antes mencionados. El efecto neto de estos fenómenos repercute en un aumento de la componente difusa. Como previamente se ha calculado en otro trabajo (2), la energía instantánea que puede esperarse del sol sobre una superficie horizontal de 1 m^2 en nuestras latitudes, fácilmente puede superar el valor de 1000 watts/m^2. (figura 4). Comparativamente, ésta es la potencia requerida para mantener encendidos 20 focos de 50 watts cada uno.

En promedio anual, el equivalente energético recibido cotidianamente en México, es del orden de 5.5 kw-hora/ m^2. Esta cantidad representa una energía considerable al comparársele con lo que podría ser el consumo mensual de energía eléctrica estimado en 100 kw-hora, en una vivienda de tamaño medio (sin requerimientos de climatización), donde habitan en promedio 5 personas disponiendo de la iluminación y enseres eléctricos más comunes.

Lo anterior significa que mediante una total conversión de la radiación solar incidente sobre un

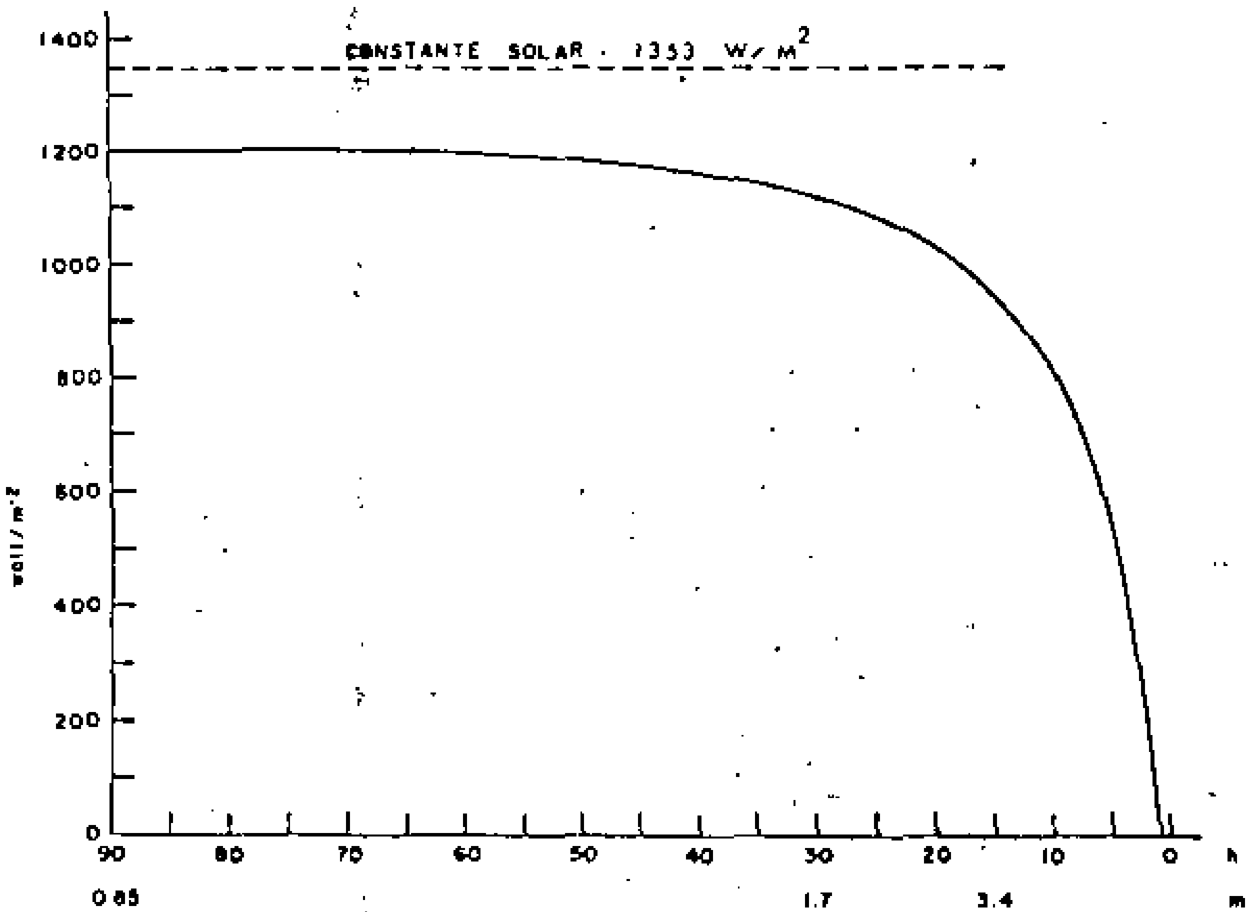


Fig. 4 Variación del flujo de radiación solar a incidencia normal I_n a 1500 metros de altitud bajo buenas condiciones de una atmósfera seca típica, cielo azul intenso (puro) y en función de la masa atmosférica y altura solar.

area de 1 m^2 durante 19 días, sería suficiente para satisfacer las necesidades energéticas mensuales de esa familia. Sin embargo, la eficiencia de captación y conversión de la energía solar a otras formas de energía es baja, aunque hay que recordar que la energía solar al ser gratuita, la convierte en una fuente de energía sumamente atractiva independientemente de su eficiencia de conversión. La eficiencia de conversión de la energía solar a energía eléctrica (conversión fotovoltaica) mediante las fotoceldas de silicio más perfeccionadas, sólo llegan a alcanzar en la actualidad un 17%. Sin embargo la conversión a energía calorífica (conversión fototérmica) permite alcanzar elevadas eficiencias del orden del 60% o más, aunque ésto sólo es posible en colectores solares operando a temperaturas relativamente bajas pero superiores a las ambientales.

En el mapa de la figura 5 se muestra la distribución anual de la radiación solar global (promedio diario) obtenida en un estudio previo (3). Es fácil observar que el Noroeste del país, princi-

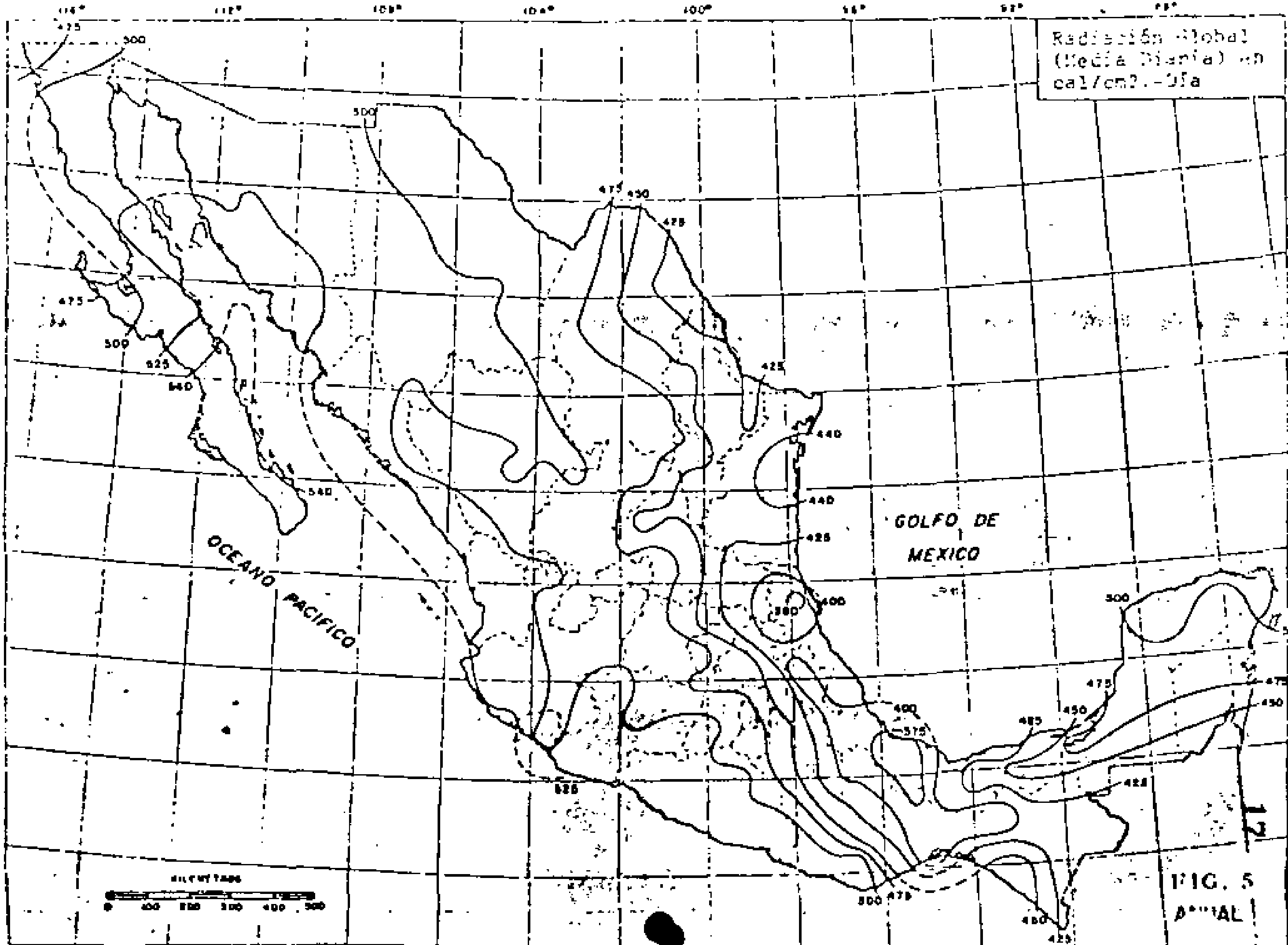
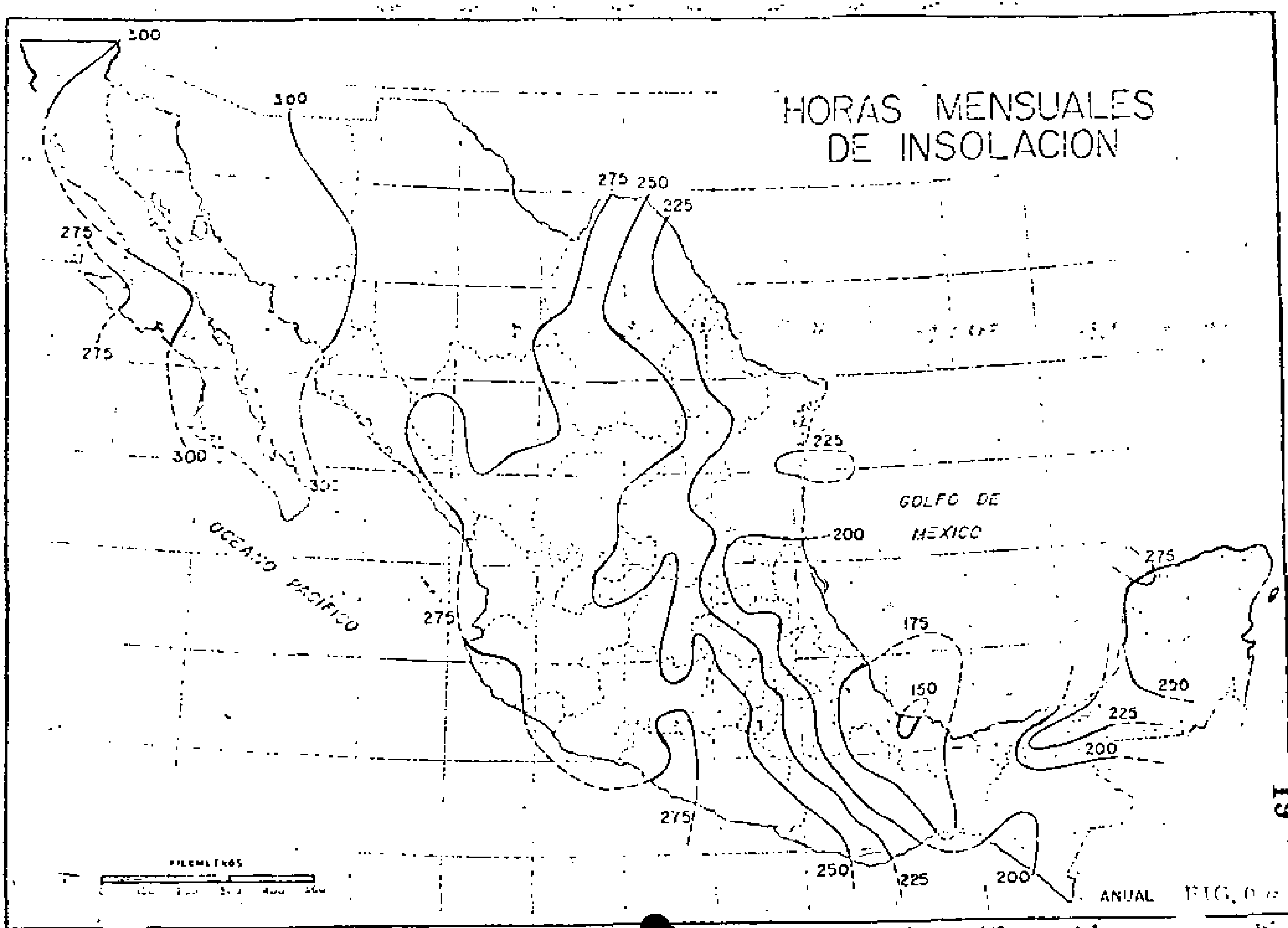

Radiación Global
(Media Diaria) en
cal/cm2.-Día
GOLFO DE
MEXICO
OCEANO PACIFICO

FIG. 5

palmente la península de Baja California y los estados de Sonora, Chihuahua, Sinaloa, Durango, etc. así como la parte norte de la península de Yucatán, gozan de magníficas condiciones de insolación. La misma descripción puede aplicarse al mapa de la figura 6 donde se muestra el promedio anual del número de horas mensuales de insolación.

Aunque de ambos mapas pueden apreciarse zonas de baja insolación, como los estados comprendidos en la vertiente del Golfo de México, los valores de insolación resultan ser relativamente elevados al comparárseles con los valores que se registran en promedio anual en otros países de América, Europa y Asia situados más al norte de nuestro hemisferio. Puede decirse que en las regiones más asoleadas de México, el aprovechamiento de la energía solar puede llevarse a cabo tanto mediante dispositivos de captación de radiación directa como difusa, o sea, mediante captadores concentradores o planos. Por el contrario en las regiones menos asoleadas (más nubladas) donde la radiación solar es predominantemente



HORAS MENSUALES
DE INSOLACION
GOLFO DE
MEXICO
OCEANO PACIFICO
300
300
275
250
225
275
275
300
300
225
200
275
175
150
250
225
200
275
250
225
200
ANUAL
KILOMETROS

FIG. 6

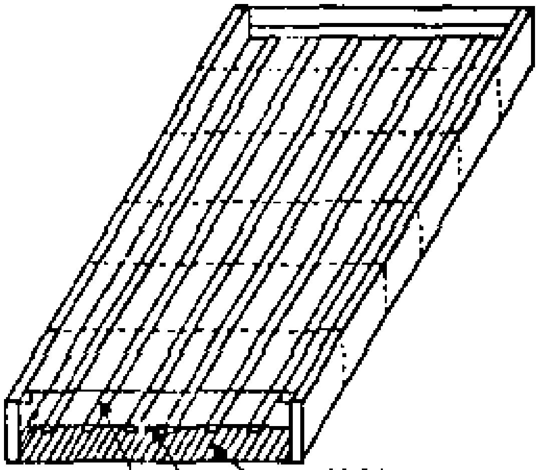
difusa, queda restringido el uso de dispositivos concentradores, siendo los colectores planos lo más eficiente en estas zonas.

En el noroeste de México, la energía que se recibe diariamente durante el verano, es en promedio cercano a los 8 kw-hora/m^2, mientras que en los estados de la vertiente del golfo de México en los meses menos soleados de Invierno, el valor mínimo es de aproximadamente 3.5 kw-hr/m^2. Estas dos últimas cantidades representan un 30 % y un -35% respecto al valor promedio diario anual considerado sobre todo el territorio nacional (5.5 kw-hora/m^2). Así en promedio, el techo de una casa con una superficie de 100 m^2 recibe durante 8 horas en un día soleado, cerca de 550 kw-hora. Esta cantidad representa el equivalente calorífico que correspondería a la combustión de 65 kg de carbón ó 55 litros de gasolina, aproximadamente.

APLICACIONES INMEDIATAS

Colectores Solares.

El calentamiento de agua se lleva a cabo mediante colectores solares;los cuales son dispositivos que interceptan, absorben y transfieren la energía solar al fluído circulante. Un dispositivo de captación de energía solar difiere de un intercambiador de calor común, en el sentido de que la transferencia de energía radiante hacia el colector se realiza desde una fuente enegética distante (el sol) a un fluído de trabajo (agua). En tales condiciones se tienen bajos coeficientes de transferencia de calor y el transporte de energía por radiación viene a ser el fenómeno de transferencia predominante. Un calentador solar comprende al colector mismo, así como un tanque de almacenamiento de agua caliente, aislado térmicamente. En la figura 7 pueden observarse los componentes esenciales de un calentador solar de agua típico. El armazón es generalmente metálico ó de plástico reforzado aunque en algunos casos llegan inclusive



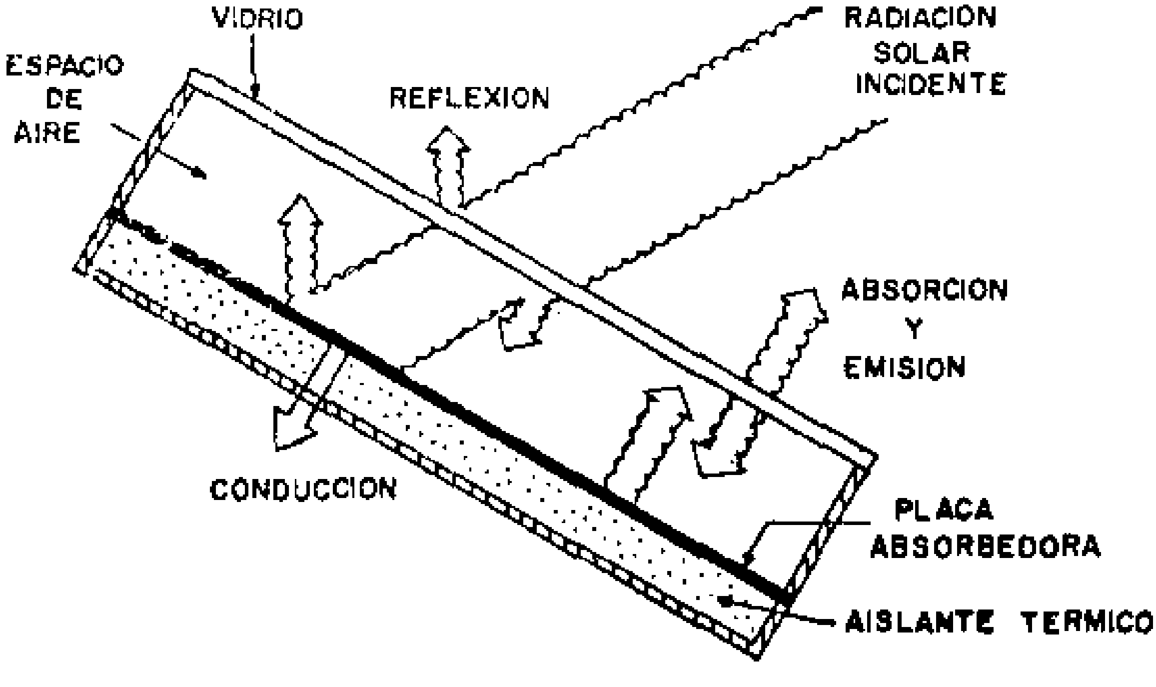


FIG. 7 DIAGRAMA DE UN COLECTOR SOLAR Y SU SECCION TRANSVERSAL MOSTRANDO EL FENOMENO DEL EFECTO INVERNADERO

a construirse de madera. La parte superior del colector, puede constar de una o varias cubiertas transparentes a la radiación solar pero opacas a la radiación calorífica desprendida por el calentamiento paulatino de la placa metálica (ennegrecida) que absorbe la radiación solar . Así, estas cubiertas transparentes además de producir el efecto de invernadero , a su vez eliminan pérdidas por convección con el aire ambiente . La placa colectora se encuentra en la parte intermedia del colector y contiene el circuito de ductos por los cuales circula el agua . Esta placa se construye de cobre , aluminio o fierro , materiales que poseen buenas conductividades térmicas y muy variadas dimensiones . Su revestimiento ennegrecido favorece la absorción de radiación solar incidente . Por debajo de la placa colectora se encuentra un material aislante que reduce las pérdidas de calor por conducción a través de la tapa inferior del colector .

La temperatura del agua en el tanque de almacenamiento puede muy fácilmente rebasar los 40°C .

Las temperaturas máximas que pueden alcanzarse generalmente son del orden de 60°C aunque éstas ya dependen de la eficiencia del colector, la cual a su vez es función de las caracterfticas especí - cas de su diseño , materiales de construcción e insolación recibida durante el día (4).

La aplicación de estas unidades está dirigi - da esencialmente a los sistemas de calentamiento de agua , aire acondicionado , refrigeración , des - tilación y secado de granos .

Por otra parte, mediante superficies reflecto - toras, los concentradores o captadores focales, di - rigen la radiación solar sobre una superficie cu - ya área es menor que aquella que intercepta a la energía incidente .

Este tipo de colectores aprovecha únicamente la radiación solar directa y por tal razón deben se - guir el movimiento del sol . Para tal fín , se re - quiere de un mecanismo apropiado (heliotropo) que eleva considerablemente el costo de un colector fo - cal respecto al colector plano , aunque las tempe - raturas alcanzadas pueden llegar hasta los 3500°C dependiendo de la perfección óptica del diseño .

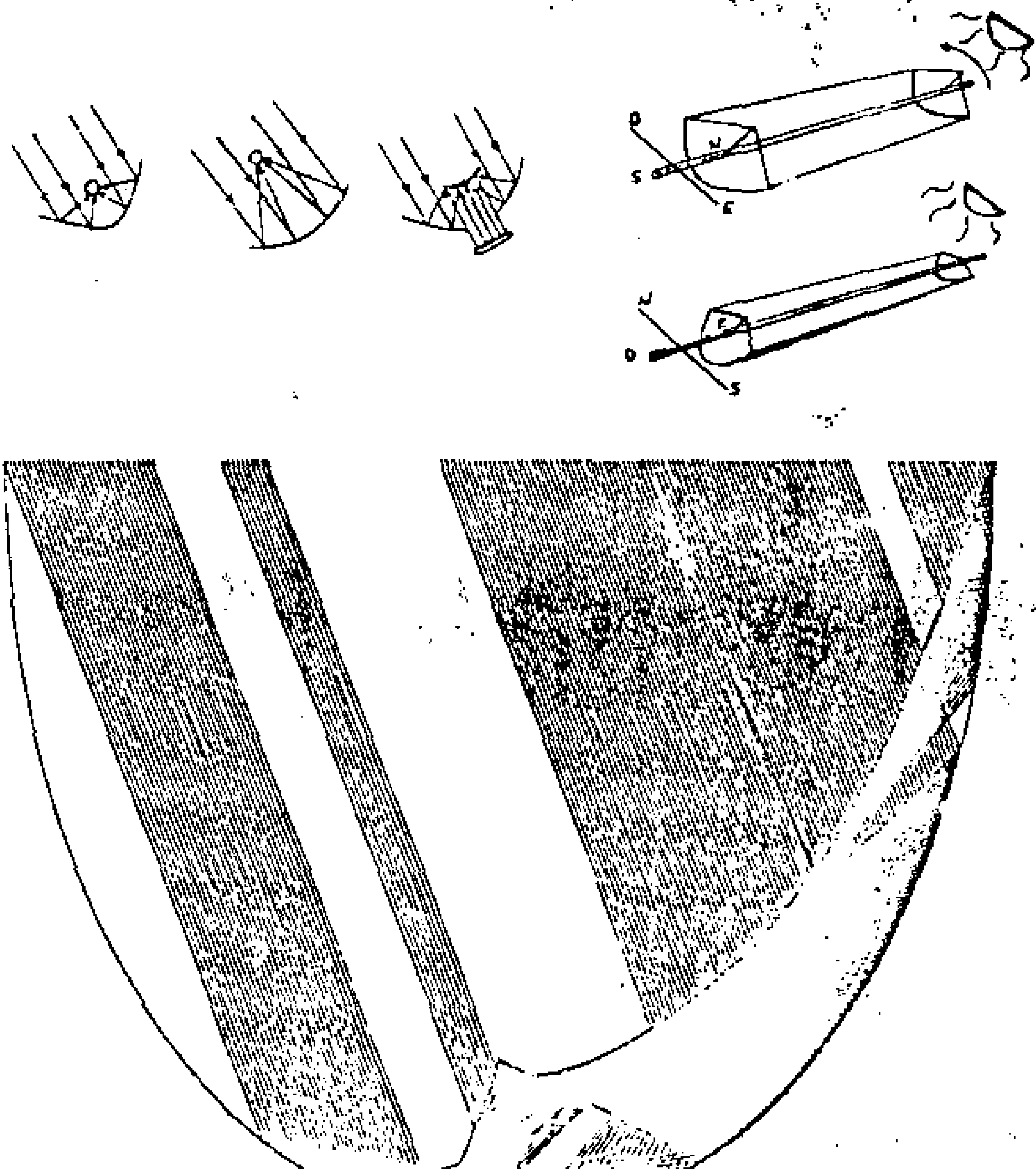


FIG. 8. CONCENTRADOR SOLAR CUYA SECCION ES DE UNA ESPIRAL LOGARITMICA

Estos se clasifican en función del tipo de super - ficies reflectoras,en : cónicos , cilíndricos-parabólicos y otras simetrías más complicadas como las de espiral logarítmica (5) (fig. 8) .

Su inclinación y orientación se fijan en base a los factores astronómicos de posición (latitud ,de - clinación solar) y climatológicos regionales (nu - bosidad) . Los factores astronómicos (6) determinan la trayectoria diaria del sol en el lugar en cues - tión (fig. 9) la cual puede examinarse durante el año mediante una gráfica solar (fig.10,11),donde el

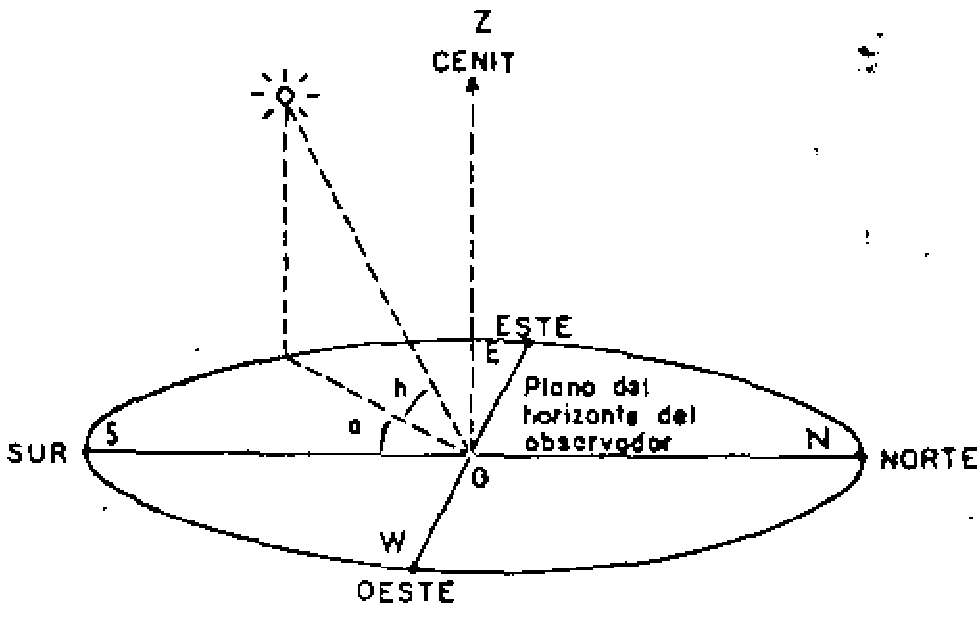
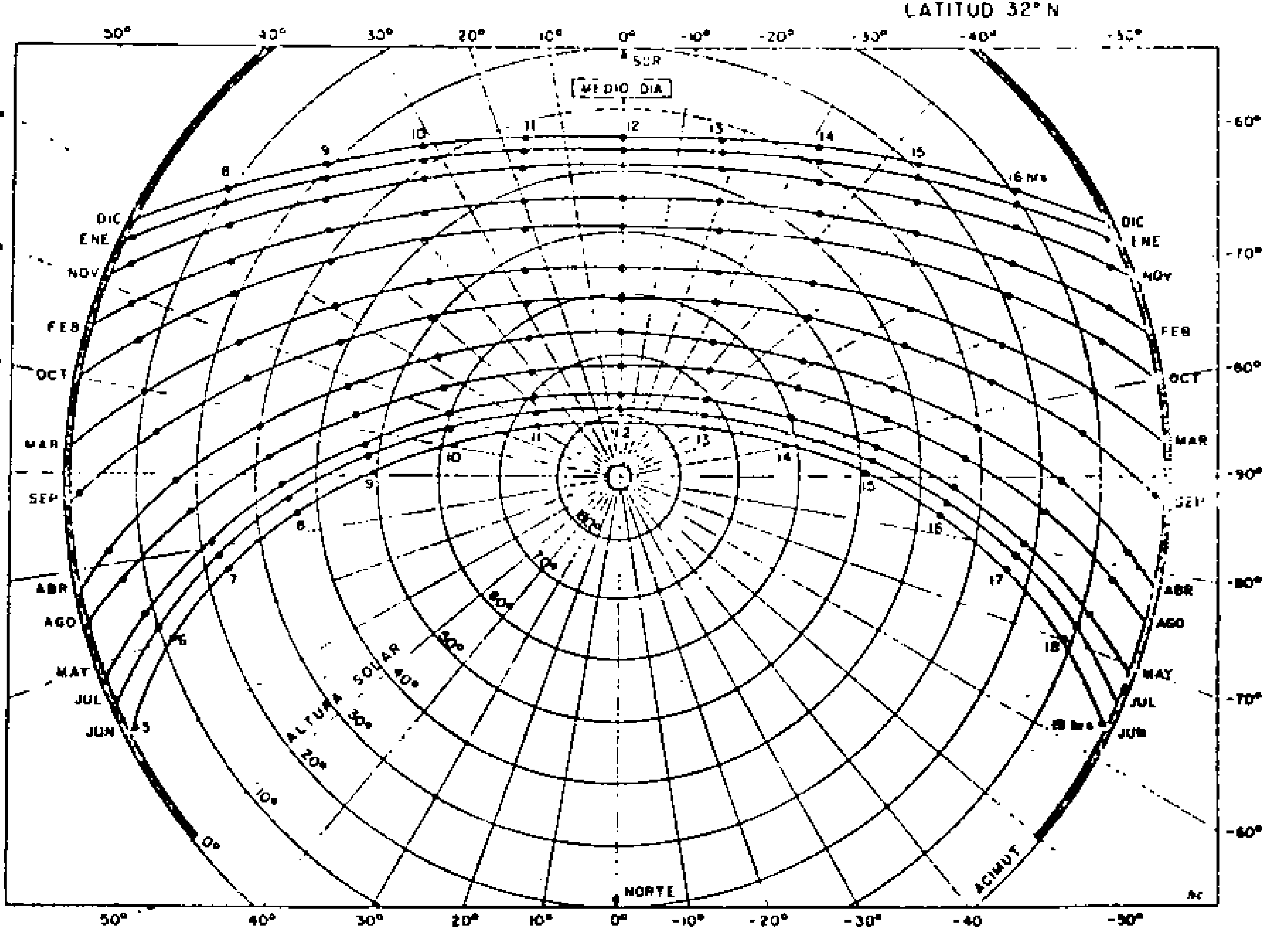


FIG. 9

Acimut y Altura Solar



PROYECCION SOBRE EL PLANO DEL HORIZONTE DE LAS TRAYECTORIAS DEL SOL

FIG. 10

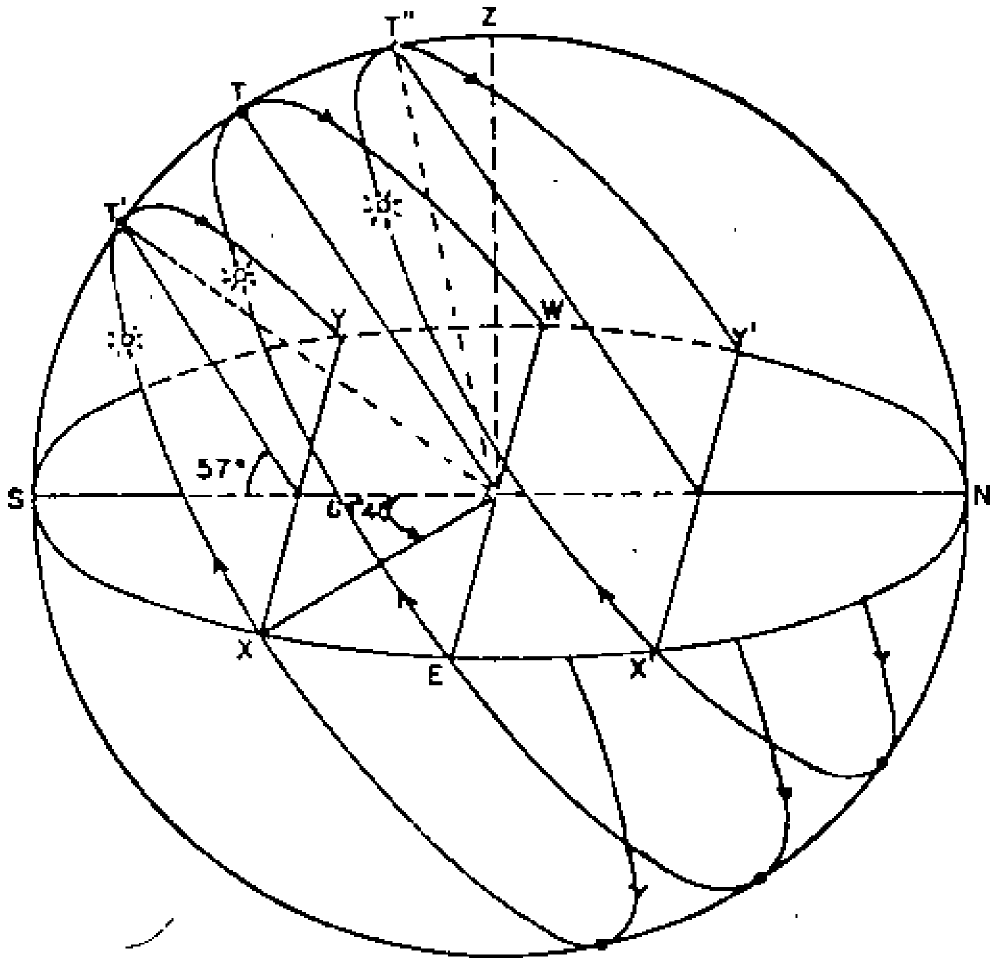


FIGURA. 11 TRAYECTORIA DIARIA DEL SOL A LA LATITUD DE:ϕ=33°
EN DIFERENTES FECHAS: XT'Y - SOLSTICIO DE INVIERNO;
ETW - EQUINOCCIOS; X'T"Y' - SOLSTICIO DE VERANO.

ángulo de la altura solar, se lee radialmente de afuera hacia adentro dentro de la gráfica a partir de cero grados (salida del sol) hasta la altura máxima (al mediodía que varía según la época del año. El ángulo azimutal (medido sobre el horizonte a partir de la dirección sur) puede leerse sobre el perímetro de la gráfica. Ambas coordenadas pueden leerse para cualquier hora solar y aproximar según la fecha del año. Debido a que cada una de las curvas representa la proyección sobre el piso de la trayectoria diaria del sol en la bóveda celeste (trayectoria promedio del mes) es posible también conocer la duración de la insolación observando el espaciamiento en tiempo que existe entre los puntos que marcan las diferentes horas solares.

Para analizar las características anuales de la insolación directa sobre fachadas orientadas hacia los cuatro puntos cardinales y de esta manera poder seleccionar una orientación preferente, conviene examinar la figura 12 tomada de un trabajo previo (2) donde se estudian las características de la radiación solar directa para toda la República Mexicana grado por grado de latitud.

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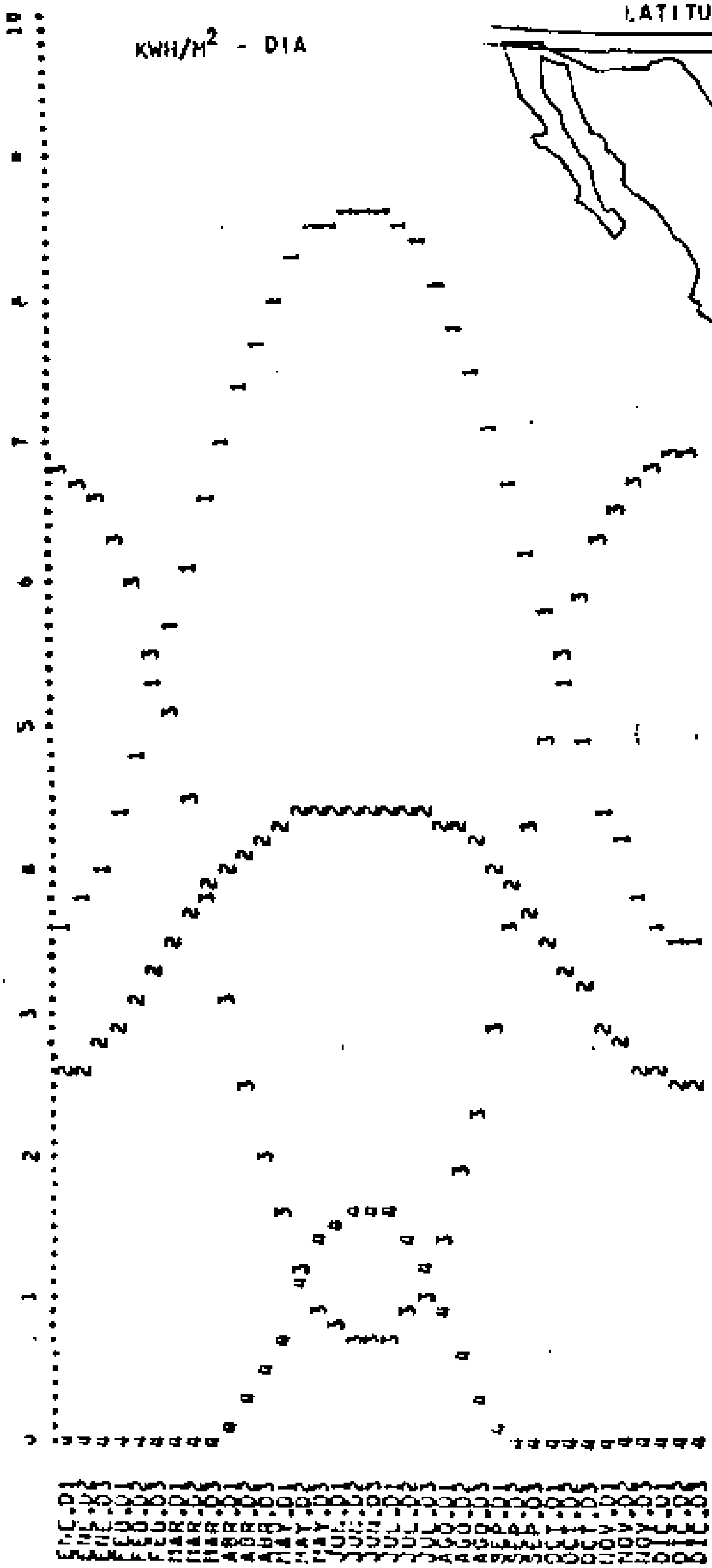
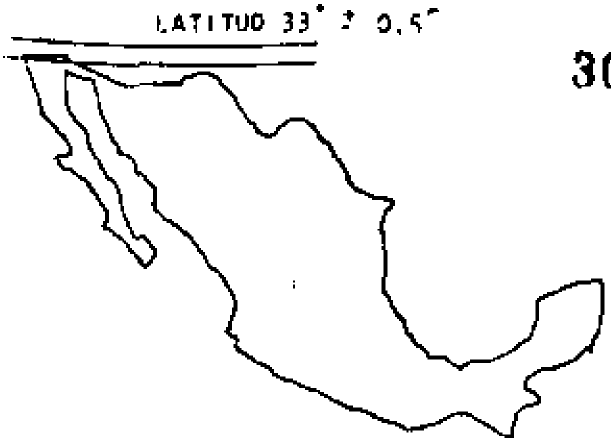




POBLACIONES:

Tijuana, B. C. N.

Cuervos, B. C. N.

Tecate, B. C. N.

Mexicali, B. C. N.

INSOLACION DIRECTA SOBRE:

1. plano horizontal.
2. fachada este-oeste
3. " " sur
4. " " norte

También en otro estudio se analizaron las orientaciones óptimas de colectores solares en nuestro país. Como es sabido para lograr la máxima captación de energía solar durante el año en un colector fijo desde el punto de vista geométrico se requiere un ángulo de inclinación igual al de la latitud del lugar, sin embargo al considerar la distribución anual de la nubosidad regional, los ángulos óptimos de inclinación pueden ser significativamente distintos por lo que se aconseja emplear el método propuesto por los autores en el trabajo anteriormente citado.

MATERIALES

En la fabricación de colectores planos se requiere de un material rígido para la caja estructural y un tipo de aislante térmico altamente eficiente. Este último no solo requerirá propiedades de baja conductividad térmica sinó características de desgaste lento, este desgaste deberá ser mínimo, tal que permita una larga vida del equipo y una amortización a corto plazo. Se ha constatado que el funcionamiento de equipos similares llega a ser hasta de 20 años.

Los mismos requerimientos son aplicables para el material constituyente de la caja estructural .

Otro aspecto que será decisivo en cuanto a la elección de estos materiales para colectores planos son los referentes a costos . Estos tres aspectos : buenas propiedades mecánicas , resistencia al intemperismo y bajo costo son los factores que influirán en la apertura del mercado de colectores actualmente limitado por sus elevados precios .

En este análisis hemos considerado los materiales existentes en el mercado y que en la actualidad son utilizados en la fabricación de colectores . Puesto que no han sido diseñados para este uso específico adolecen de muchas fallas que los fabricantes de módulos tratan de eliminar agregando otros elementos protectores repercutiendo negativamente en sus costos . Otros materiales ; como el aluminio o latón , con buenas propiedades mecánicas y anticorrosivas elevan exageradamente los precios de estos dispositivos .

Bajo estas consideraciones se ha iniciado una investigación para el desarrollo de materiales compatibles en el aprovechamiento de la energía solar . Materiales que resistan holgadamente los requerimientos más críticos en las zonas del país de clima más riguroso e inhóspito, donde deberán asegurar un servicio eficáz y amplio al usuario. Si a estas cualidades fisicoquímicas se agrega la de un bajo costo se tendrán los elementos para lanzar competitivamente una tecnología que propicie la apertura masiva en el mercado nacional y extranjero y de esta manera contribuir a lograr un significativo ahorro energético, tan vital y urgente en estos días.

En la elección de las materias primas se pensó en productos nacionales, de fácil acceso, preferentemente agrícolas y que tal empleo de dichos materiales permitiera mejorar las condiciones económicas de la población campesina en zonas baja productividad agrícola.

Las investigaciones llevadas a cabo en el Departamento de Tecnología de Materiales del CIM-UNAM han incluído fibras duras como elemento principal para un compuesto idóneo en la fabricación de módulos solares por su alta resistencia tensil, a la torsión, desgaste y ligereza que son características ideales para los propósitos perseguidos.

Como elementos adhesivos afines a las fibras duras, se han empleado polímeros de desecho tales como el polietileno de alta y baja densidad, cloruro de polivinilo (PVC) y polipropileno. Estos polímeros recubren totalmente las fibras eliminando el factor higroscópico y proporcionándoles impermeabilidad. A su vez las fibras duras aportan al laminado sus buenas propiedades mecánicas dando por resultado un material de excelentes características térmicas, mecánicas, resistente al ataque químico y al intemperismo. Se ha comprobado que en un colector plano de $1m^2$, en cuya estructura se empleó en un 80% la combinación fibra-polímero la conductividad térmica resultó sensiblemente menor elevando la eficiencia del colector.

En base a estas experiencias los autores pretenden en un futuro próximo lograr la obtención de un aislante térmico a base de fibra dura de muy baja conductividad térmica. Las fibras duras además de su gran resistencia mecánica son elementos ligeros y esta cualidad le agrega versatilidad al colector. Por otra parte los aislantes actuales que ofrecen mejores propiedades térmicas tales como el poliuretano y el poliestireno, son derivados del petróleo y en consecuencia no renovable por la limitación del recurso , motivo por el cual no es garantizable su existencia a largo plazo .

Otros materiales como la fibra de vidrio y el asbesto aunque de buenas características aislantes involucran riesgos a la salud ya que se ha comprobado que algunos tipos de asbestos son claramente cancerígenos así como la fibra de vidrio produce escoriaciones en la piel y trastornos respiratorios hasta llegar a afecciones más graves .

En pruebas preliminares se ha comprobado que la acción de la radiación ultravioleta degrada el polietileno aflorando las fibras a la superficie . En estabilidad dimensional se han observado deformaciones de un 10% con respecto a la probeta testigo . Para eliminar este problema es recomendable adicionar al material una carga de arena, con lo que aumenta la resistencia a la acción de los rayos ultravioleta y en general al intemperismo . Al someter muestras de intemperismo acelerado de 100 y 200 hrs. no se encontraron alteraciones superficiales , la coloración permaneció idéntica y el acabado de la pieza preservó su textura original . Respecto a estabilidad dimensional no se encontraron deformaciones del material al integrarse la carga mineral.

Estos elementos vienen a ampliar la gama de materiales y su aplicabilidad en la construcción que a futuro estará vinculada al diseño helioarquitectónico. En la actualidad es posible prever su utilización en diversos componentes de la vivienda solar especialmente donde se requieran materiales ligeros pero resistentes a la acción de intemperismo , aislantes termoacústicos cuyas características estructurales sean más ventajosas . Estas propiedades lo sitúan en un mejor plano con respecto a materiales típicos existentes en el mercado . La innovación de incorporar las fibras duras como elemento de refuerzo en materiales de construcción tradicionalmente utilizados en jarciería y cordelería permitiría reactivar su uso ante la actual expansión de las fibras sintéticas (7) las cuales han cerrado parcialmente el mercado de exportación y de consumo interno con la consiguiente repercusión negativa en la economía de las empresas procesadoras de estas fibras , a tal grado , que incurren en cuantiosos subsidios federales . Es necesario recordar que en el caso del Ixtle un millón de campesinos obtienen un 80% de su ingreso por la explotación de estas fibras y en lo que respecta al henequén dependen de este cultivo unas cien mil familias . El empléo en la construcción ,de materiales polímero-fibra-carga mineral ofrece una alternativa promisoria — — a este recurso agrícola .

CLIMATIZACION(Enfriamiento y Calentamiento)

Como previamente se ha mencionado, en la actualidad una de las transformaciones más eficientes de la energía solar a calorífica, se encuentra en el calentamiento de fluídos. Las aplicaciones directas e inmediatas conciernen a calentamiento de agua y aire para climatización de viviendas.

Según el modo de operación, los sistemas de alimentación pueden dividirse en dos categorías básicas activas y pasivas. En general los sistemas activos utilizan alguna otra fuente de energía para transferir la energía absorbida por el colector solar desde los lugares de captaciónhasta los lugares de almacenamiento o distribución. Contrariamente, lossistemas pasivos usan solamente medios naturales de transferencia de calor (convección, radiación y conducción).

Debido a que los sistemas pasivos prácticamente no requieren de un nivel de temperatura para operar, estos sistemas pueden funcionar continuamente.

Sistemas Pasivos.

El calentamiento o enfriamiento pasivo utiliza la arquitectura misma de la vivienda tanto para colectar como para almacenar la energía calorífica. Aunque existen muchos diseños, los sistemas pasivos esencialmente requieren de grandes cantidades de material cuya masa sea capaz de captar y almacenar energía calorífica. Los materiales más usados han sido principalmente: concreto, piedra, adobe y agua. La distribución de la energía colectada es transferida ya sea por radiación de la envolvente misma de la vivienda o por convección natural del aire caliente sobre el frío. (figuras 13 y 14).

Las técnicas de climatización pasiva incluyen procesos de ganancia directa de radiación solar através de un vidrio (muchas veces doble) así como materiales de gran capacidad calorífica, creando una especie de "colector solar habitable" que según sean

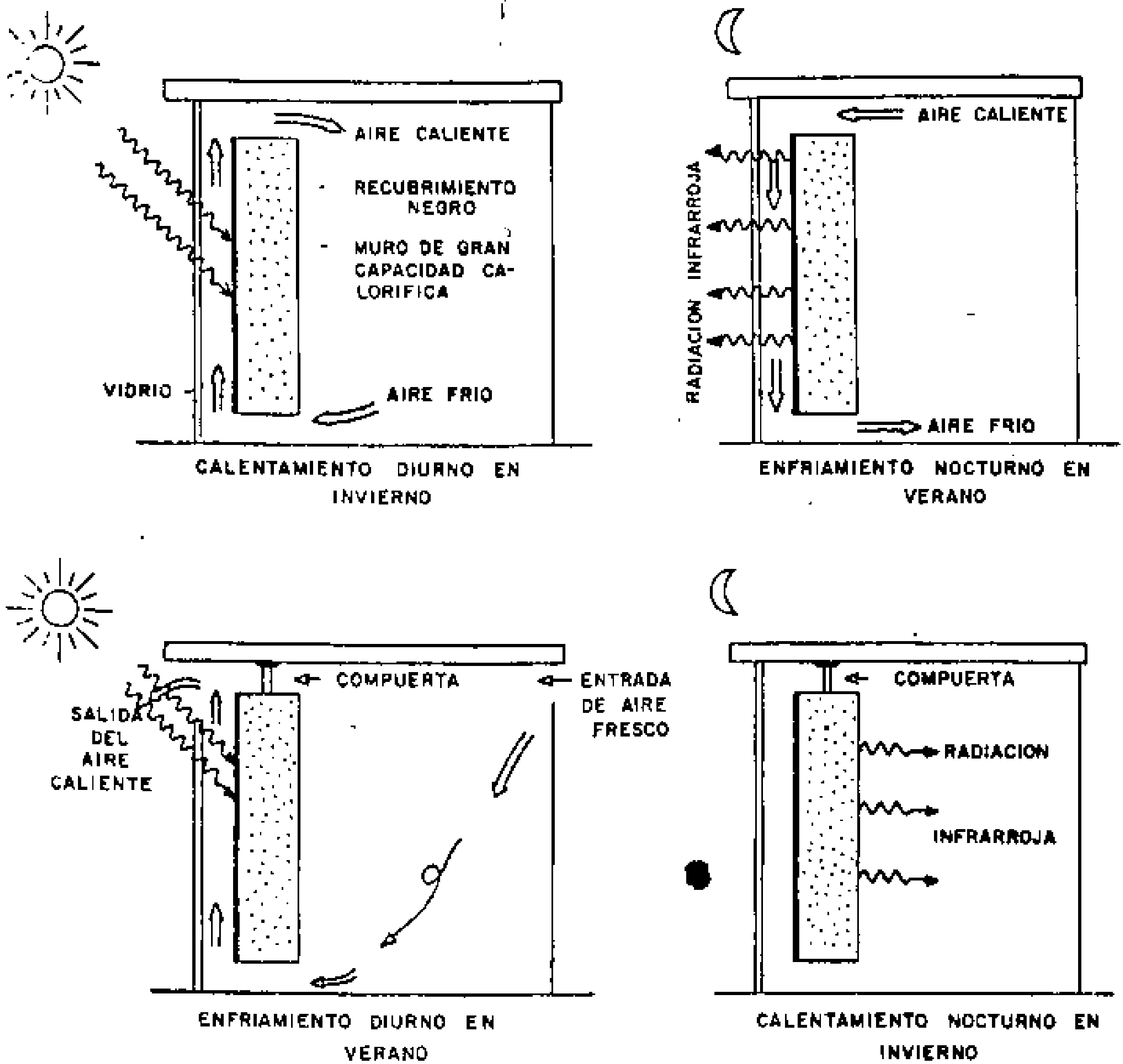


FIG. 13 SISTEMAS PASIVOS BASADOS EN:

— LA TERMOCIRCULACION NATURAL DEL AIRE (ASCENDENTE Y DESCENDENTE)

— LA EMISION DE RADIACION INFRARROJA HACIA EL INTERIOR Y EXTERIOR DE LA HA-BITACION (MURO EMISOR TIPO TROMBE)

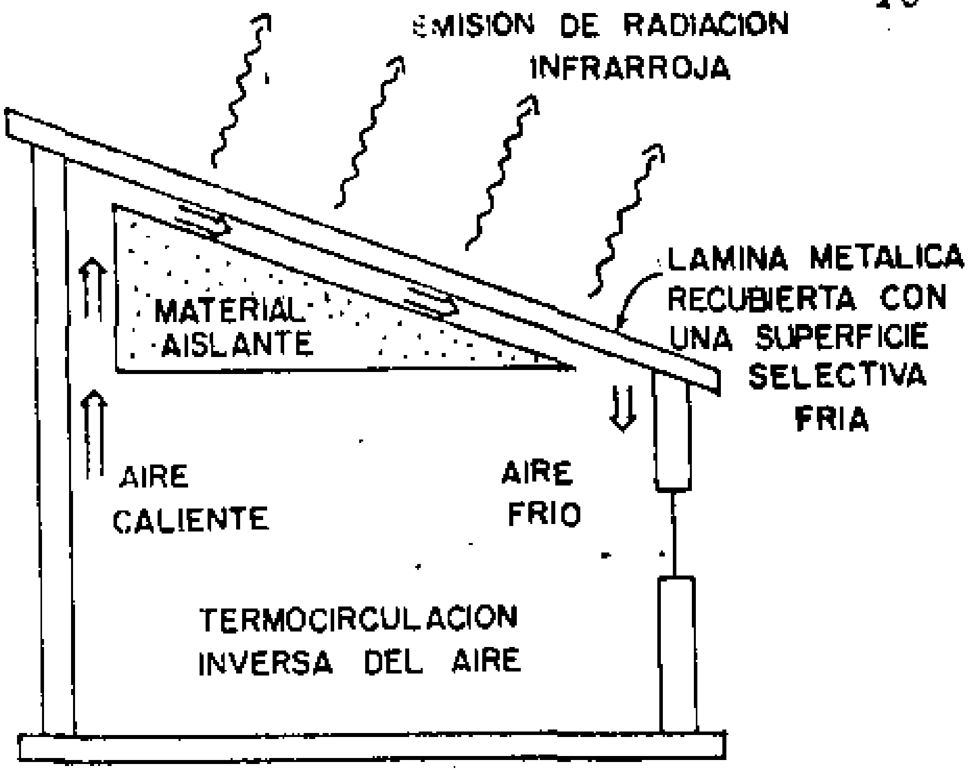


FIG. 14(a) SISTEMA PASIVO DE ENFRIAMIENTO NOCTURNO

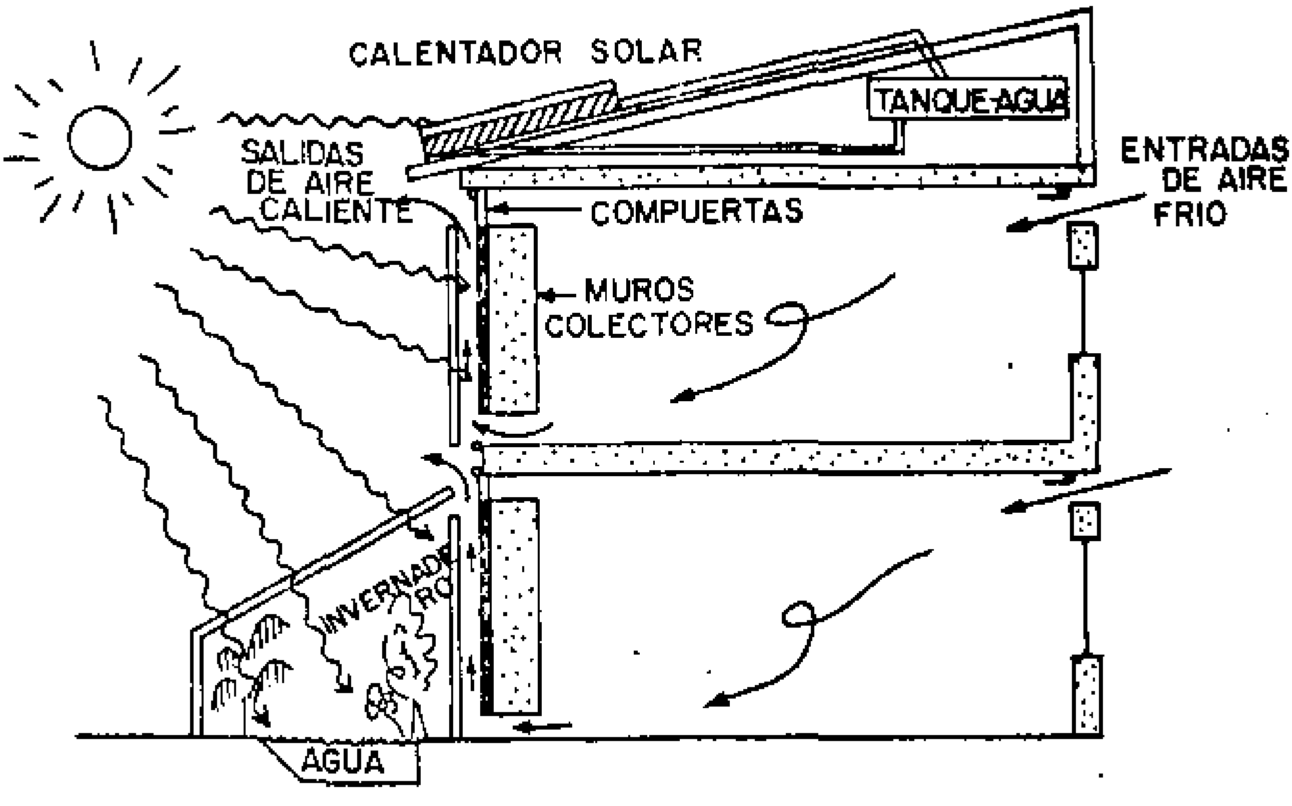


FIG. 14(b) SISTEMA PASIVO INTEGRAL: CALENTAMIENTO DE AGUA VENTILACION POR TERMOCIRCULACION DEL AIRE Y HUMIDIFICACION POR INVERNADERO

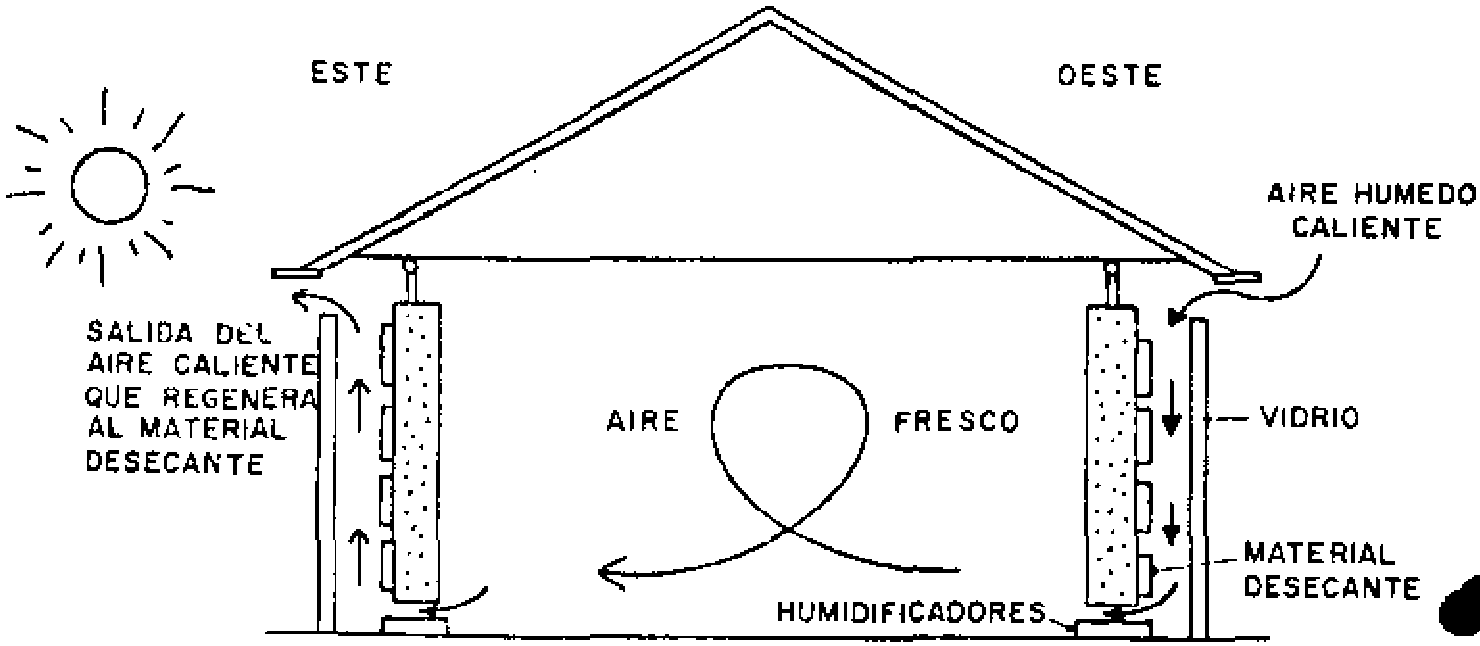


FIG. 14(c) SISTEMA PASIVO DE ACONDICIONAMIENTO DE AIRE. DURANTE LA MAÑANA PENETRA EL AIRE HUMEDO CALIENTE QUE ES DESHUMIDIFICADO Y EN CONSECUENCIA SE CALIENTA. AL PASAR POR EL HUMIDIFICADOR SE ENFRIA Y PENETRA AL INTERIOR COMO AIRE FRESCO. COMO POR LA MAÑANA EL SOL CALIENTA LA FACHADA ESTE, SECA Y REGENERA EL MATERIAL DESECANTE QUE QUEDO HUMEDECIDO LA TARDE ANTERIOR CUANDO EL SOL CALENTABA LA FACHADA OESTE; DE TAL MANERA, QUE LA CIRCULACION DEL AIRE SE EFECTUABA EN SENTIDO INVERSO AL MATUTINO.

los requerimientos, puede producir la circulación hacia el interior o el exterior de aire caliente o frío.

En los muros donde se desea almacenar la energía calorífica atrapada al atravesar el vidrio es conveniente utilizar pinturas y recubrimientos oscuros. Estos muros almacenan la energía y proporcionan el calor necesario para calentar las capas de aire adyacentes con lo cual se origina el ascenso del aire caliente que va siendo reemplazado por el aire frío proveniente de los niveles inferiores de las habitaciones.

Para propósitos de calefacción en el Norte del país y algunas zonas del Altiplano, los sistemas pasivos permiten prescindir completamente de los sistemas convencionales de calefacción que operan en base al consumo del petróleo, gas o diesel. Debido a que el agua es capaz de almacenar el doble de la energía que el concreto, en ocasiones se recurre a depósitos metálicos pintados en negro y ubicados a cierta distancia por detrás de los ventanales de la casa, la que se diseña en función de la climatización requerida.

Durante los períodos que no sea conveniente el almacenamiento de energía o en la que se desee preservar el calor interno pueden usarse cortinas reflectoras o aislantes entre la ventanería y las paredes interiores, de esta manera se reducen las pérdidas o ganancias del calor por radiación, debido ya sea a la absorción o reflexión de la radiación infraroja de los cuerpos calientes (8).

Los sistemas pasivos pueden incluir también grandes o pequeños invernaderos integrados a las viviendas. Estos, además de almacenar considerables cantidades de energía permiten optimizar las condiciones de humedad en regiones muy secas independientemente de las mejoras estéticas del conjunto que pueden alcanzarse y del placentero impacto anímico que proporciona la vegetación.

Otro fenómeno hasta ahora poco explotado a nivel habitacional, lo es el del aprovechamiento del fenómeno de enfriamiento nocturno por disipación de radiación infraroja hacia el espacio (9).

A través de las llamadas superficies selectivas frías, es decir, aquellos recubrimientos que permiten el enfriamiento de los cuerpos debido a su propiedad de reflejantes a la radiación solar, y al mismo tiempo capaces de emitir radiación calorífica desprendida del interior de los cuerpos, es posible el enfriamiento interno de las viviendas. Para este efecto es necesario cierto tipo de diseño y techado metálico. Para lograr aprovechar este fenómeno se requiere tres condiciones: baja humedad relativa, gran oscilación de temperatura ambiente entre el día y la noche, y preferentemente que el sitio sea elevado respecto al nivel del mar (más de 500 m.); aunque esta última condición es ideal más no indispensable. Existe un sistema pasivo (figura 15) que utiliza el fenómeno de enfriamiento por radiación infraroja nocturna y que además puede proporcionar el efecto de calentamiento al interior de la vivienda. Eneste caso se utiliza un techado metálico encima del cual se colocan recipientes plásticos conteniendo agua. Según la hora del día y estación del año estos recipientes se

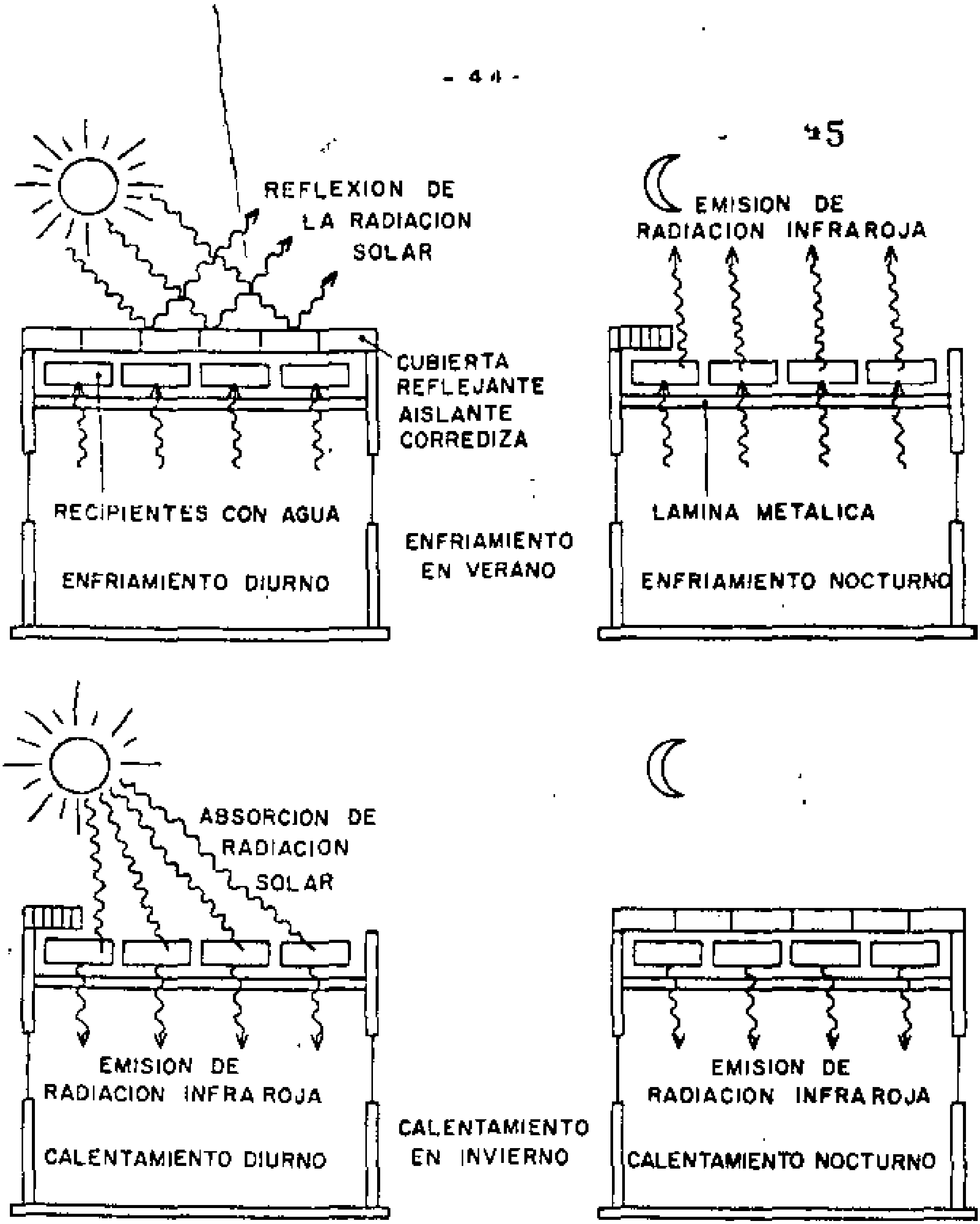


FIG. 15 SISTEMA PASIVO BASADO EN LA ABSORSION DE RADIACION SOLAR Y EMISION DE RADIACION INFRA ROJA HACIA EL EXTERIOR O INTERIOR PRODUCIENDO EL ENFRIAMIENTO O CALENTAMIENTO RESPECTIVO.

ponen al sol durante el día o al cielo abierto durante la noche. Estos pueden taparse con una cubierta corrediza que sea reflejante tanto de la radiación solar como de la calorífica desprendida al interior. Reexaminando el mapa climático de la figura 2 pueden identificarse las regiones donde este sistema resulta ideal, especialmente en las zonas áridas y semiáridas del Norte y centro del país. No obstante que los principios de operación de los sistemas pasivos son de apariencia simple es importante hacer notar que para su funcionamiento y óptima eficiencia es necesario realizar previamente un concienzudo estudio que involucre: características de insolación; condiciones del microclima local; volumen de la construcción; características mecánicas y térmicas de los materiales; diseño adecuado de muros, pisos y techo, especialmente su forma y dimensiones; tipo de función que desempeña la edificación: habitacional, escuela, fábrica, centro comercial, hospital, iglesia, etc; estimación de la transferencia de calor por radiación, convección y conducción en la construcción misma y con su medio ambiental.

Respecto a las características climáticas del lugar donde desee implantarse un sistema pasivo ya sea esto para ventilación, enfriamiento o calefacción, es necesario examinar los siguientes elementos meteorológicos: temperatura del aire, humedad, velocidad del viento, precipitación, duración e intensidad de la insolación, nubosidad y contaminación atmosférica.

Deben considerarse además características como la vegetación circundante y muy importante es también la topografía del sitio ya que determinará la pendiente, orientación, elevación de la construcción y su exposición a los rayos solares durante el año.

Las características del suelo en su estado natural o modificado son importantes porque su reflectividad puede influir positiva o negativamente sobre la construcción al reflejar más o menos radiación solar sobre ésta. Pueden esperarse repercusiones similares cuando alrededor de la construcción existen objetos (casas, edificios, árboles, etc) capaces de desviar la dirección de los vientos locales predominantes y de proyectar sombras sobre la construcción, las cuales pueden ser benéficas quizá en verano cuando se requiere enfriamiento o perjudiciales en invierno cuando se necesita calentamiento. El estudio del movimiento anual de las sombras proyectadas por los cuerpos adyacentes a la construcción es indispensable al considerar cualquier sistema de climatización ya sea de tipo pasivo o activo. Para esto debe recurrirse nuevamente al empleo de las gráficas solares (figuras 10 y 11).

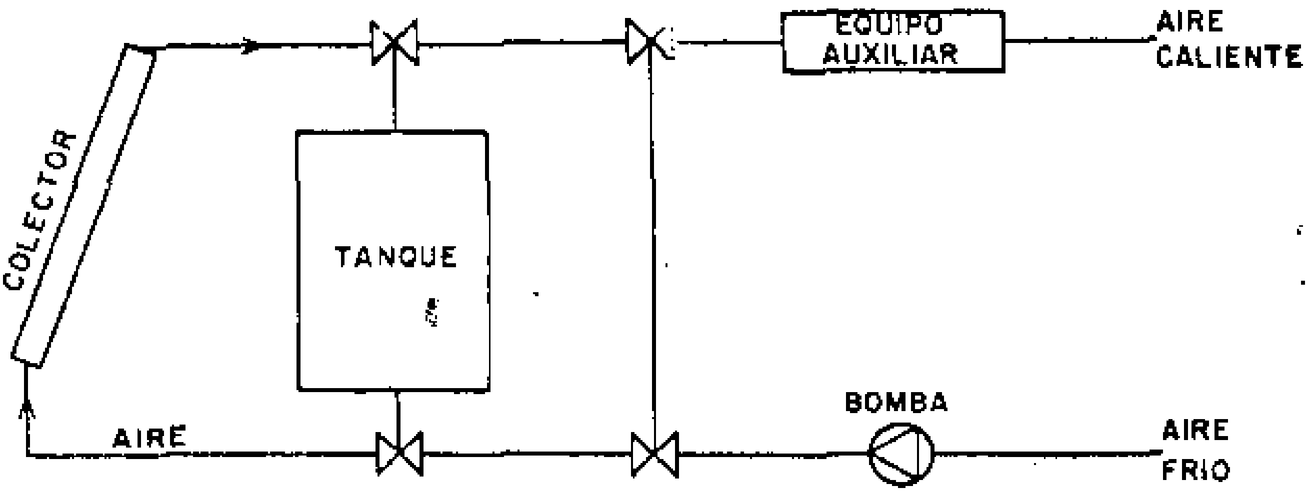
En México, el CIM- UNAM se encuentra desarrollando dos proyectos de investigación de climatización pasiva de vivienda y de un establo piloto. Estos proyectos se llevan a cabo en dos regiones de clima extremoso: el cálido seco y el cálido húmedo; las localidades escogidas fueron Hermosillo, Sonora y Martínez de la Torre, Veracruz. Los resultados de estos proyectos serán publicados en su oportunidad.

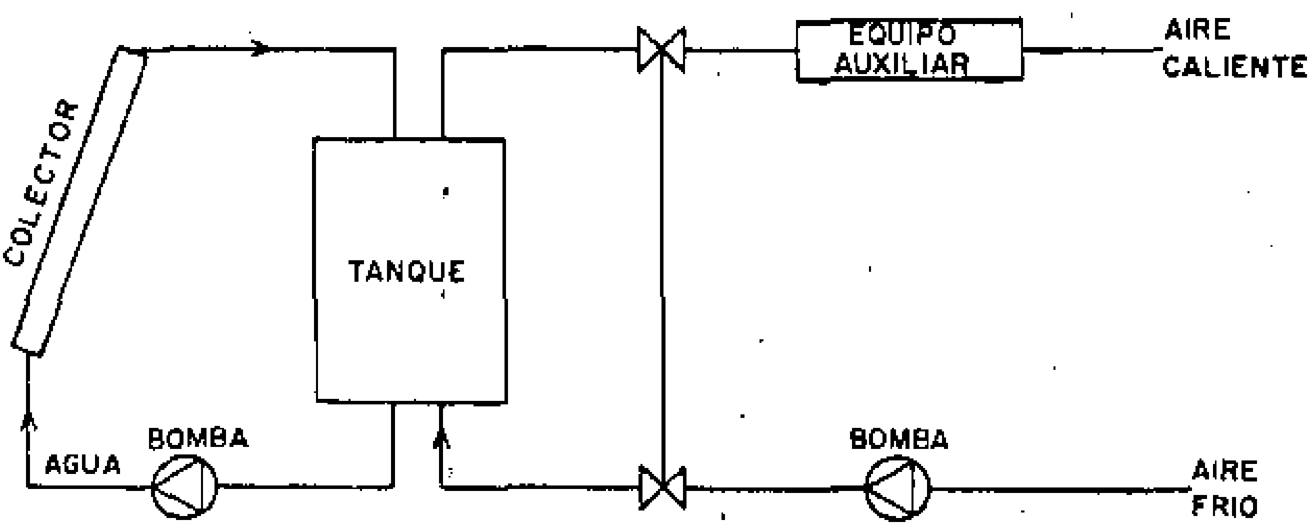
Sistemas Activos

Estos sistemas en general están menos expuestos a pérdidas de calor debido a que su diseño se caracteriza por ser más hermético. En consecuencia estos sistemas son más eficientes que los pasivos aunque definitivamente son mucho más costosos en inversión inicial y mantenimiento.

Dependiendo del fluído usado como elemento de transferencia de la energía solar captada los sistemas activos usan un gas (comúnmente aire) o algún líquido (usualmente agua).

Los colectores vienen a ser la parte más importante de estos sistemas (figuras 16 y 17), ya que en ellos se capta la energía solar disponible. Aprovechando el efecto invernadero que produce el calentamiento, descrito anteriormente estos casi siempre constan de captadores planos aunque es frecuente encontrar concentradores focales tales como espejos o lentes de Fresnel cuando se requieran temperaturas elevadas. Estos concentradores se usan especialmente en sistemas de enfriamiento por absorción (figura 18), donde el refrigerante empleado requiere elevadas temperaturas de evaporación (10). Los sistemas de almacenamiento de





FIGS. 16 y 17 SISTEMAS ACTIVOS PARA EL CALENTAMIENTO DE AIRE A BASE DE AIRE Y AGUA RESPECTIVAMENTE.

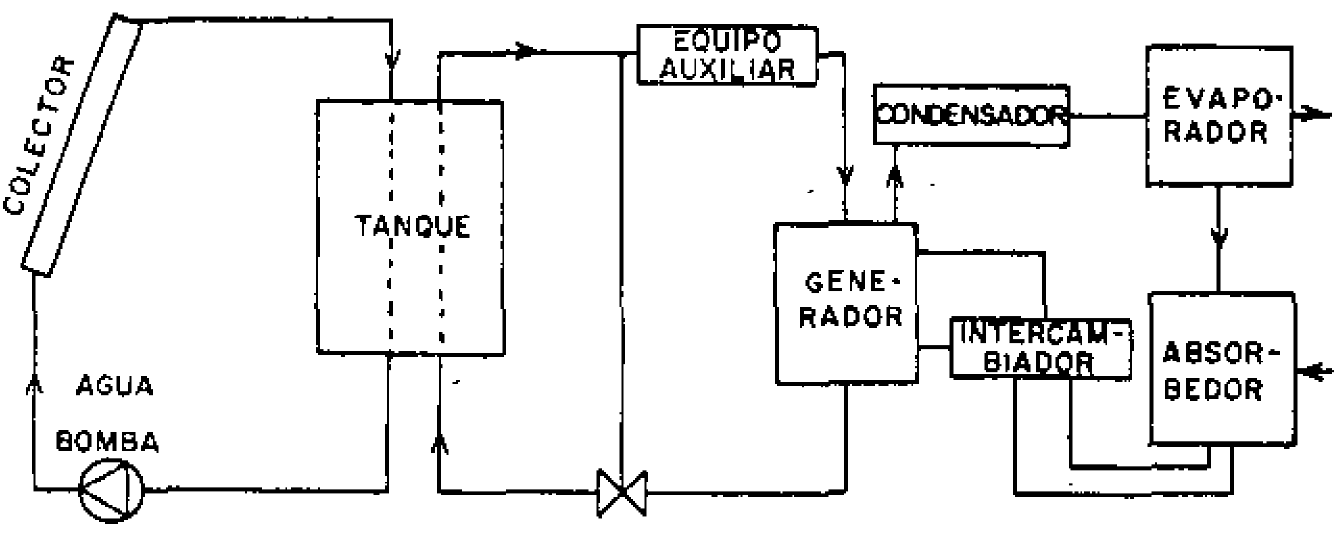


FIG. 18 SISTEMA ACTIVO DE ENFRIAMIENTO POR ABSORCION

energía de los sistemas ac vos retienen el exceso de calor colectado durante el día para su posterior aprovechamiento durante las noches o períodos muy nublados.

Como materiales para el almacenamiento de calor frecuentemente se usan piedras porosas de elevada capacidad calorífica, agua o productos químicos. La selección de estos materiales se hace en base del volumen requerido y de su costo. Cuando se usa agua se requiere un volumen de almacenamiento de aproximadamente un m^3 por cada m^2 de colector las piedras sin embargo, requieren un volumen tres veces mayor para retener la misma cantidad de calor que el agua. Los productos químicos permiten disminuir el volumen requerido a una décima parte , aunque su elevado costo y los riesgos de contaminación del fluído circulante restringen mucho su uso.

En el transporte y distribución del calor en los circuitos de calefacción, enfriamiento o ventilación son los procesos más complicados de este sistema, ya que para hacer circular el fluído por los ductos respectivos, se necesita una bomba o ventilador lo que implica una circulación forzada activada mediante el consumo de un energético convencional.

Para regular los procesos de colección-almacenamiento y almacenamiento-distribución (a los volúmenes de climatizar) se requieren dispositivos de control similares a los usados en sistemas convencionales; principalmente termostatos. Muchas veces también se requieren otros dispositivos adicionales, como pueden ser: intercambiadores de calor líquido-aire o gas-agua, los cuales incrementan notablemente los costos iniciales y de mantenimiento.

La mayoría de los sistemas activos se encuentran acoplados a sistemas de climatización convencional. Esto sucede cuando los requerimientos energéticos globales superan la capacidad del sistema solar, en cuyo caso pasa a ser un sustituto del sistema convencional. No obstante, reduce los costos de climatización aunque la amortización del equipo solar se realiza en un plazo mucho más largo.

Comparativamente los sistemas de calefacción a base de líquidos , como también los sistemas de

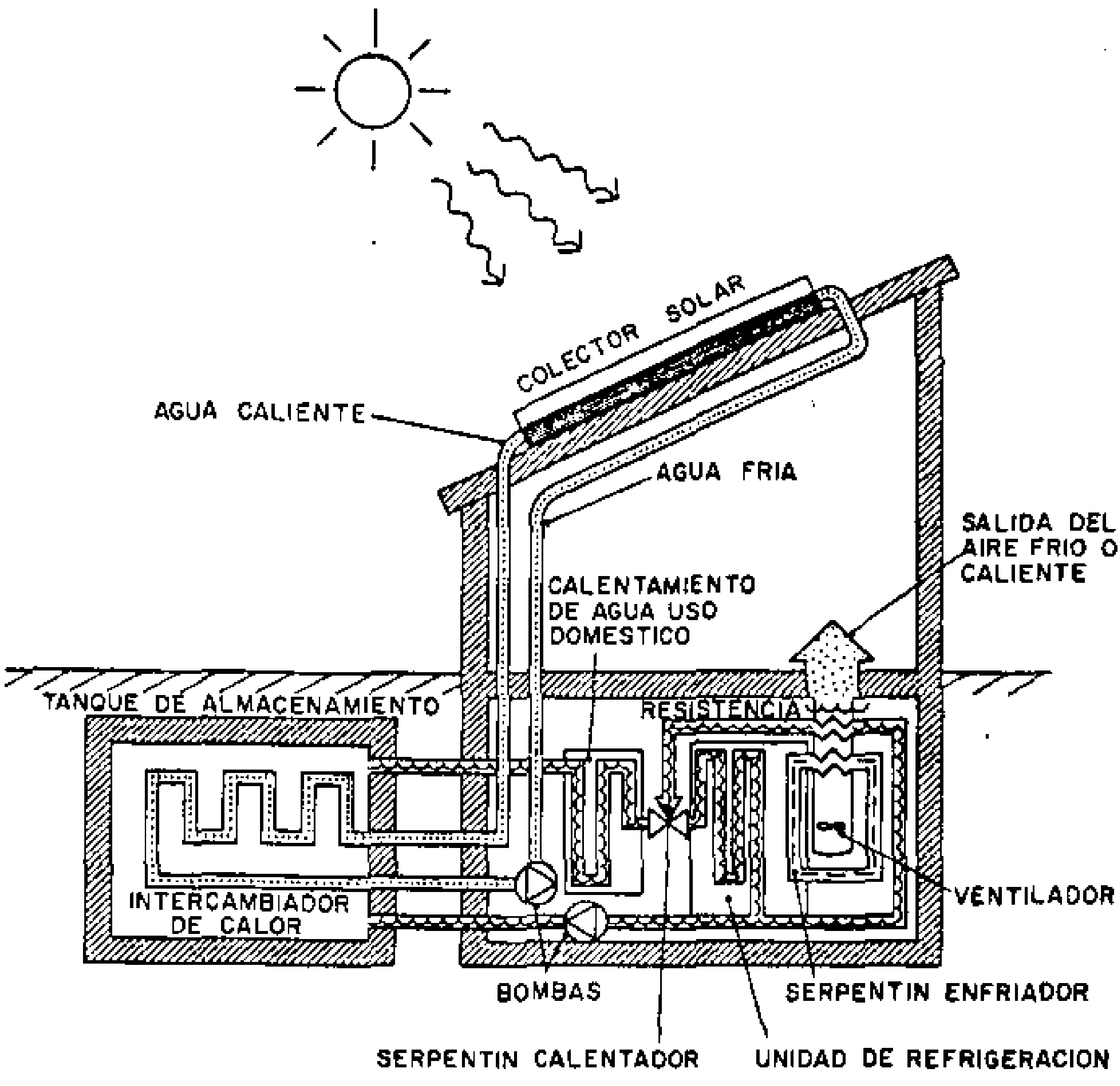


FIG. 19 SISTEMA ACTIVO DE ENFRIAMIENTO Y CALENTAMIENTO

calentamiento de agua para uso doméstico, calentamiento de albercas, lavado industrial, etc. se consideran como los más eficientes. Sin embargo aunque los líquidos pueden hacerse circular más eficientemente, pueden llegar a presentar problemas de corrosión, fugas y en lugares muy fríos pueden congelarse. Por su parte el aire no es corrosivo y no se congela, no provoca problemas cuando se fuga pero sin embargo los volúmenes de almacenamiento son mucho mayores y requieren también mayores areas de intercambio. Ocasionalmente el aire circulante llega a contaminarse con polvos y malos olores, cuando se descuida la limpieza del depósito y cuando llegan a proliferar microorganismos en los materiales porosos contenidos en él.

La figura 19 muestra un sistema activo de calentamiento y enfriamiento común

CONCLUSIONES GENERALES

Se ha mostrado la importancia de reenfocar el diseño arquitectónico de las construcciones hacia la finalidad original con que fueron diseñadas y que con -

siste en proporcionar abrigo y confort térmico a sus ocupantes. Resulta evidente que para lograr este propósito es indispensable reconsiderar, entre otros, los siguientes factores: conocimiento de las condiciones microclimaticas locales; propiedades térmicas de los materiales de construcción empleados; intercambios energeticos del ocupante con su medio ambiente (radiación, convección y conducción); aprovechamiento de las fuentes energéticas disponibles "in situ", principalmente la solar y la del viento.

Al analizar las características de intensidad y duración de la insolación en México puede constatarse que la energía solar disponible representa un recurso inmenso e inagotable, capaz de suministrar, en la medida que las posibilidaes tecnológicas de conersión lo permitan, ungran porcentaje de los requerimientos energéticos domésticos e industriales.

Se considera que mediante la conversión fototérmica de la energía solar es perfectamente factible abordar de inmediato los problemas de climatización de la vivienda (sobre todo en regiones inhóspitas) en función del estudio previo del tipo de clima regional y sistemas más compatibles con éste.

En la actualidad el calentamiento solar de agua representa la aplicación más común y rentable en nuestro país. Por su parte, el calentamiento de aire (más fácil de realizar) sólo tiene antecedentes respecto al secado de productos alimenticios y agrícolas; no siendo hasta la fecha utilizado en México para propósitos de climatización mediante termocirculación natural; por lo que, conviene empezar a explotar éste fenómeno a través de sistemas de climatización de tipo pasivo. Al respecto se recomienda el diseño de construcción aplicando conjuntamente los principios de termocirculación del aire y emisión de radiación infraroja los cuales se han ilustrado de manera simple y objetiva en este trabajo; sin olvidar que para su funcionamiento eficaz y utilidad práctica, es necesario hacer previamente las consideraciones y cálculos necesarios de los factores involucrados (capacidad técnica, orientación, transferencia de calor, insolación, etc) ya que de no hacerlo así, por simples que parezcan los principios de funcionamiento, se ha comprobado que el diseñador puede fracasar irremisiblemente en su intento logrando muchas veces el efecto de climatización contrario al deseado; o en el mejor de los casos, un funcionamiento deficiente.

Las características climatológicas de México y las condiciones económicas de la inmensa mayoría de su población, indican como solución más conveniente a problemas de climatización y aprovechamiento racional de la energía solar, el uso de sistemas pasivos cuyas ventajas económicas son indiscutibles. No obstante, en algunos casos particulares los sistemas activos pueden ser una solución económicamente factible dada su gran eficiencia.

BIBLIOGRAFIA

(1) Hernández, E., 1976, "The Seasonal Distribution of the Incoming Solar Radiation In Mexico", Proceedings of the "Sharing the Sun-Solar Technology", Amer. Section, Int. Solar Energy Society, Winnipeg,Canada Vol. 10.

(2) Hernández, E., Martínez R., 1977 "La Variación Anual en México de la Radiación Solar Directa sobre Planos Verticales Orientados hacia los Cuatro Puntos Cardinales", Publicación especial del Centro de Investigación de Materiales, UNAM

(3) Hernández, E., 1976, " On the Numerical Computation of Solar Radiation Para-Meters from Satellite Cloud Cover Data", Proceedings of the UNESCO/World Meteorological Organization- Solar Energy Symposium, Ginebra, Suiza.

(4) Martínez, R., 1977, "Análisis del Funcionamiento de un Calentador Solar de Agua a Circulación Natural", Tesis de de Licenciatura, Fac. de Química, UNAM.

(5) Regalado, E., 1977, "Diseño de un Captador de Energía Solar Fijo con Concentración", Tesis de Licenciatura, Facultad de Ciencias, UNAM.

(6) Hernández, E., 1977, "Las Coordenadas Horarias de la Trayectoria Diaria del Sol sobre el Horizonte y su Representación Polar en la República Mexicana", Publicación especial Centro de Inv. de Materiales, UNAM.

(7) Villalobos, L., 1975 "Tecnología contra Naturaleza Fondo de Cultura Económica, México, D F.

(8) Hernández E., Herrera, R., Alvarez, I. 1978 "Anticonvective Antiradiative Systems", Proceedings of the Intern. Solar Energy Congress, New Delhi, India.

(9) Hernández, E., Mayer., 1977 "Nocturnal Infrared Radiative Coolings Experiments in Mexico", Proceedings of the "Solar Building Technology", London Polytechnical Institute. London, England.

(10) Best, G., Best, R., Geffroy, E., 1978 "Refrigeración y Aire Acondicionado Solares en el CIM_UNAM", presentado en el Congreso Latinoamericano de Energía Solar, Joao Pessoa, Brasil.

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

LA VARIACION ANUAL EN MEXICO DE LA RADIACION SOLAR DIRECTA SOBRE PLANOS VERTICALES ORIENTADOS HACIA LOS CUATRO PUNTOS CARDINALES.

AGOSTO, 1979

C O N T E N I D O

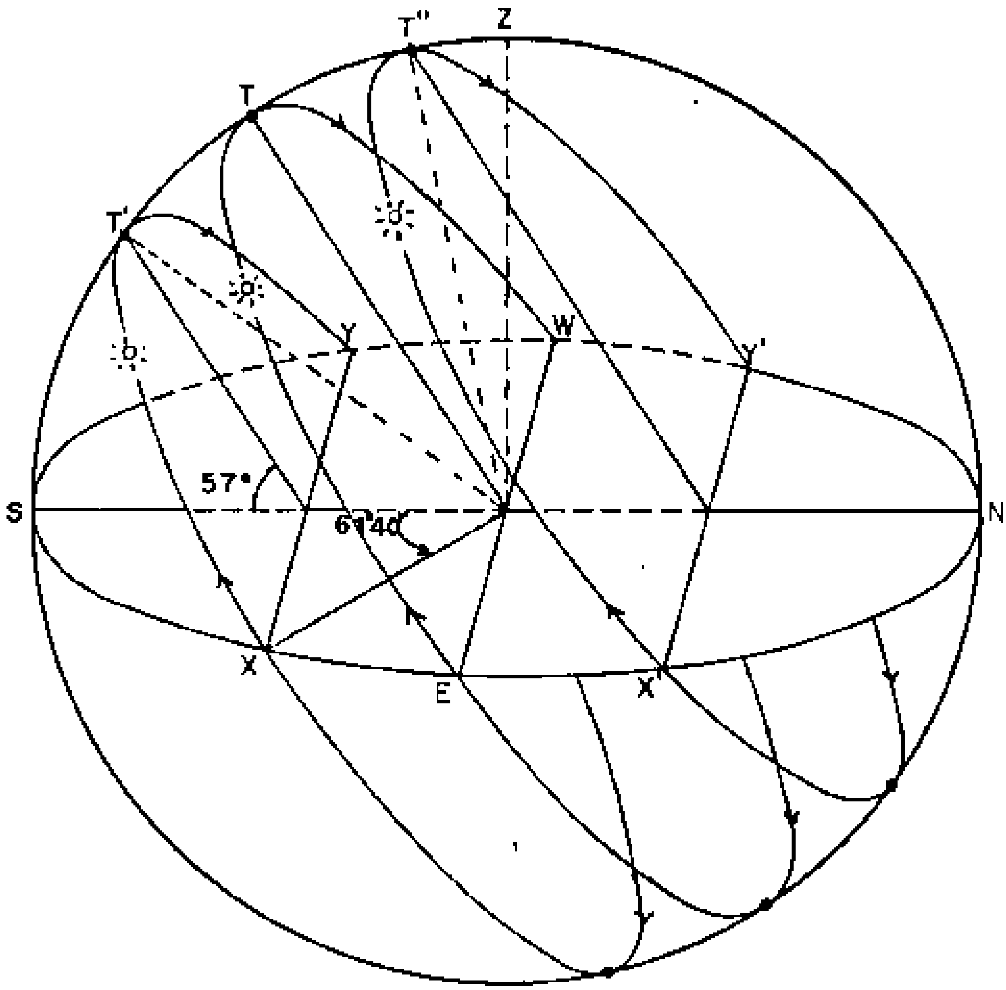

FIGURA.4 TRAYECTORIA DIARIA DEL SOL A LA LATITUD DE: ϕ=33°
EN DIFERENTES FECHAS: XT'Y - SOLSTICIO DE INVIERNO;
ETW - EQUINOCCIOS; X'T"Y' - SOLSTICIO DE VERANO.

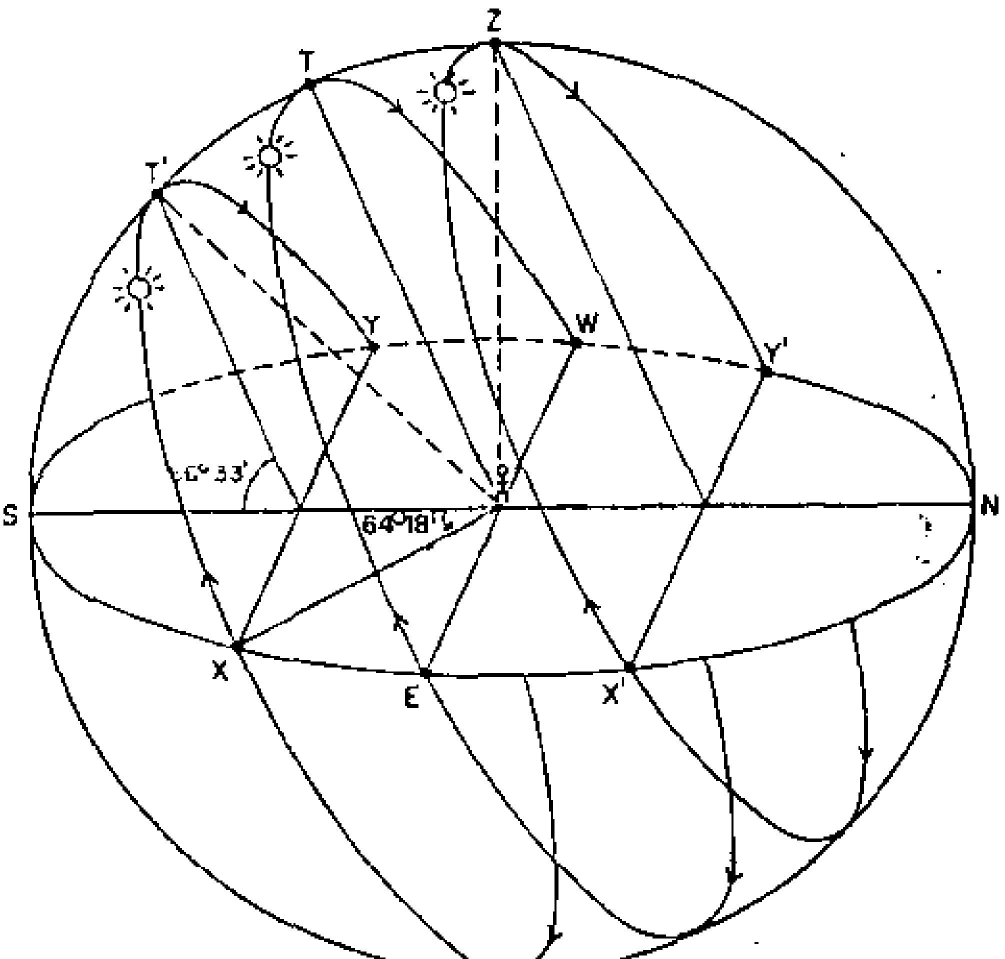

FIGURA 5 . TRAYECTORIA DIARIA DEL SOL A LA LATITUD DEL TROPICO DE CANCER (23°27') EN DIFERENTES FECHAS : XT'Y - SOLSTICIO DE INVIERNO; ETW - EQUINOXIOS; X'ZY' - SOLSTICIO DE VERANO.

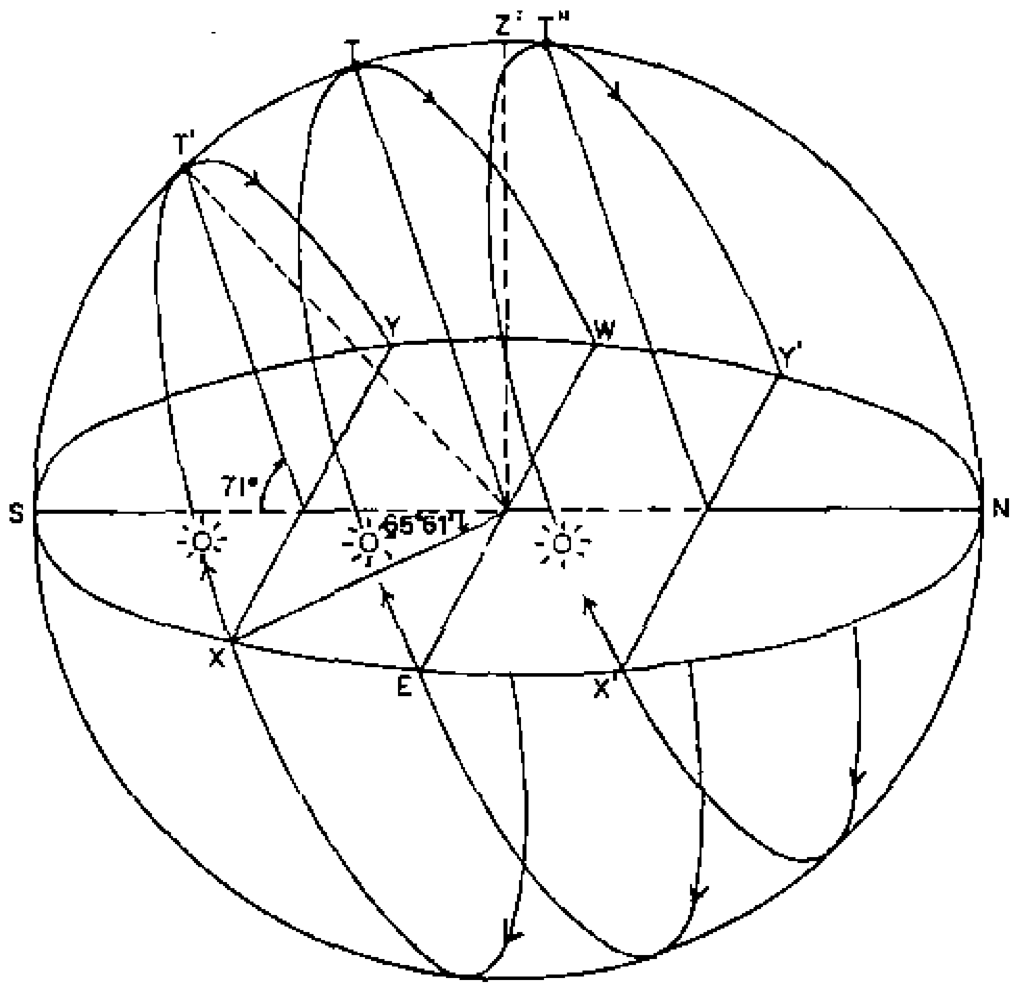

FIGURA.6 TRAYECTORIA DIARIA DEL SOL A LA LATITUD DE:Ø=19°
EN DIFERENTES FECHAS: XT'Y - SOLSTICIO DE INVIERNO;
ETW - EQUINOCCIOS; X'T"Y' - SOLSTICIO DE VERANO.

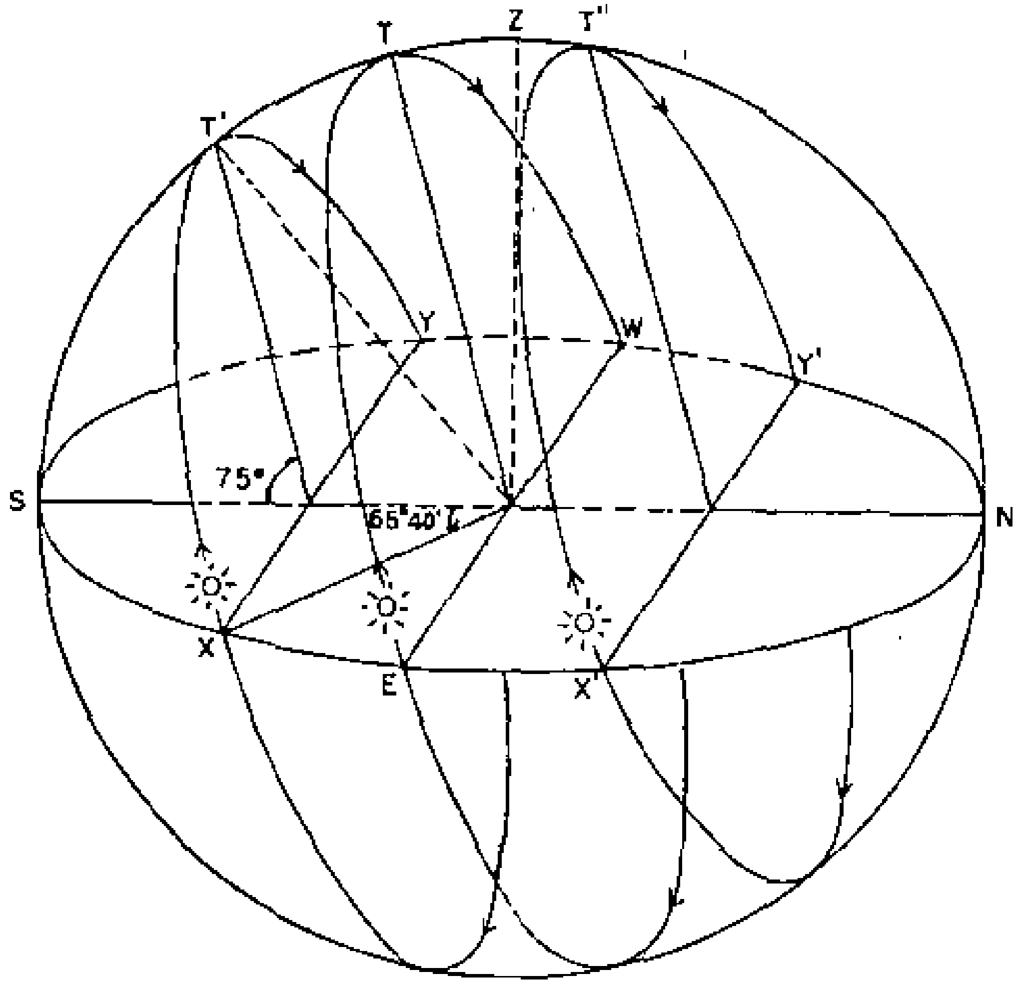

FIGURA.7 TRAYECTORIA DIARIA DEL SOL A LA LATITUD DE: Ø=15° EN DIFERENTES FECHAS: XT'Y - SOLSTICIO DE INVIERNO; ETW - EQUINOCCIOS; X'T"Y' - SOLSTICIO DE VERANO.

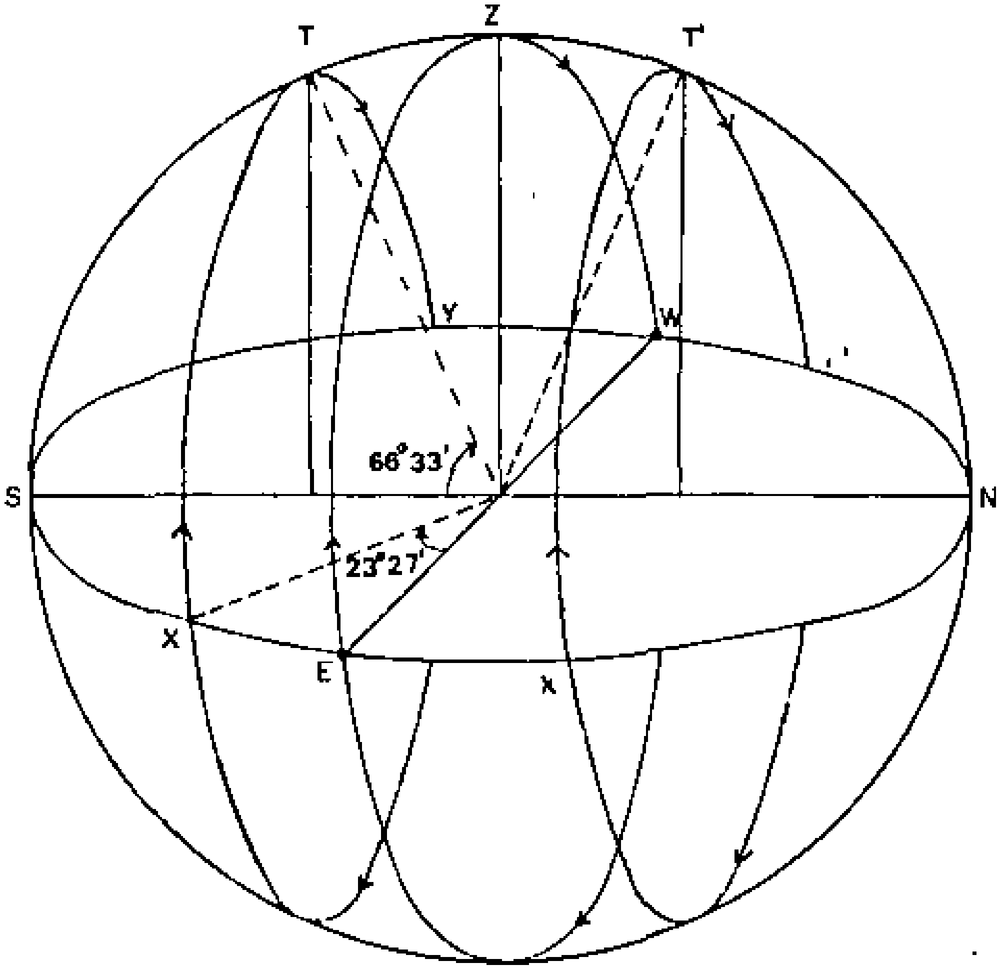

FIGURA.6 TRAYECTORIA DIARIA DEL SOL A LA LATITUD DE:ϕ:0° (ECUADOR) EN DIFERENTES FECHAS: XT Y - SOLSTICIO DE INVIERNO; EZW - EQUINOCCIOS; X'T'Y' - SOLSTICIO DE VERANO.

En general, para cualquier latitud y época del año, el ángulo i siempre equivale a 90° menos el ángulo de la latitud del lugar.

$$i = 90° - \phi \qquad (1)$$

Así, para el trópico de cáncer (ϕ = 23°27'), el ángulo de inclinación será de 66° 33' .

Además, como la altura del sol al medio día verdadero h_m, en cualquier latitud equivale a 90° menos el ángulo que forma el arco meridiano entre el lugar y el paralelo donde en esa fecha los rayos solares inciden verticalmente (ó sea a la latitud ϕ igual a la declinación solar δ de ese día), se tiene que como:

$$h = 90° - (\phi - \delta) \qquad (2)$$

en el trópico de Cáncer el sol sólo se encontrará en el cenit una vez al año, es decir, cuando $\phi = \delta = 23°27'$ Más al norte de esta latitud obviamente el sol nunca alcanza una posición cenital.

Como consecuencia de la Ecuación (1), se tiene que conforme se reduce la latitud geográfica, aumenta la inclinación de las trayectorias diarias solares hasta hacerse verticales en el Ecuador Figura (8).

III. CARACTERISTICAS DE LA RADIACION SOLAR A INCIDENCIA NORMAL.

Refiriéndonos a la Figura (9), sea In, la energía recibida por unidad de tiempo sobre una superficie uni

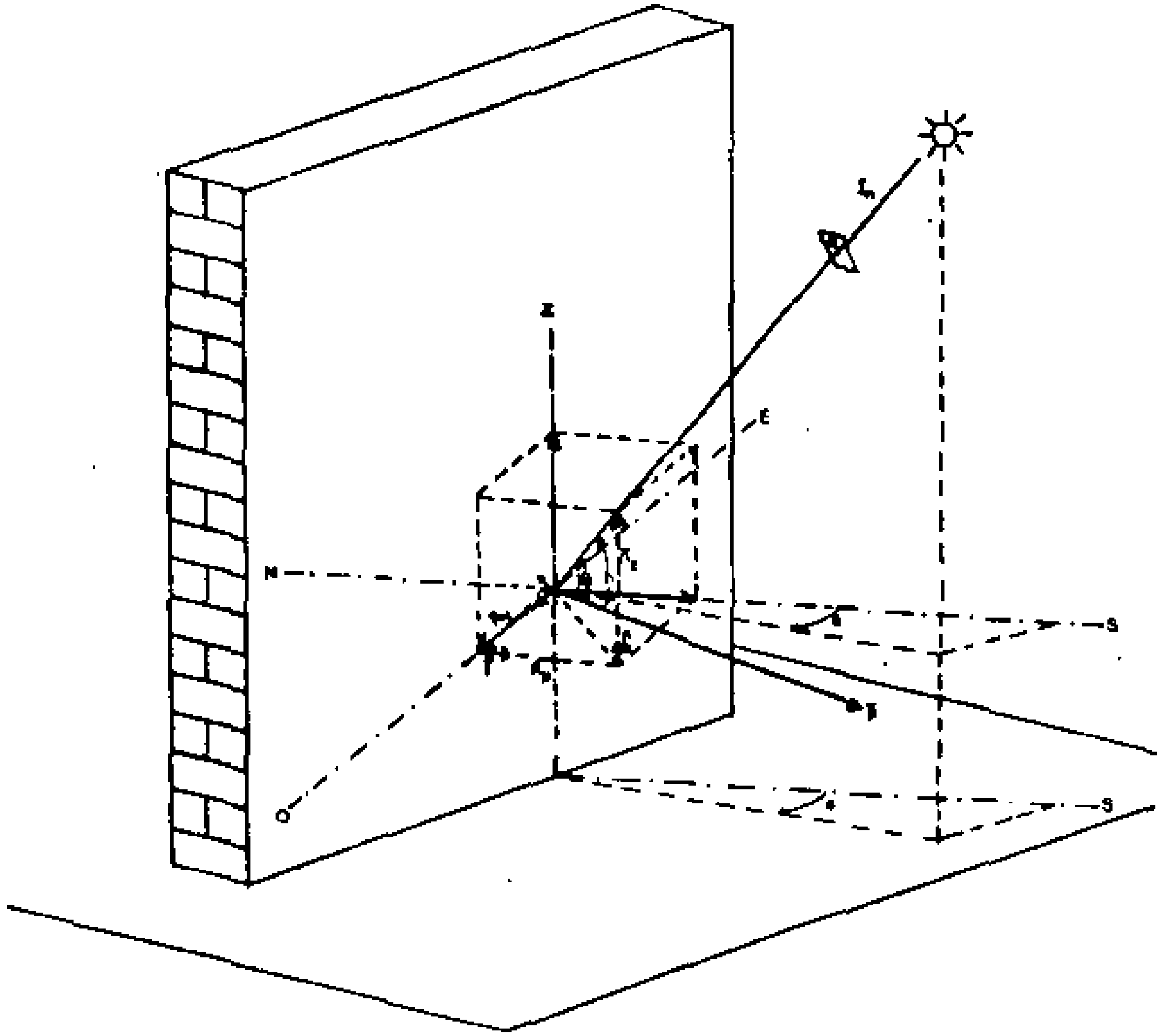

FIGURA 9 . DIAGRAMA QUE MUESTRA LAS COMPONENTES DE LA RADIACION SOLAR DIRECTA A INCIDENCIA NORMAL I_n Y LA NORMAL A LA PARED $\overline{p}$.

taria a expuesta perpendicularmente a la dirección de incidencia de la radiación solar proveniente directamente del disco solar, y sea θ el ángulo comprendido entre la dirección de incidencia en un instante dado y la normal $(\bar{p})$ a la pared receptora. En tales circunstancias, la energía recibida sobre esta última será:

$$I_p = I_n \cos \theta \qquad (3)$$

Si $\bar{n}$ y $\bar{p}$ representan los vectores unitarios en las direcciones de I_n y la normal a la pared, entonces:

$$\bar{I}_n = n_x\hat{i} + n_y \hat{j} + n_z\hat{k} \qquad (4)$$

y $$\bar{p} = p_x \hat{i} + p_y \hat{j} + p_z\hat{k} \qquad (5)$$

El producto escalar entre $\bar{I}_n$ y $\bar{p}$, será:

$$\bar{I}_n \cdot \bar{p} = n_x p_x + n_y p_y + n_z p_z = \cos \theta \qquad (6)$$

De la expresión (3) y observando nuevamente la Figura (9), se tienen las siguientes relaciones:

$$n_x \hat{i} = (\cos h \cos a)\ \hat{i}$$
$$n_y \hat{j} = (\cos h \operatorname{sen} a)\ \hat{j}$$
$$n_z \hat{k} = (\operatorname{sen} h)\ \hat{k} \qquad (7)$$

Por lo que la energía recibida por unidad de tiempo sobre un elemento de superficie s' de la pared será:

$$I_p = I_n (n_x \cosh \cos a + n_y \cos h \operatorname{sen} a + n_z \operatorname{senh}) \quad (8)$$

Para calcular la cantidad total de energía Q, re cibida durante un cierto intervalo de tiempo $\Delta\tau$, la Ecuación (8) puede ser integrada expresándola previamente en función del tiempo al través del ángulo horario solar ω. Esto se logra refiriéndonos a los ángulos de la altura solar h y el acimut a, transportados a la esfera celeste de la Figura (10) {4}. De trigonometría esférica {5}, se tiene:

$$h = \text{sen}^{-1} (\text{sen}\,\phi\ \text{sen}\,\delta + \cos\phi\ \cos\delta\ \cos\omega) \quad (9)$$

$$h = \cos^{-1} \left(\frac{\text{sen}\phi\ \cos\delta\ \cos\omega - \text{sen}\delta\ \cos\phi}{\cos a}\right) \quad (10)$$

$$\text{y} \quad h = \cos^{-1} \left(\frac{\text{sen}\,\omega\ \ \cos\delta}{\text{sen}\,a} \right) \quad (11)$$

En consecuencia Q se puede expresar como:

$$Q = \int_{\omega^1}^{\omega^2} I_n \{n_x(\text{sen}\phi\ \cos\delta\ \cos\omega - \text{sen}\delta\ \cos\phi) + n_y (\text{sen}\omega\ \cos\delta) + n_z\ (\text{sen}\phi\ \text{sen}\delta + \cos\phi\ \cos\delta\ \cos\omega)\}\ d\omega \quad (12)$$

La variación de I_n en el transcurso del día depende de factores astronómicos, geométricos y atmosféricos.

Entre los astronómicos se encuentra la constante solar I_0, definida como la intensidad media del flujo de radiación solar extraterrestre {6} (Figura 11) en el límite superior de la atmósfera sobre una superficie plana unitaria orientada normalmente a la dirección de los rayos solares y a la distancia media tierra-sol.

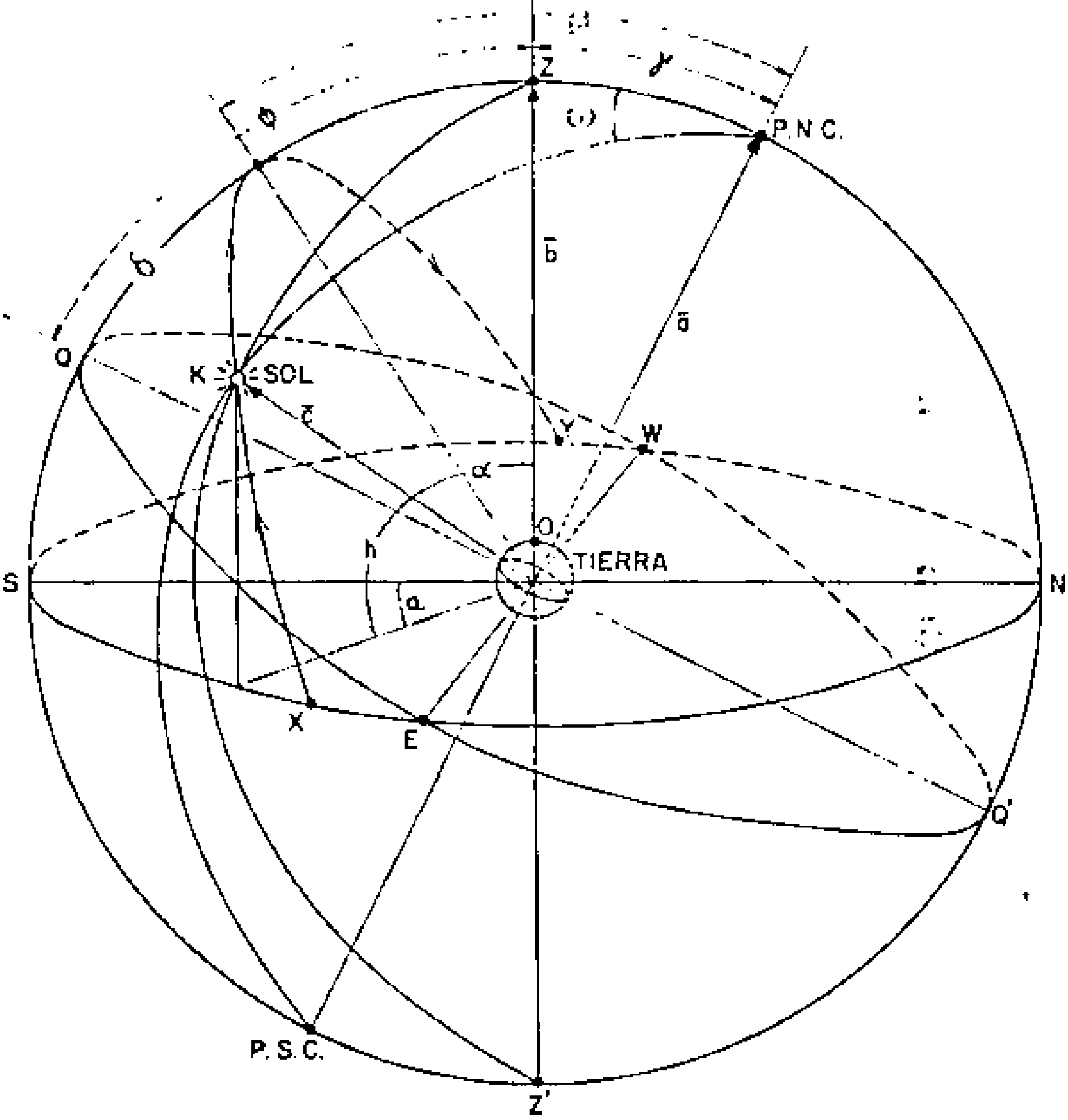

FIG.10.- TRAYECTORIA DIARIA DEL SOL PROYECTADA EN LA ESFERA CELESTE Y VISTA POR UN OBSERVADOR SITUADO EN O A LA LATITUD GEOGRAFICA Φ.

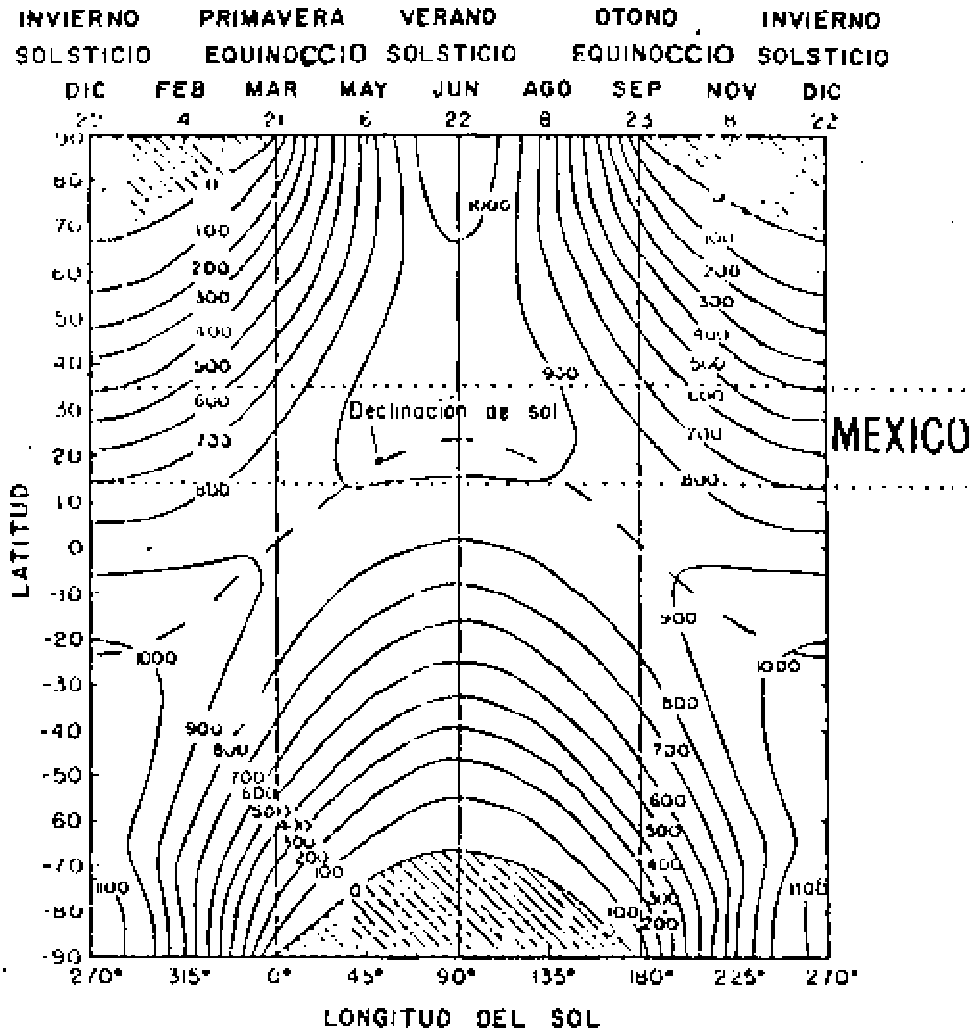

FIGURA 11. DISTRIBUCION DE LA RADIACION SOLAR EXTRATERRESTRE (cal. cm^{-2}. $día^{-1}$)

El valor más aceptado actualmente de la constante solar, es el obtenido inicialmente por Johnson {7} y verificado posteriormente por Drummond y Thekaekara {8}, que es:

$$I_o = 1.94 \text{ cal. cm}^{-2} \text{ min}^{-1} = 1353 \text{ watt m}^{-2}$$

Debido a la naturaleza elíptica de la órbita de translación terrestre, la variación de la distancia tierra-sol, produce una fluctuación de I_o de un $\pm 3.5\%$ anual. Además las irregularidades del ciclo de actividad solar (11 años) alteran el valor de I_o en un 1.5 ó 2%.

El valor de I_o se obtiene al integrar el área bajo la curva de la distribución espectral de la irradiación solar dentro del intervalo de longitudes de onda del espectro solar, que practicamente puede considerarse comprendido entre 0.2μ y 5μ. Figura (12) {9}, por lo que puede expresarse:

$$I_o = \int_o^{\infty} I_{o\lambda}\, d\lambda \approx \int_{0.2\mu}^{5\mu} I_{o\lambda}\, d\lambda \qquad (13)$$

donde $I_{o\lambda}$ es la irradiancia espectral (watt $m^{-2}\mu^{-1}$)

El factor geométrico más relevante que interviene en el valor de I_n, es la algura solar h. También influye la altitud del lugar ya que a mayor altitud, menor es el camino óptico que recorre la radiación solar en su trayecto atmosférico.

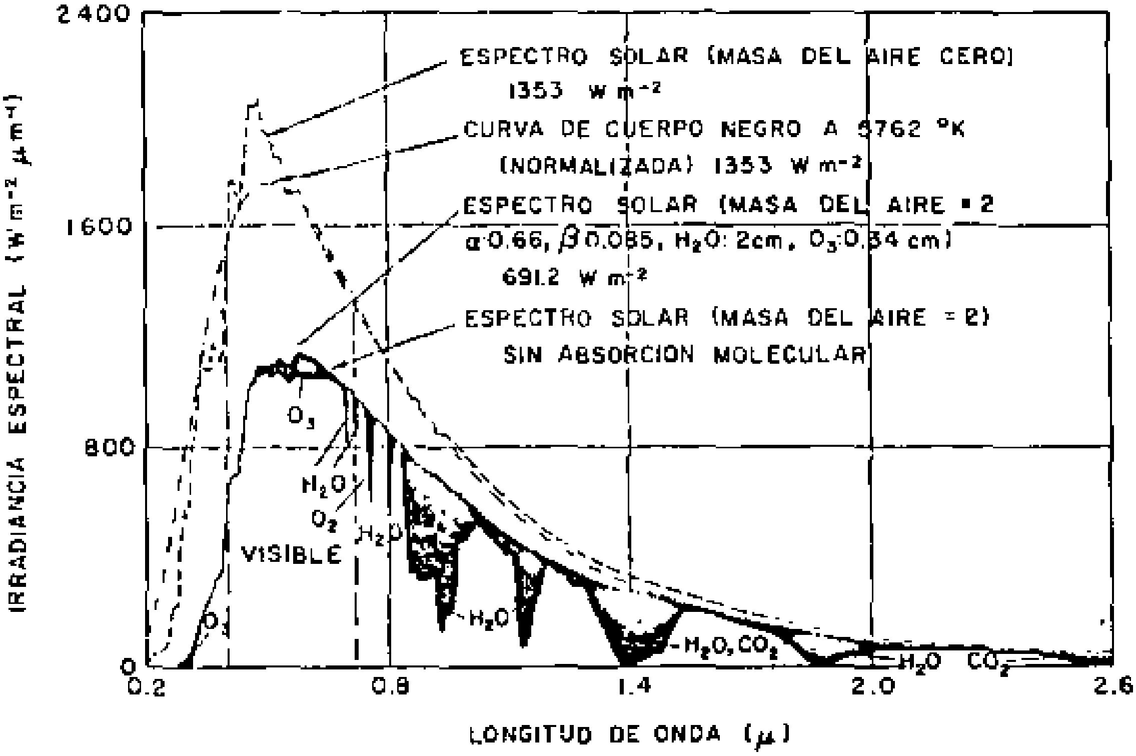

FIGURA 12. CURVA DE IRRADIANCIA ESPECTRAL DEL SOL [15]

Finalmente, debido a las variaciones del espesor de la película atmosférica, así como a la fluctuante concentración de los principales constituyentes atmosféricos reguladores ó nó del clima, fenómenos tales como la dispersión (molecular del aire, vapor de H_2O y aerosoles), absorción (del ozono en el ultravioleta y del vapor de H_2O en el infrarrojo y del CO_2)yla reflexión, atenúan en mayor o menor grado, la intensidad de la radiación solar que finalmente alcanza el suelo, ya sea en forma directa (a lo largo del haz proveniente directamente del disco solar) ó difusa (dispersada hacia abajo principalmente por las nubes).

La radiación solar directa normal puede medirse mediante un pirheliómetro, dispositivo que consta de una fotorresistencia o termopila como elemento sensor, y el cual aunque no puede discriminar irradiancias espectrales específicas, si en cambio es sensible a la irradiancia global de todo el espectro solar que alcanza a llegar a nivel de la tropósfera y que comprende longitudes de onda entre las 0.29μ y 2.5μ.

La atenuación que sufre la radiación solar directa normal en una atmósfera seca y limpia, puede considerarse pequeña, ya que en este caso, sólo habría que tomar en consideración la dispersión molecular de Rayleigh. En contraste, en atmósferas húmedas ó contaminadas, el vapor de agua, polvo y aerosoles contribuyen notablemente al fenómeno global de atenuación.

Estudios basados en las formulaciones de Ångström {10}, muestran que la radiación directa normal I_n, puede expresarse analíticamente mediante la siguiente expresión, que comprende teóricamente a todo el espectro.

$$I_n = \left(\frac{R_o}{R}\right)^2 \int_0^{\infty} I_{o\lambda}\, 10^{-\{m\sigma_\lambda + m_r\sigma_{\lambda d} + m_r\sigma_{\lambda o} + f(\omega, m_r)\}} d\lambda$$

donde:

R_o/R: es el factor de corrección de la distancia tierra-sol en la fecha considerada.

$I_{o\lambda}$: es la irradiancia espectral.

σ_λ: es el coeficiente de extinción por dispersión molecular de Rayleigh. Se tiene que la atenuación por dispersión del haz de radiación incidente es función de la densidad molecular, por lo cual satisface las leyes de la transmisión; es decir, si $I_{o\lambda}$ es el flujo de la radiación entrante, e I_λ es el flujo saliente después de haber atravesado un trayecto de longitud 1 dentro del medio difusor, se tiene que:

$$I_\lambda = I_{o\lambda}\, 10^{-\sigma_\lambda l}$$

donde σ_λ es el coeficiente decimal de extinción por unidad de longitud. Al producto $\sigma_\lambda l$ comunmente se le llama densidad óptica ó factor de extinción. Resultados empíricos (11) muestran que σ_λ puede expresarse como:

$$\sigma_\lambda = 0.00386\ \lambda^{-4.05} \qquad (16)$$

en donde se incluye la corrección al efecto debido a la anisotropía molecular del aire.

$\sigma_{\lambda d}$ es el coeficiente de extinción por la dispersión que causan los aerosoles y que según Schüepp {17}, puede expresarse como:

$$\sigma_{\lambda d} = B \quad (2\lambda)^{-\alpha} \qquad (17)$$

donde B es el factor de turbidez atmosférica de Schüepp y α tiene una magnitud de 1.5 en la región espectral: $0.30\mu < \lambda < 3.00\mu$. Moon {13} encontró que para polvos el coeficiente de extinción es similar al molecular del aire, tal que para m=1 y una concentración de partículas al nivel del suelo de $800/cm^3$:

$$\sigma_{\lambda d} = 0.0353\lambda^{-0.75} \qquad (18)$$

$\sigma_{\lambda o}$: es el coeficiente de extinción promedio debido a absorción selectiva del ozono en la región espectral: $0.28\mu < \lambda < 0.64\mu$ (bandas de Hartley-Huggins y Chappuis). El ozono se encuentra concentrado principalmente entre los 20 y 35 Km. (depende de ϕ y de la época del año) aunque puede encontrársele hasta los 70 Km. El espesor reducido de la capa de ozono fluctúa entre 0.1 cm. y 0.6 cm.

$f(\omega, m_r)$: es el factor de absorción selectiva del vapor de H_2O para todo el espectro de la radiación solar. Debido a que no ha sido posible expresarlo explícitamente, comunmente se recurre a la corrección empírica de Mügge-Möller aplicada a la fórmula de Fowle {14}, la cual es:

$$f(\omega, m_r) = 0.172 \ (\omega, \ m_r)^{0.3028} \qquad (19)$$

donde:

m : es la masa real del aire.

m_r : es la masa relativa del aire.

El grado de contaminación del aire se acostumbra representar mediante los llamados coeficientes de turbidez atmosférica de Ångström α y β, los cuales dependen de los aerosoles existentes en la masa atmosférica considerada. La expresión:

$$I_\lambda = I_{o\lambda} \, e^{-c_\lambda m} \qquad (20)$$

donde $c_\lambda = \beta / \lambda^\alpha$, expresa el fenómeno de atenuación por turbidez. Todas aquellas partículas suspendidas en la atmósfera en interface líquida ó sólida (polvos, gotitas, etc.) pueden considerarse aerosoles.

Si las dimensiones de los aerosoles son lo suficientemente grandes comparados con las longitudes de onda de la radiación solar incidente, se tiene que la absorción por difusión es prácticamente independiente de λ (absorción neutra que sería proporcional a $\lambda^{0.0}$). En el caso contrario, ó sea cuando el tamaño de las partículas difusoras es mucho mayor que λ, se tiene que la difusión molecular del aire (puro) es proporcional a $\lambda^{-4.05}$. Así el exponente α de λ, puede variar (entre 0 y -4.5) según el tamaño de los aerosoles. Se ha encontrado que efectivamente α fluctúa entre -0.5 y -2.5 y que bajo condiciones ideales de cielo no contaminado y completamente despejado, α puede aproximarse a -1.3 . Este valor es el que generalmente se escoge al calcular las irradiancias espectrales bajo condiciones atmosféricas óptimas al nivel del mar y para distintos valores de la masa at mosférica, Figuras (13) {15}, (14) {15}, y (15) {16}. El coeficiente de turbidez atmosférica β, se define como la cantidad de aerosoles (de 10^2 a $10^5/cm^3$) al nivel del suelo, que pueden encontrarse dentro de la masa atmosférica unitaria a la vertical del observador. Los valores de β generalmente varían entre 0.05 y 2.0, encontrándose que disminuye sensiblemente con la altitud y aumenta en atmósferas contaminadas como las urbanas e industriales.

A una cierta altura solar h, el camino óptico de la radiación solar en su trayecto atmosférico, dependerá del espesor de la capa de aire. Este espesor tomado respecto al suelo, puede medirse en base a un camino óptico unitario. Como referencia se toma el espesor atmosférico que corresponde al de una atmósfera homogénea, es decir, aquella cuya densidad ρ es constante independientemente de la altitud z.

$$\rho = \rho_o = \text{constante} \qquad (21)$$

ρ_o representa la densidad del aire a nivel del suelo, z = o. En tales condiciones la fórmula barométrica puede expresarse como:

$$p = p_o - \rho_o gz \qquad (22)$$

por lo que la presión disminuye linealmente con la altitud hasta hacerse nula a un nivel H, ó sea:

$$p_o - \rho_o gH = o \qquad (23)$$

por lo que la altura de la atmósfera homogénea viene a ser:

$$H = \frac{p_o}{\rho_o g} \qquad (24)$$

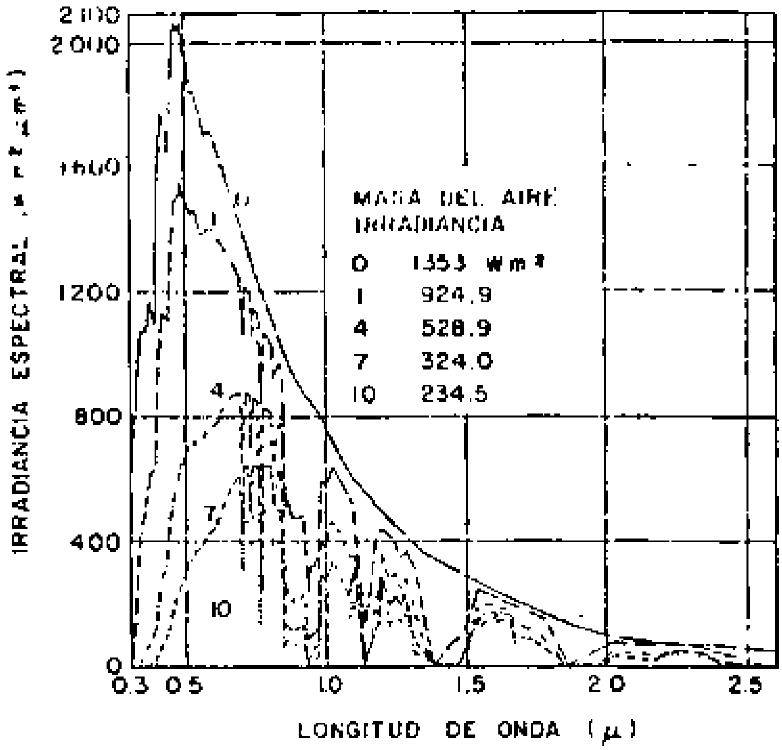

FIGURA 13. IRRADIANCIA SOLAR PARA DIFERENTES MASAS DEL AIRE (ATMOSFERA STANDARD) [15]

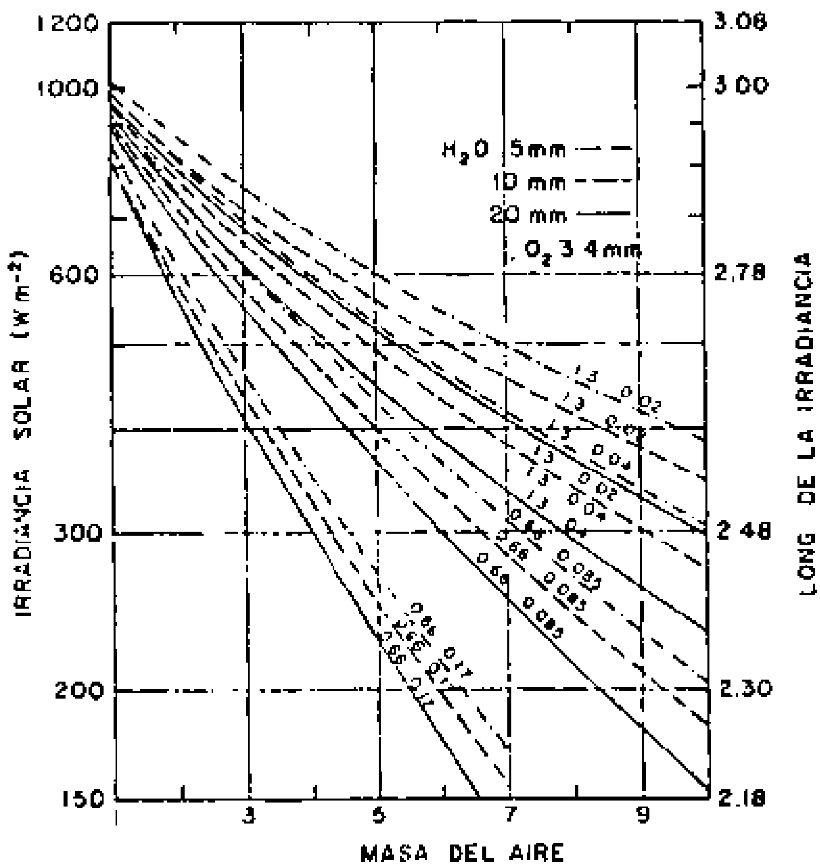

FIGURA 14. GRAFICA SEMILOGARITMICA DE LA IRRADIACION ESPECTRAL VS. MASA DEL AIRE. [15]

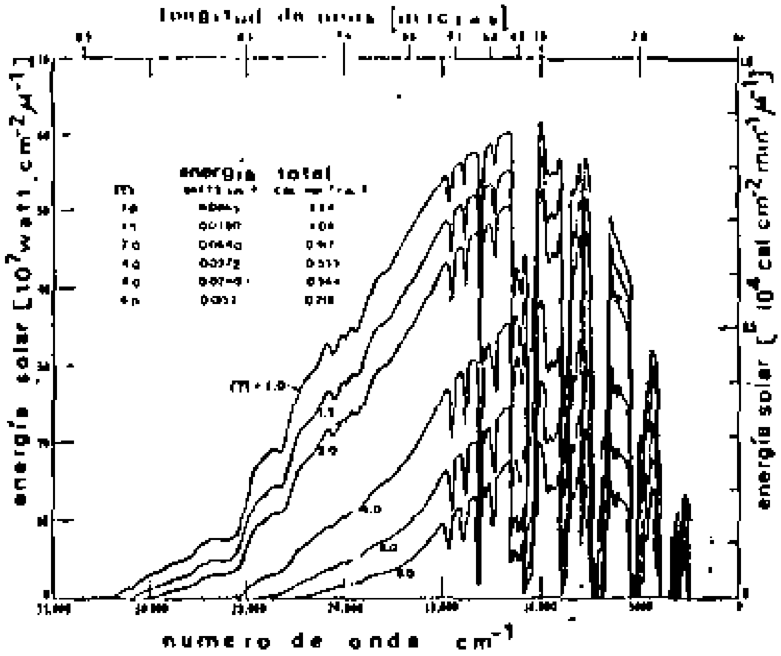

Fig. 15a. Distribución espectral en función de la longitud de onda (frecuencia) de la radiación solar directa incidente a nivel del mar sobre una superficie perpendicular a los rayos solares (I_n) para varias trayectorias de masa del aire (1.0 a 8.0). Características: H_2O: 10 mm, aerosoles: 200 $\frac{\text{partículas}}{cm^3}$; O_3: 0.35 cm.[16]

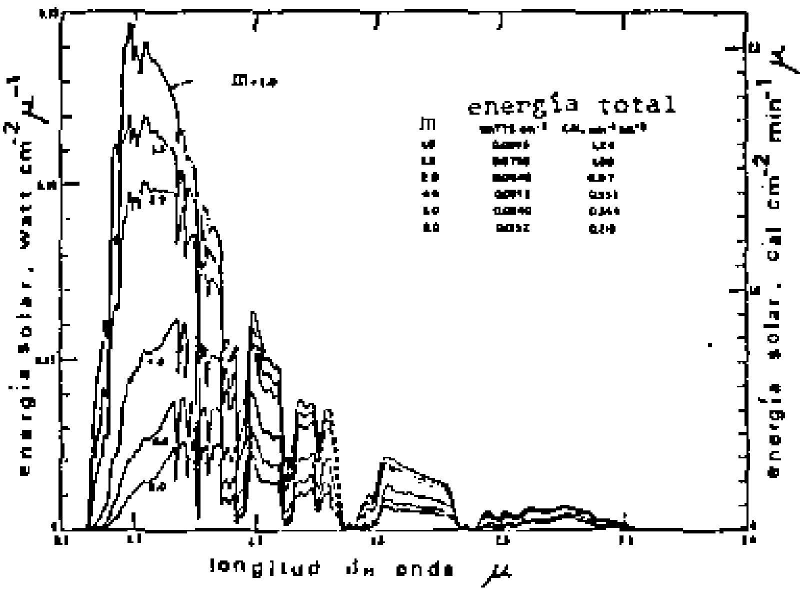

Fig. 15b. Distribución espectral en función de la longitud de onda de la radiación solar directa a incidencia normal (a nivel del mar) para varios valores de la masa atmosférica. (1 a 8). H_2O: 10 mm.; O_3: 0.35 cm; aerosoles: 200 partículas/cm^3 [16]

considerando además la ecuación de estado para el aire seco, se tiene que:

$$p_o = R_s \rho_o T_o \qquad (25)$$

donde R_s es la constante específica de los gases que corresponde al aire seco ($R_s = 287\ m^2\ seg^{-2}\ °K^{-1}$) y T_o es la temperatura del aire en z=o. Por lo tanto la Ecuación (24) viene a ser:

$$H = \frac{R_s\ T_o}{g} \qquad (26)$$

o sea que H sólo depende de la temperatura del aire a nivel del suelo. Si $T_o = 273°K$, entonces H_o se aproxima a los 8000 metros.

Puesto que la condición de homogeneidad (ρ = cte.) implica una disminución de la presión con la altura, esta atmósfera ficticia puede estratificarse en planos paralelos al través de los cuales el trayecto de la radiación solar es rectilíneo, ya que como puede verse en la Figura (16), a grandes altitudes, el segmento $\overline{PQ}$ puede aproximarse a una recta y en consecuencia $\overline{PQ}$ resulta perpendicular a $\overline{OQ}$, de ésta manera, se obtiene un triángulo rectángulo cuya hipotenusa representa el trayecto rectilíneo de la radiación solar. En tales condiciones, se tiene que:

$$\text{sen } h = \frac{\overline{OQ}}{\overline{OP}} \qquad (27)$$

por lo que el camino óptico $\overline{OP}$ resulta ser inversamente proporcional al seno de la altura solar h:

$$C.O. = \overline{OP} = \frac{\overline{OQ}}{\text{sen } h} \qquad (28)$$

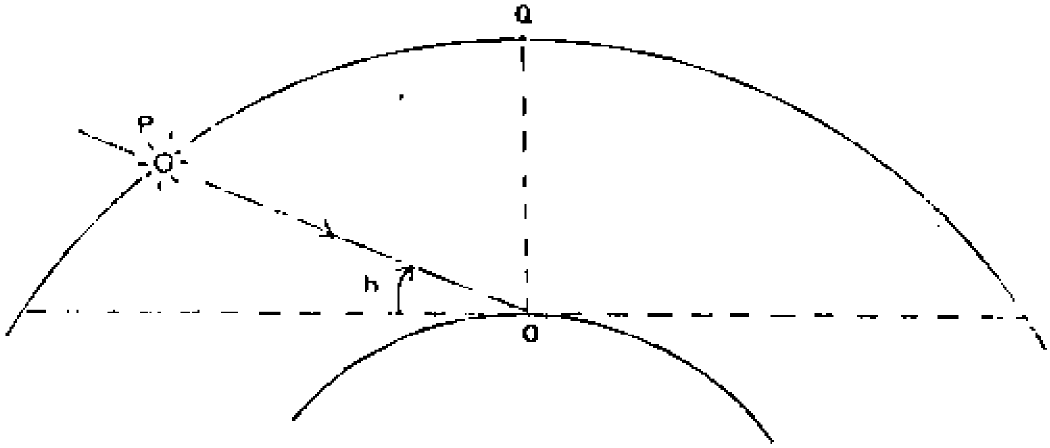

Fig. 10. Para grandes altitudes y considerando al triángulo PQO el sol se sitúa en ángulo recto, ∡ PQO. En tales condiciones el arco PQ puede ser reemplazado con suficiente aproximación por una recta obteniéndose consecuentemente la relación: $\csc h = \frac{\overline{OP}}{\overline{OQ}}$

En términos de masa, la integral:

$$m_h = \int_0^P \rho \, dl \qquad (29)$$

representa la masa atmosférica de la columna de aire inclinada $\overline{OP}$ a un ángulo h. Si m_o representa la masa atmosférica de la columna de aire de la vertical al punto O, se tiene que para una atmósfera homogénea en la que se desprecia el efecto de la refracción del aire:

$$m_r = \frac{m_h}{m_o} = \frac{1}{\text{sen } h} = \text{csc} h \qquad (30)$$

m_r representa la llamada masa del aire relativa ó simplemente masa del aire, la cual es inversamente proporcional al seno de la altura solar. La interpretación física de m_r corresponde al número de atmósferas entre el observador y el sol, tal que m_r= 1 para h=90º m_r=2 para h=30ºetc.

Debido a la refracción atmosférica y a la curvatura de la tierra, la expresión (30) no se satisface con un buen grado de aproximación cuando h es pequeña (h < 15º). En una atmósfera real y caracterizada por un índice de refracción n (que depende de ρ y de λ) y en la cual la densidad del aire disminuye con la altura, puede aplicarse la ley de refracción usada en Astronomía y que Linke {17} expresa como:

$$m_r = \frac{\int_0^{\infty} \rho \left[1 - \left(\frac{R}{R+Z} \; \frac{n_o\lambda}{n\rho\lambda} \right)^2 \cos^2 h \right]^{-1/2} dh}{\rho_o \; H} \qquad (31)$$

donde n_o = 1.00029. Sin embargo, puesto que n depende de ρ y de λ, la integral es difícil de calcularla con exactitud. Es por esto que los valores más aceptados de m_r son los que obtuvo Bemporad {18} mediante radiosondeos atmosféricos, y que son lo suficientemente precisos hasta en 5% para $h = 1°$ (para el sol al horizonte $m_r \approx 34$). La Tabla I muestra la diferencia entre los valores de la expresión (30) y los de Bemporad.

Debido a la reducción de la masa atmosférica con la altitud, la presión atmosférica varía notablemente sobre todo en lugares altos y que es el caso del Altiplano Mexicano ($z > 1000$ m). En tales condiciones, se aplica el factor de corrección altimétrica (expresado en términos del cociente de las presiones a la altitud z y al nivel de 1000 mb·). Así, se obtiene la llamada masa real del aire m verdadera (también llamada masa absoluta).

$$m = \frac{p}{p_o} m_r = \frac{p}{p_o} \csc h \qquad (32)$$

La gráfica de la Figura (17), muestra la variación del factor de corrección altimétrica en función de la altitud z.

Con el objeto de analizar la variación de la radiación directa a incidencia normal I_n con la altura solar h a diferentes horas del día, en las Figuras de la (18) a la (25), se muestran las curvas correspondientes tomadas de varias fuentes {19}, {20}, {21}, {22}, {23} y {24}.

El contorno de las curvas puede explicarse si consideramos que tanto el flujo de radiación solar como

TABLA I

Masa Relativa del Aire m_r									
Altura Solar h	90°	60°	30°	20°	10°	5°	2°	1°	[illegible]
m_r (Bemporad)	1.0	1.154	1.995	2.904	5.60	10.40	19.8	27.0	[illegible]
m_r (Link)	1.0	1.154	1.995	2.904	5.60	10.50	20.1	27.5	--
m_r,w(Schnaidt)	1.0	1.155	1.998	2.917	5.71	11.11	24.5	35.6	7[illegible]
csc h	1.0	1.155	2.000	2.924	5.76	11.47	26.7	57.3	∞
m_r(para Z=25 Km)	1.0	1.153	1.975	2.835	5.11	7.92	10.2	10.72	[illegible]

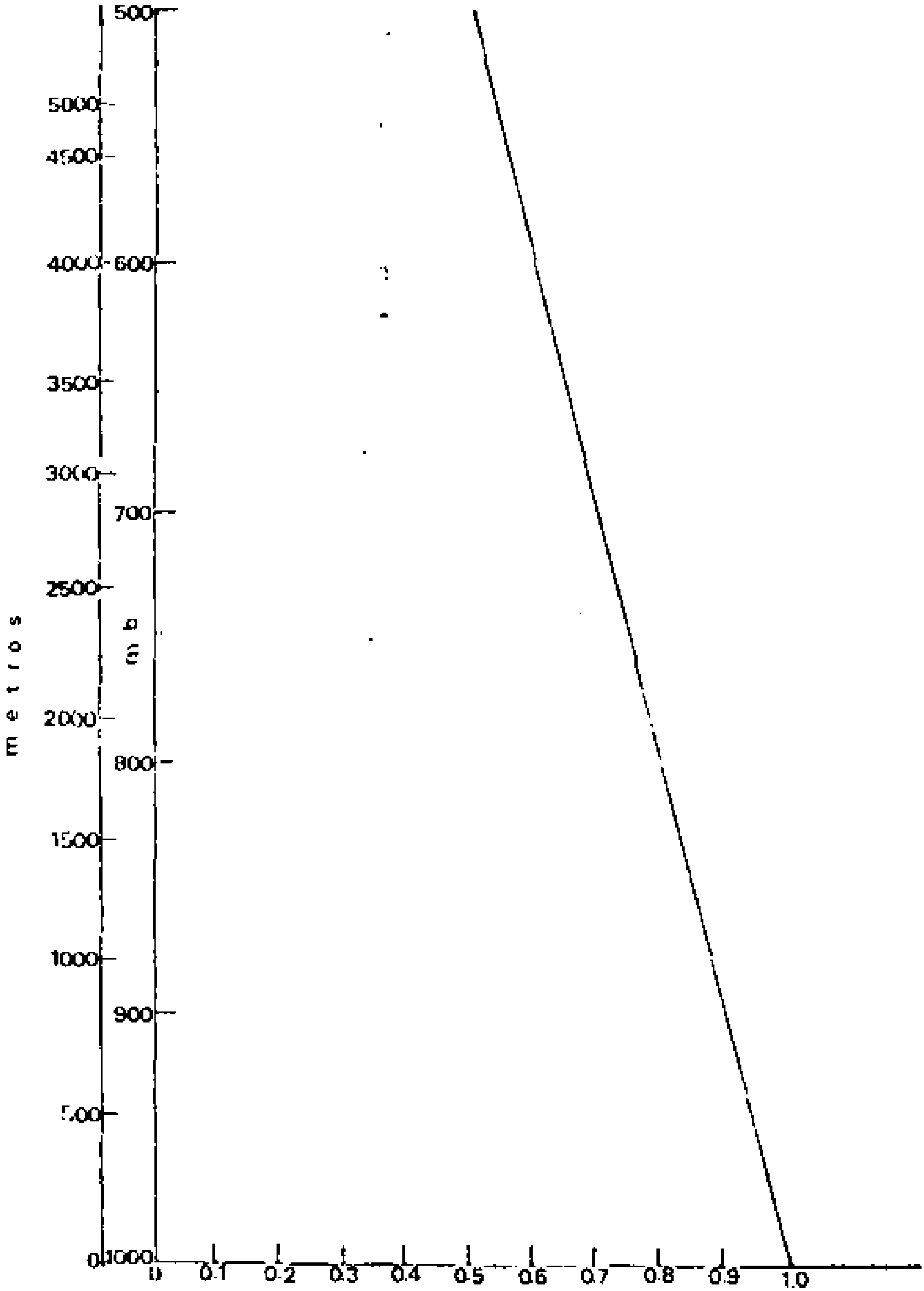

Fig. 17. Gráfica de la variación del factor de corrección altimétrica de la masa atmosférica.

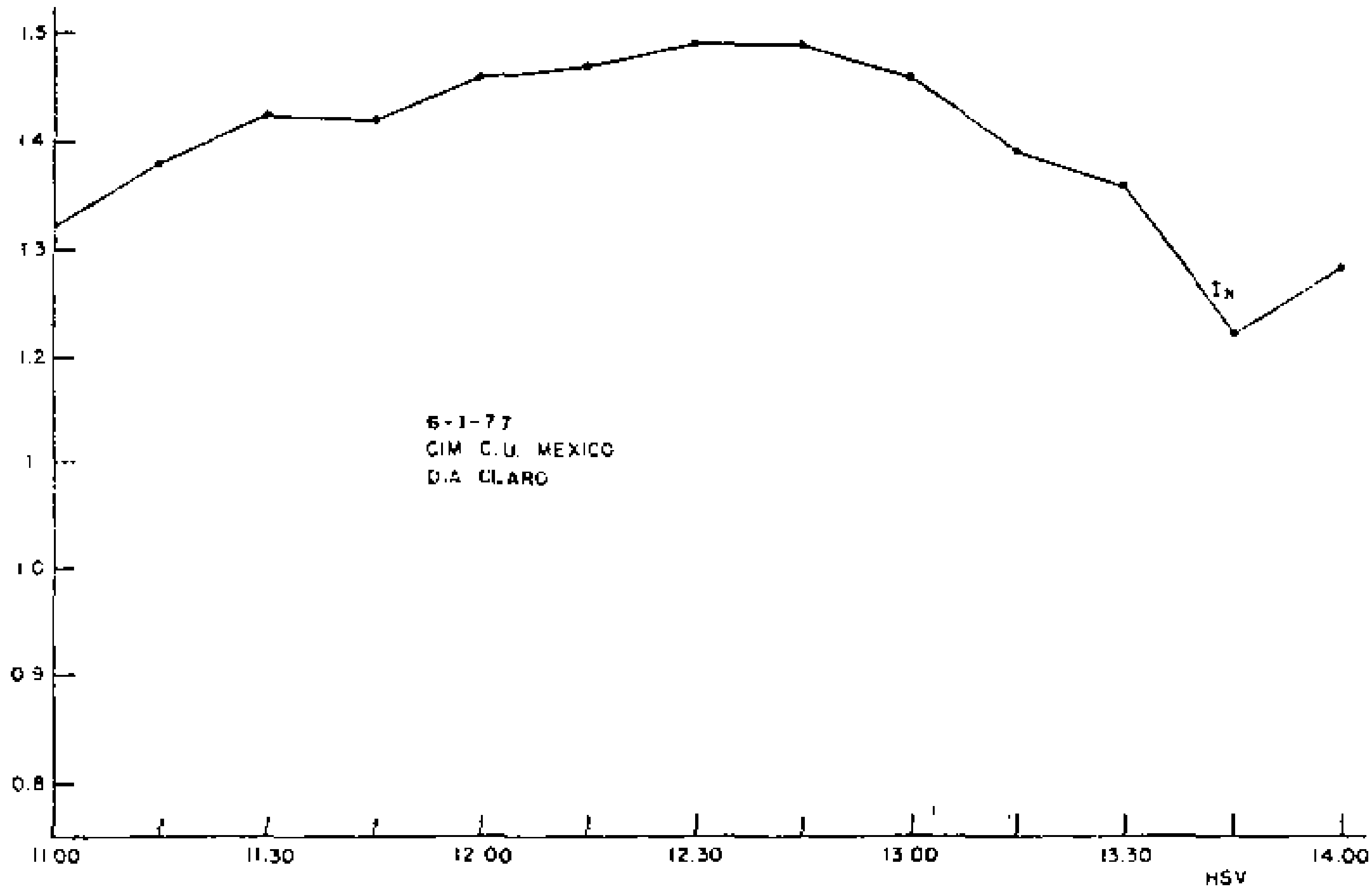

FIGURA 18 VALORES TIPICOS DE LA RADIACION SOLAR A INCIDENCIA NORMAL EN UN DIA DESPEJADO(C.I.M. U.N.A.M. MEXICO D.F. 6 - I - 77)

LATITUD 24° N

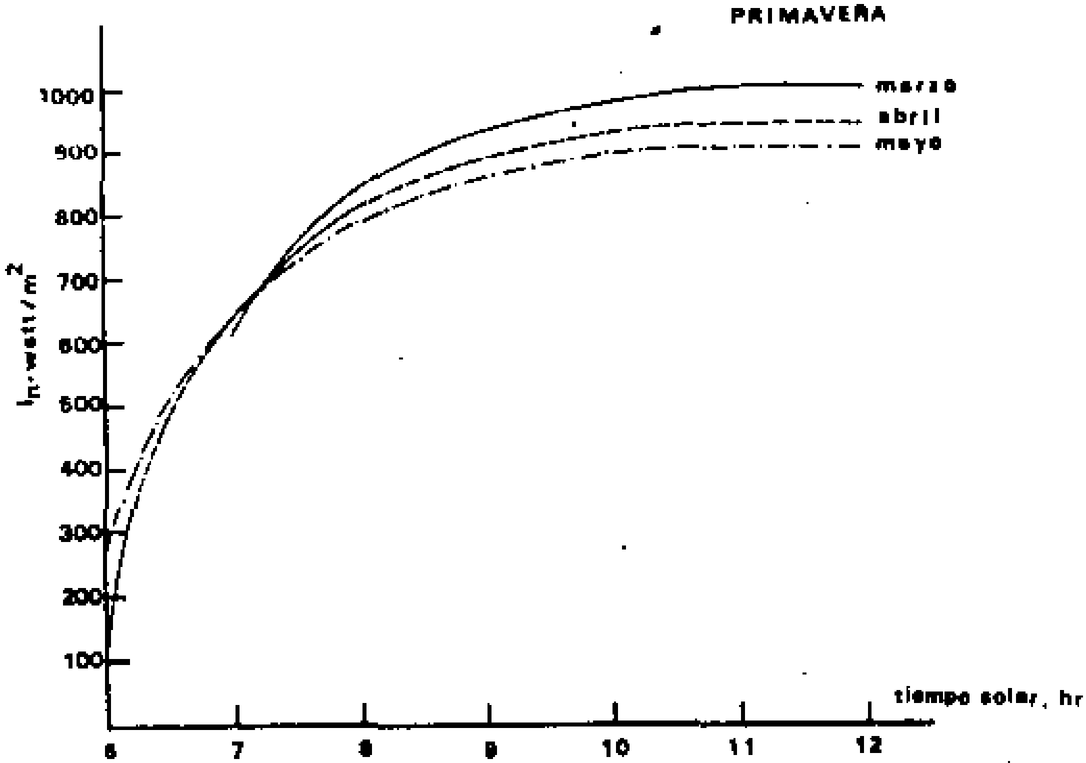

Fig. 19a. Relación entre la hora del día y la radiación directa a incidencia normal I_n. Estos valores son representativos de lo que puede esperarse en promedio en días despejados. Los valores máximos de I_n pueden ser incluso un 15% mayores (20).

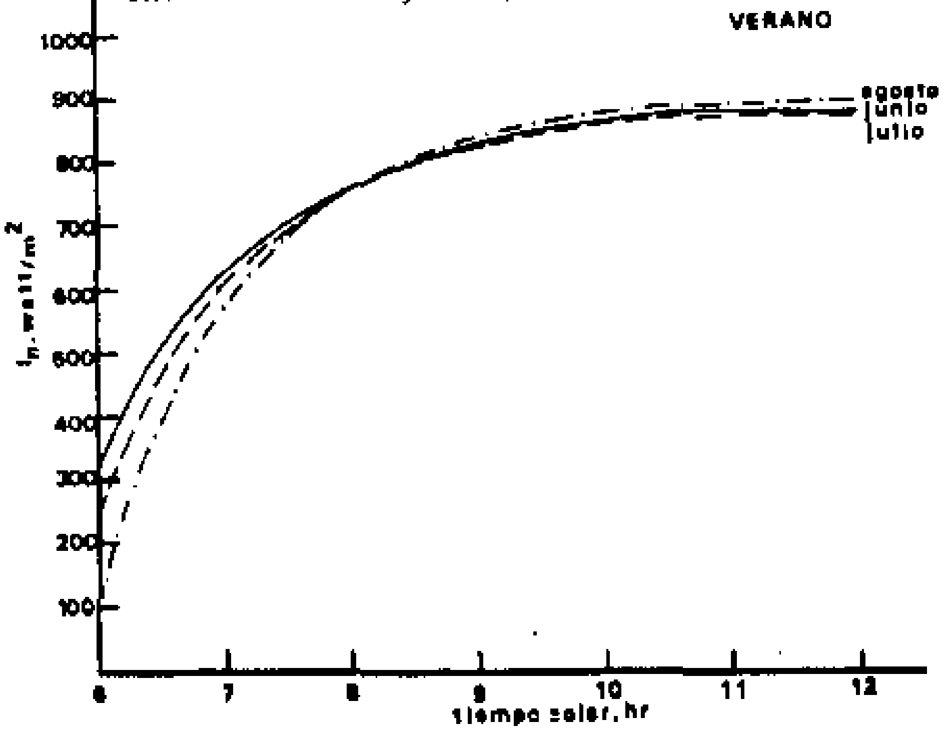

Fig. 19b. Idem.

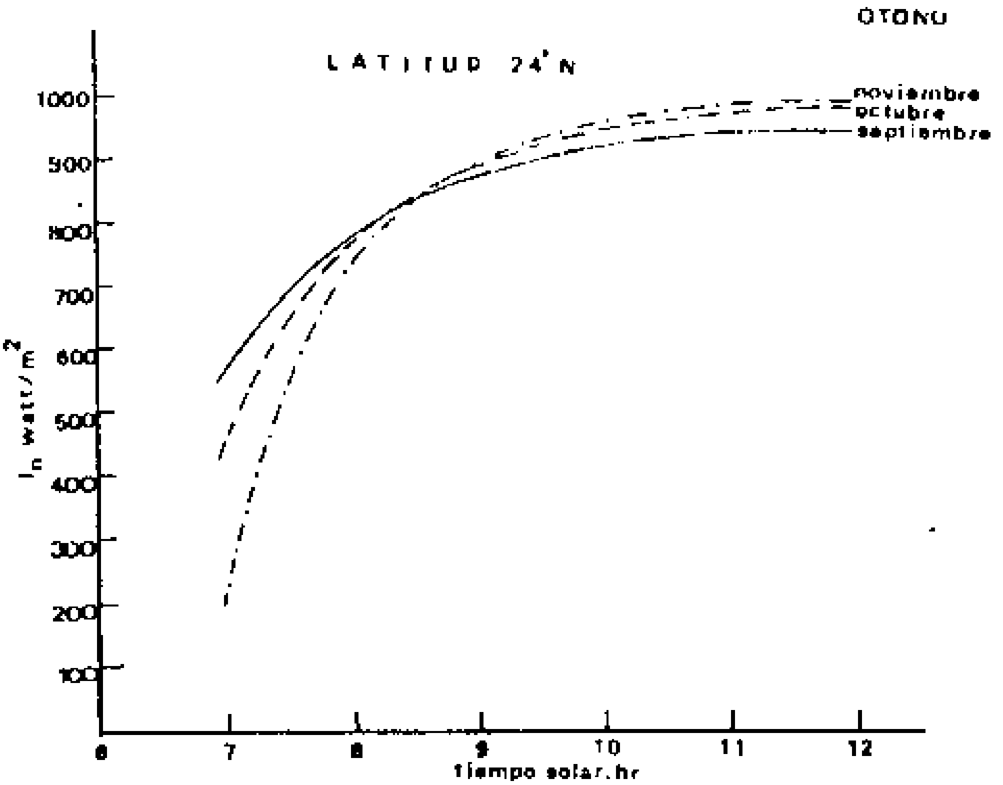

Fig. 19c. Idem.

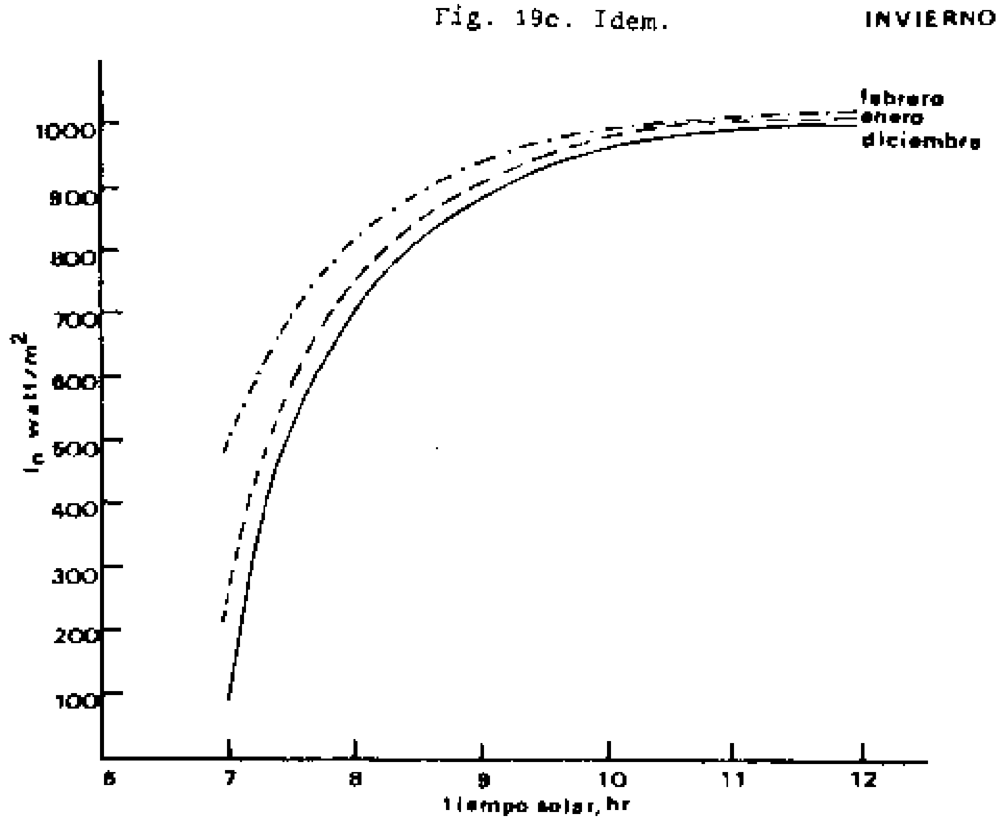

Fig. 19d. Idem.

LATITUD 32°N

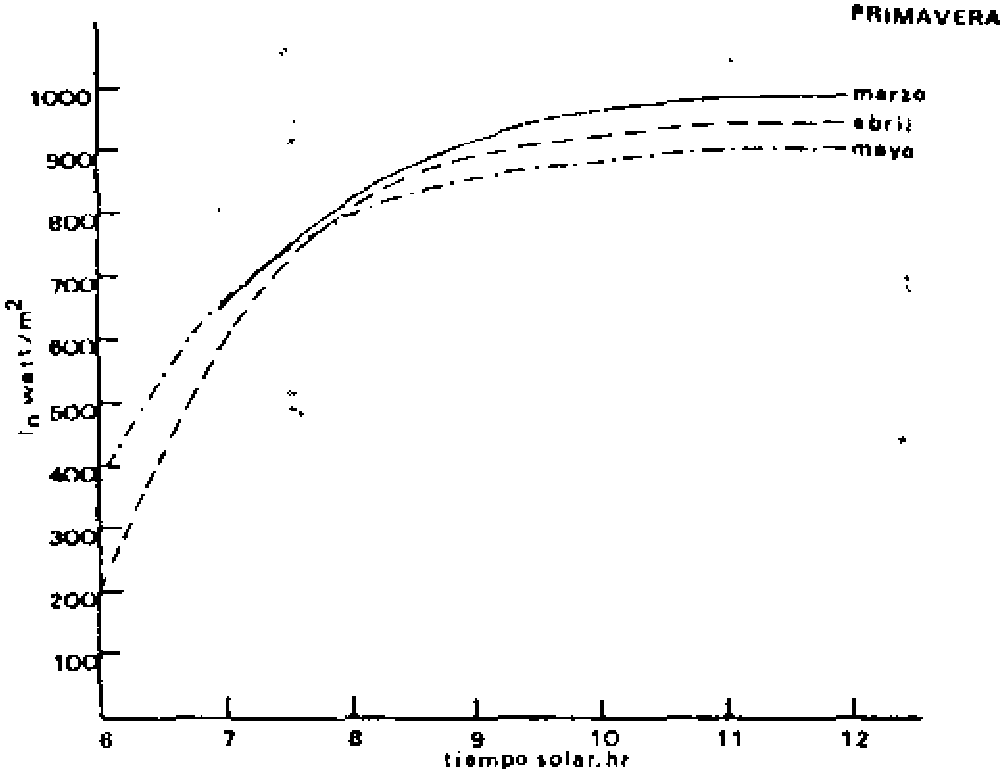

Fig. 20a. Idem.

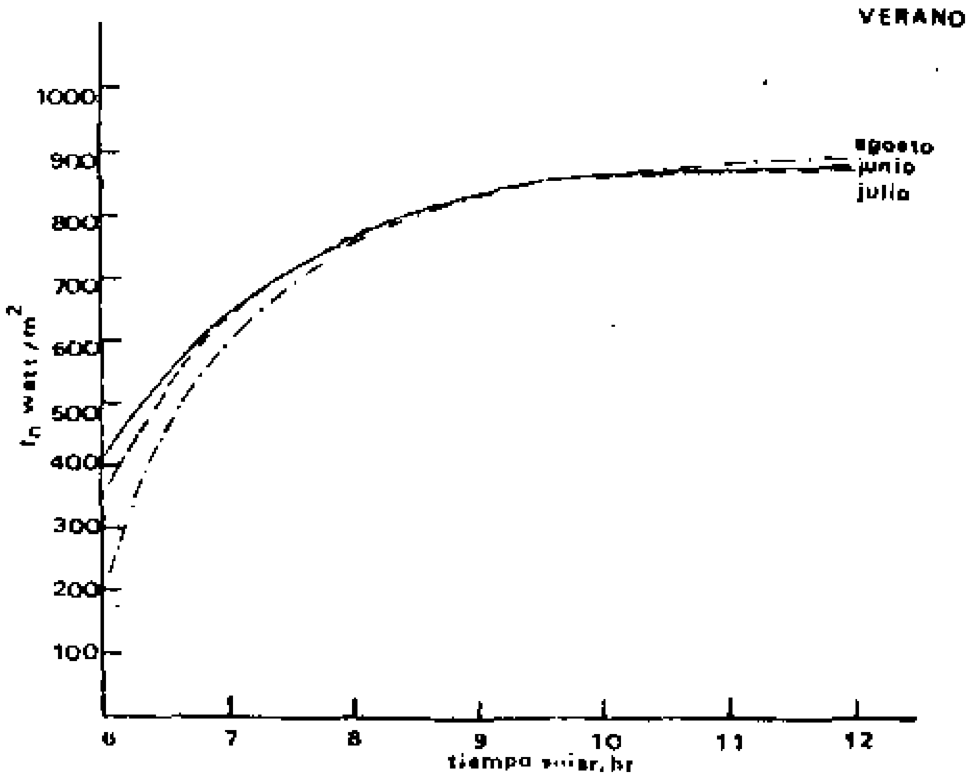

Fig. 20b. Idem.

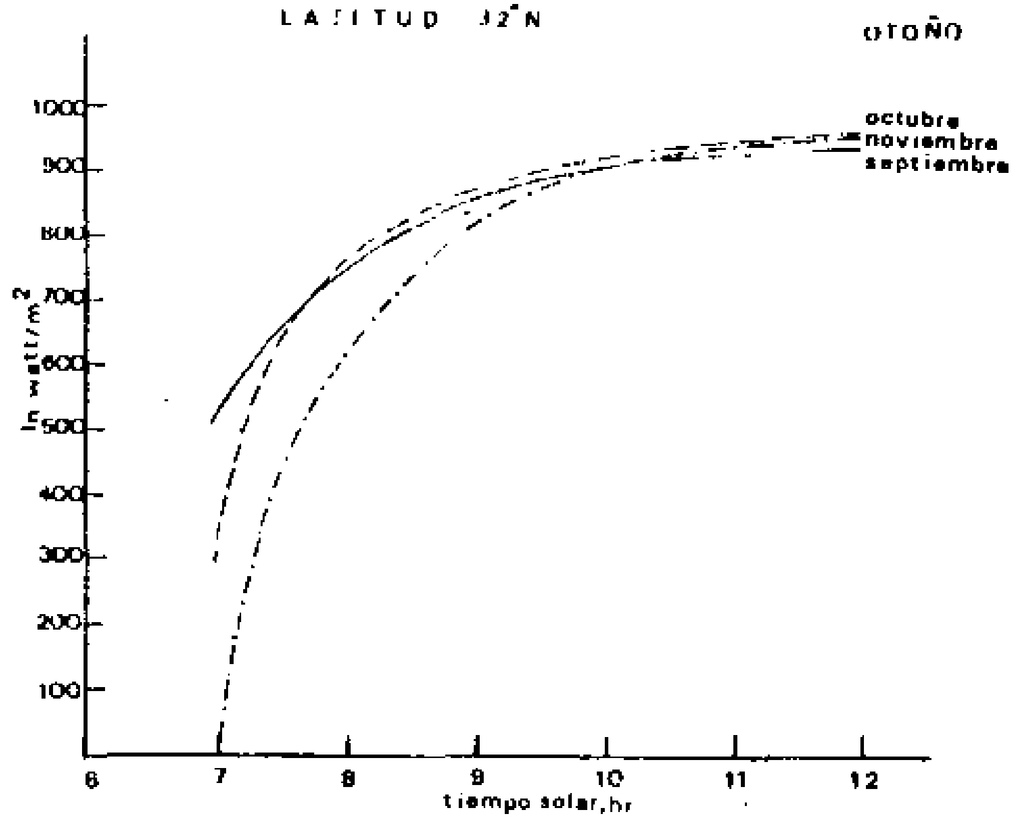

Fig. 20c. Idem.

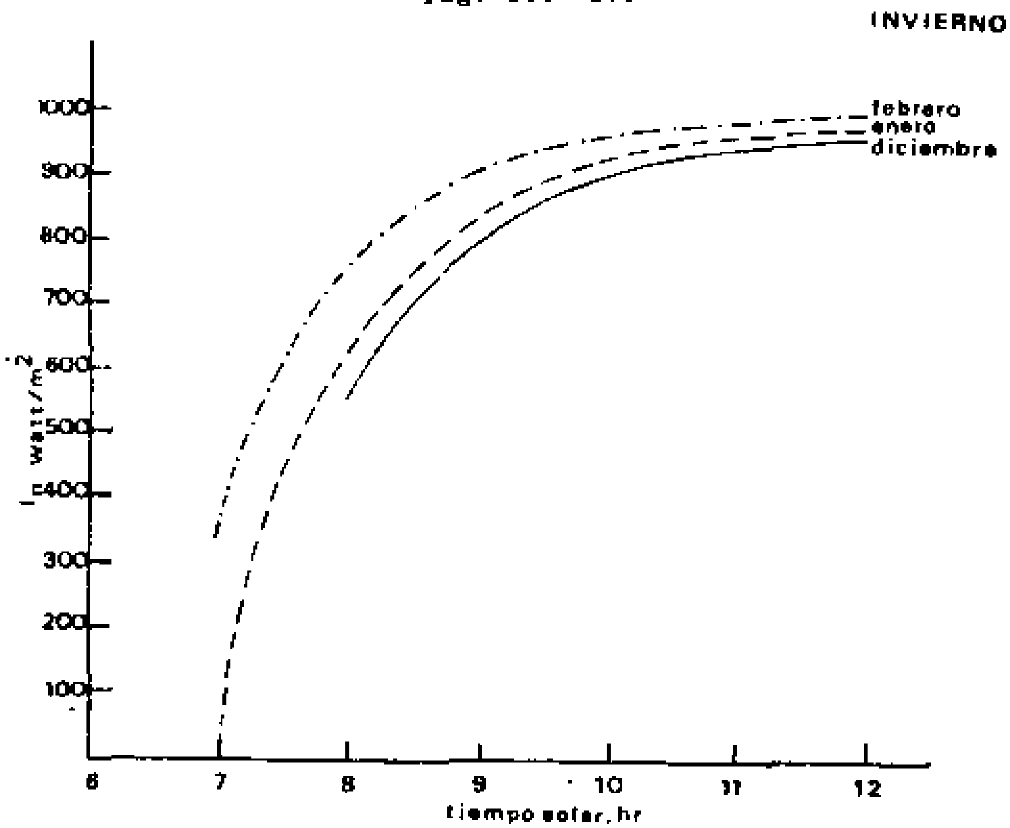

Fig. 20d. Idem.

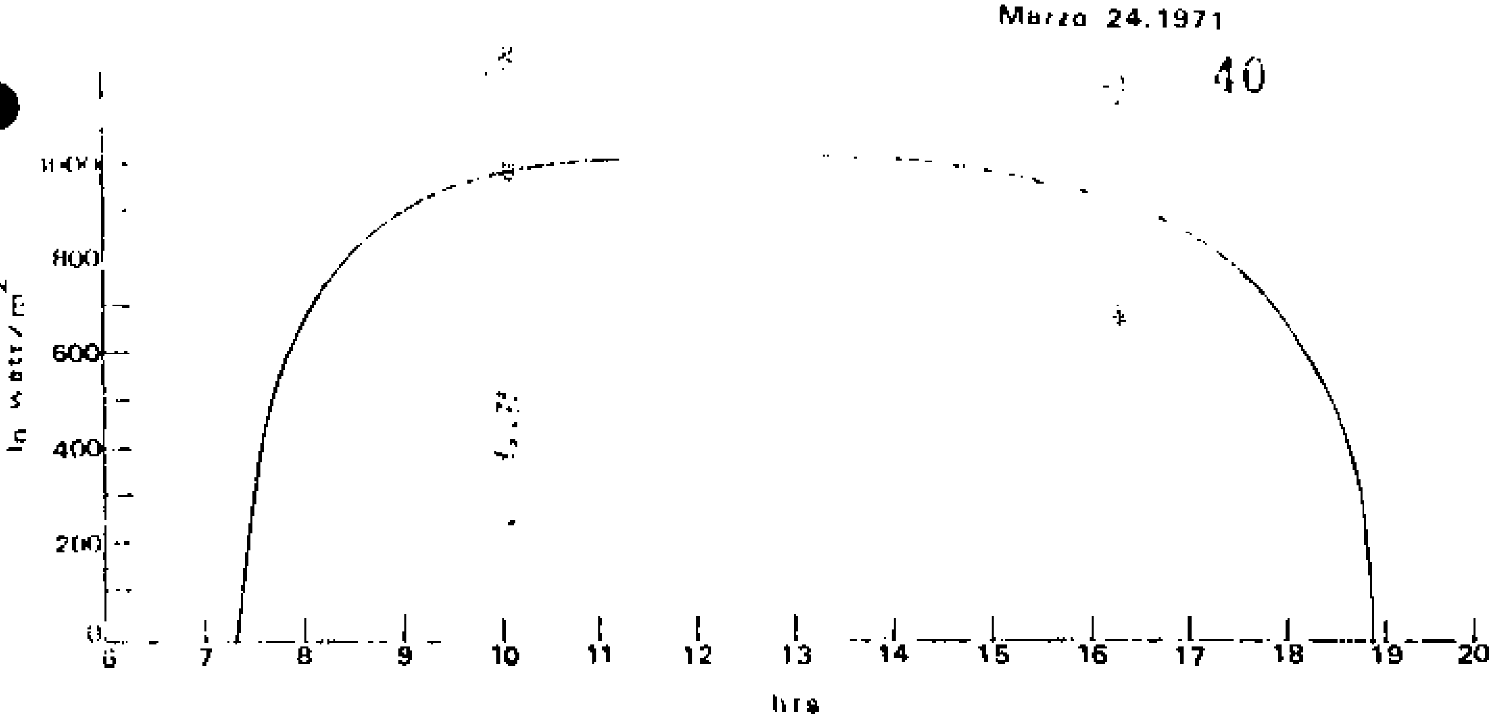

Fig. 21a. Radiación directa a incidencia normal recibida en la estación de Odeillo Font Romeu Francia (ϕ=42° 31') durante días despejados { 21 }.

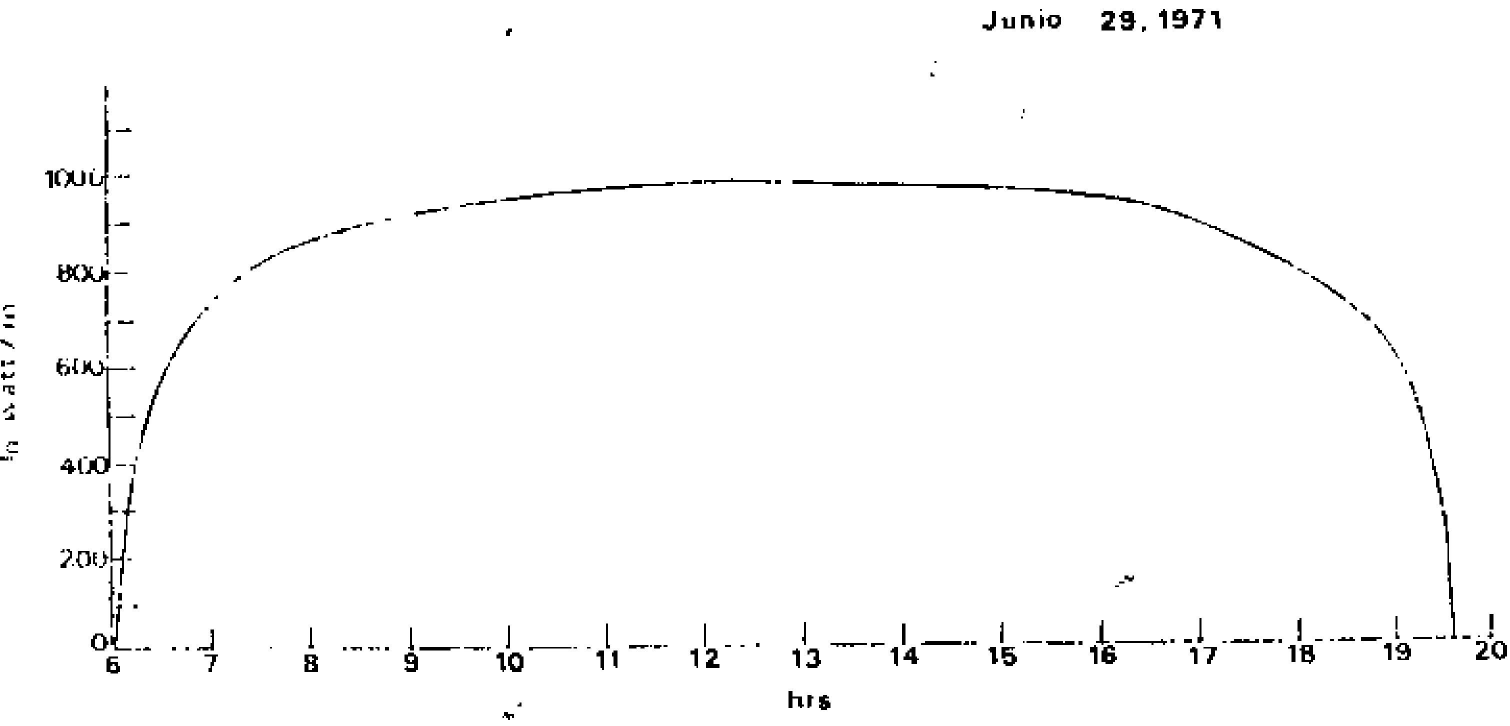

Fig. 21b. Idem.

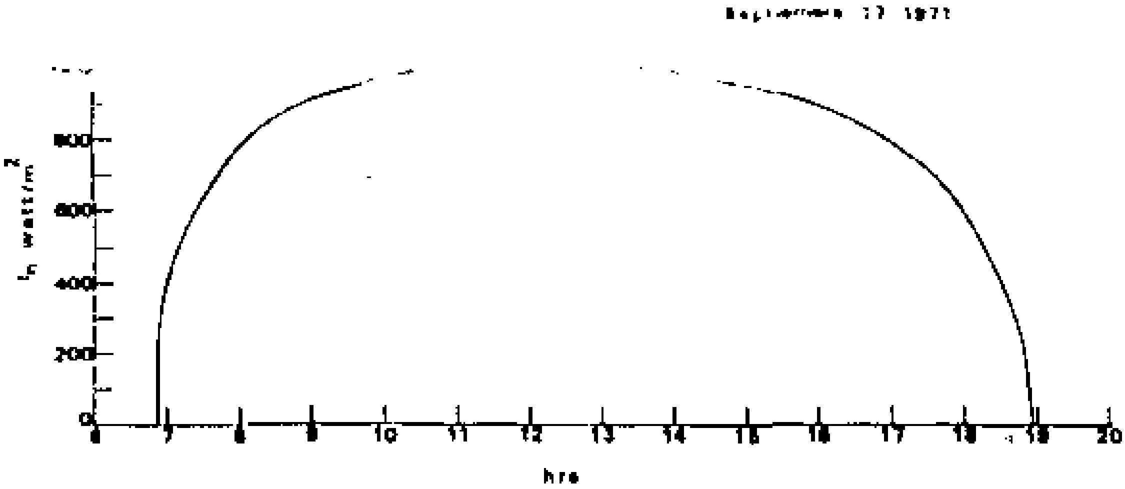

Fig. 21c. Idem.

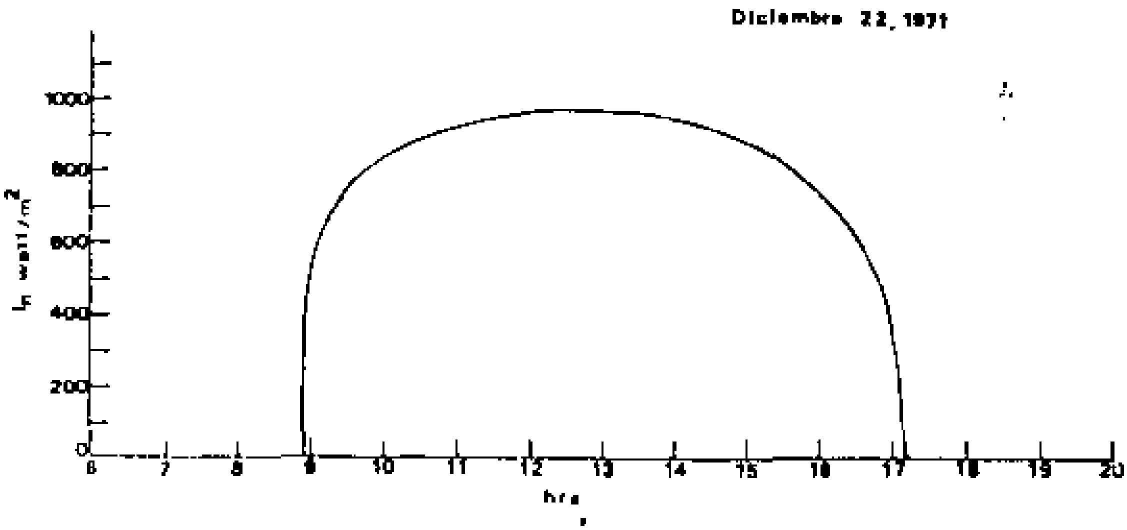

Fig. 21d. Idem

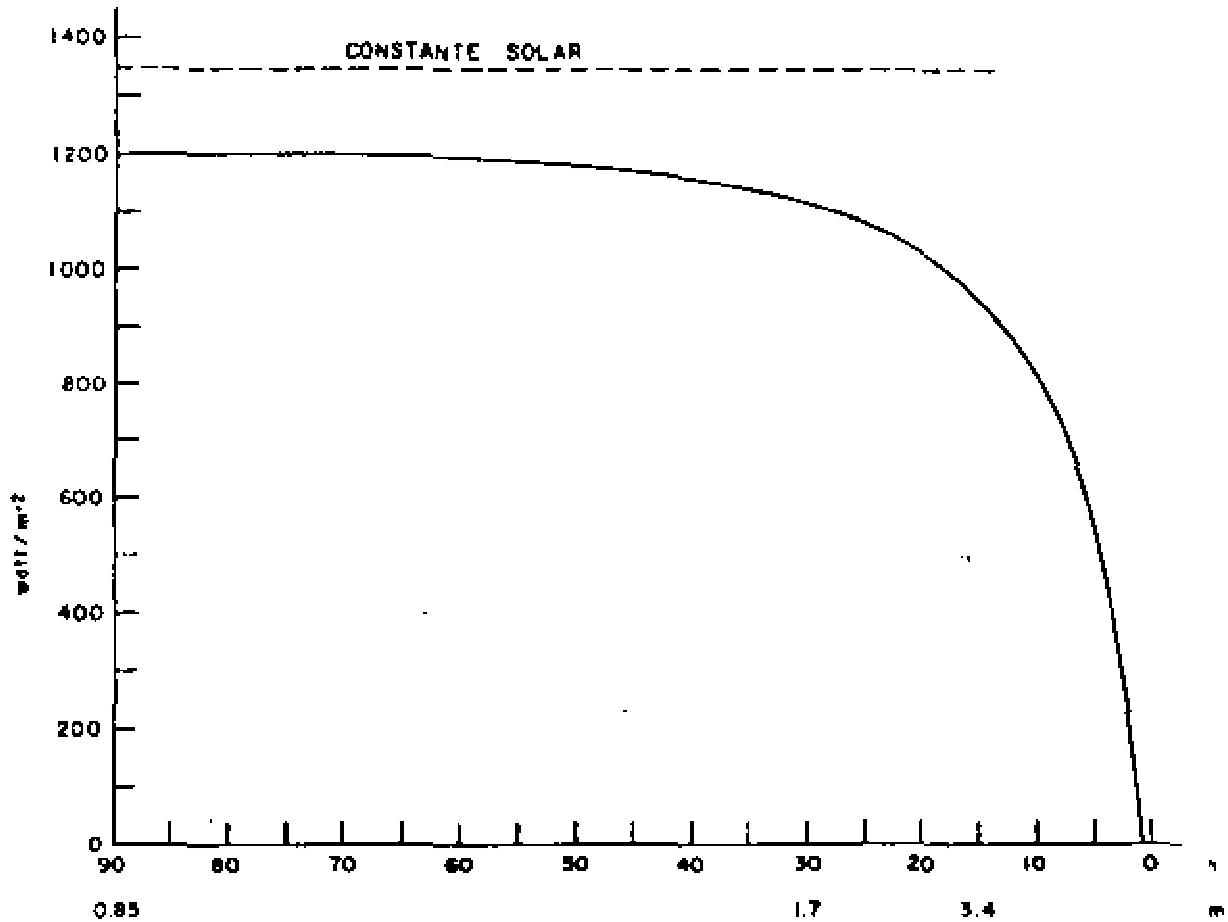

Fig. 22 Variación del flujo de radiación solar a inciden cia normal I_n a 1500 metros de altitud bajo buenas condi ciones de una atmósfera seca típica, cielo azul intenso (puro) y en función de la masa atmosférica y altura solar. [22]

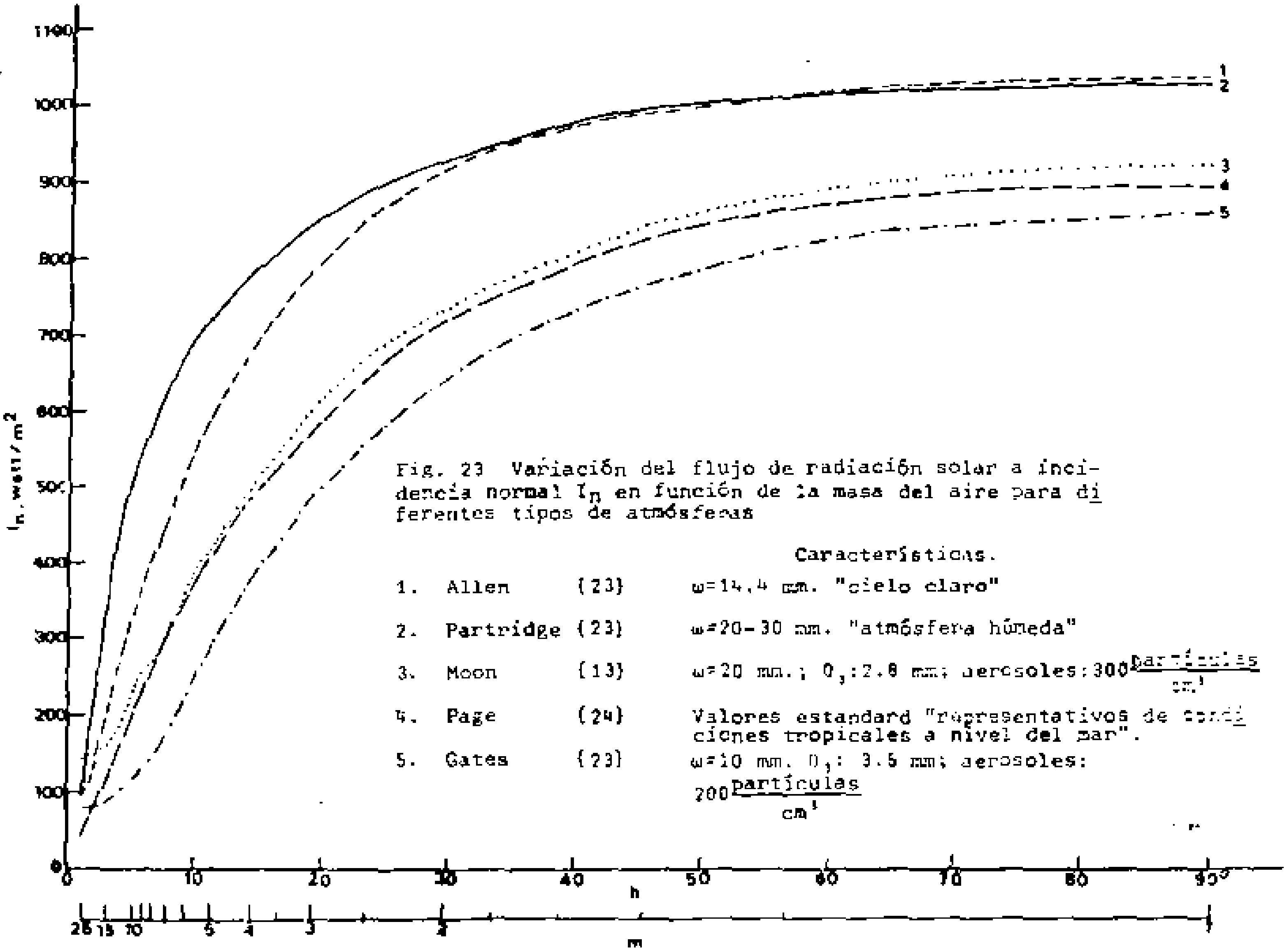

Fig. 23 Variación del flujo de radiación solar a incidencia normal I_n en función de la masa del aire para diferentes tipos de atmósferas

Características.

1. Allen (23) ω=14,4 mm. "cielo claro"
2. Partridge (23) ω=20-30 mm. "atmósfera húmeda"
3. Moon (13) ω=20 mm.; O_3:2.8 mm; aerosoles:300 $\frac{\text{partículas}}{\text{cm}^3}$
4. Page (24) Valores estandard "representativos de condiciones tropicales a nivel del mar".
5. Gates (23) ω=10 mm. O_3: 3.5 mm; aerosoles: 200 $\frac{\text{partículas}}{\text{cm}^3}$

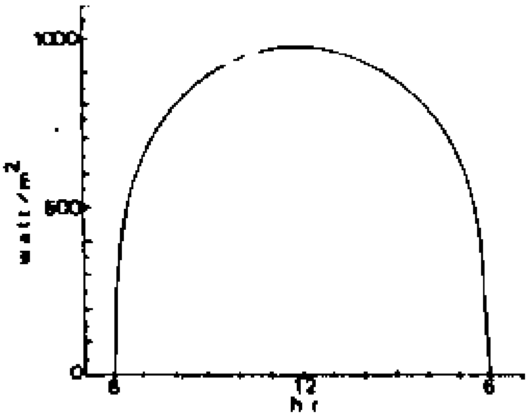

FIGURA 24 a. Radiación Solar Directa a Incidencia Normal a la latitud de 25°, en las fechas de los equinoccios. (28)

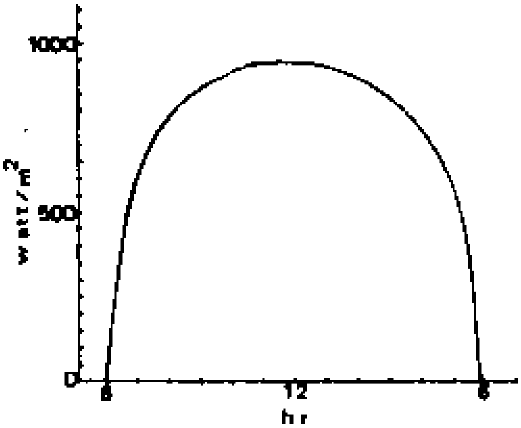

FIGURA 24 b. Radiación Solar Directa a Incidencia Normal a la latitud de 30°, en las fechas de los equinoccios.

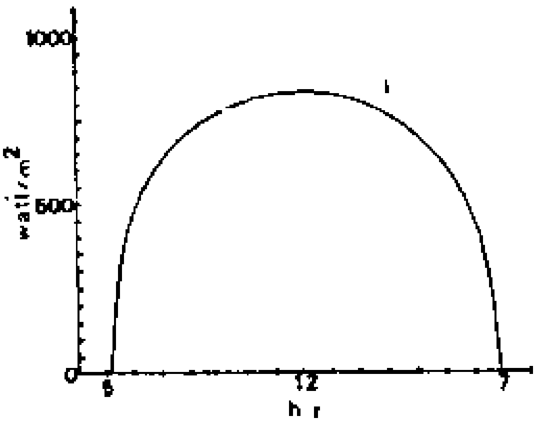

FIGURA 24 c. Radiación Solar Directa a Incidencia Normal a la latitud de 25°, en el solsticio de Verano.

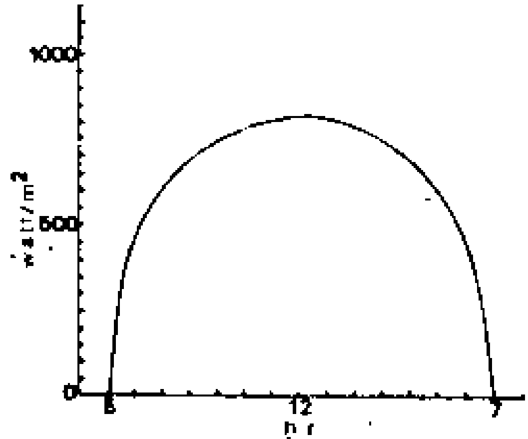

FIGURA 24 d. Radiación Solar Directa a Incidencia Normal a la latitud de 30°, en el solsticio de Verano.

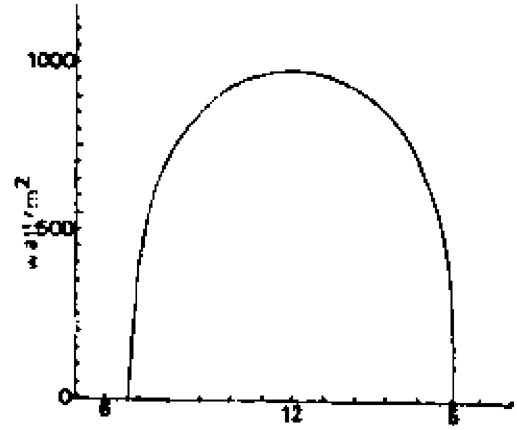

FIGURA 24 e. Radiación Solar Directa a Incidencia Normal a la latitud de 25°, en el solsticio de Invierno.

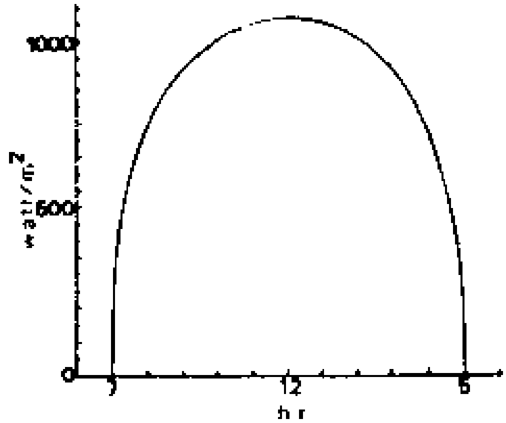

FIGURA 24 f. Radiación Solar Directa a Incidencia Normal a la latitud de 30°, en el solsticio de Invierno.

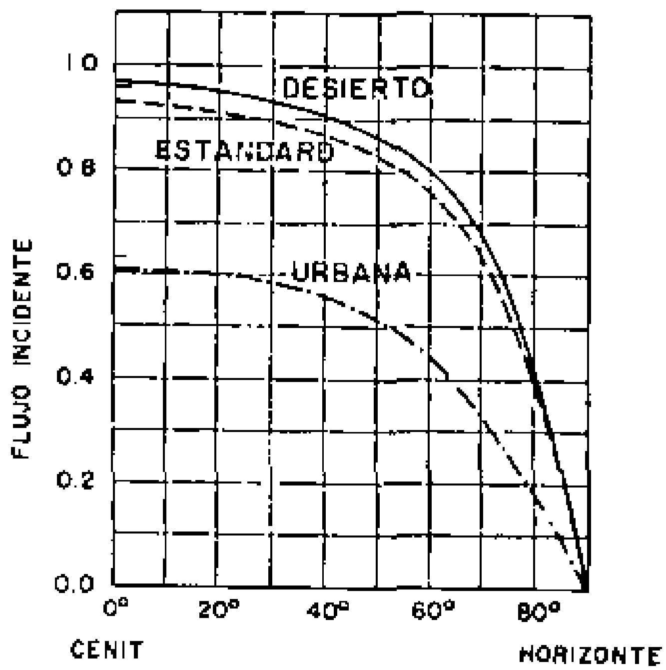

FIG. 25

Variación del flujo solar directo respecto a la altura solar para tres distintos tipos de atmósfera: urbana, estándard y de desierto. La curva que corresponde a la atmósfera urbana se deriva de observaciones hechas en la costa este de los Estados Unidos de Norteamérica [27].

la masa del aire varían en la misma proporción durante el día, es decir, su variación es rápida para alturas solares pequeñas (al amanecer y atardecer) y rápida para alturas solares grandes. Esto se debe a que al disminuir la altura del sol y acercarse al horizonte, se incrementa rápidamente el camino óptico y en consecuencia la masa de aire, mientras que en las horas cercanas al mediodía, la variación es mucho más lenta pudiéndosele considerar casi constante en condiciones óptimas de cielo limpio y despejado.

Bajo condiciones de óptima transparencia atmosférica, caracterizada por un cielo azul intenso (en la cual la atenuación se debe fundamentalmente a la dispersión del color azul por las moléculas del aire) es posible registrar pirheliométricamente valores de I_n superiores a 1000 watts m^{-2} (Figuras: 23 y 24), sobre todo a altitudes mayores a los 1000 metros y aún para alturas solares pequeñas (del orden de los 20°). Es por esta razón, que para calcular los valores diarios (promedios decadarios) de la cantidad de energía recibida sobre los planos verticales, se ha considerado en la evaluación de I_n, la gran extensión territorial de nuestro país (más de la mitad) cuyas altitudes son superiores a los 1000 metros. Esto puede apreciarse al examinar las isohipsas del mapa altimétrico de la Figura (26).

En tales condiciones altimétricas y considerando atmósferas rurales no contaminadas de elevada transparencia en días despejados, la influencia del factor p/p_o sobre I_n, permitirá suponer valores de I_n superiores a los 1000 watt m^{-2}. En consecuencia, este último valor es el que ha sido considerado en los cómputos

CARTA ALTIMETRICA

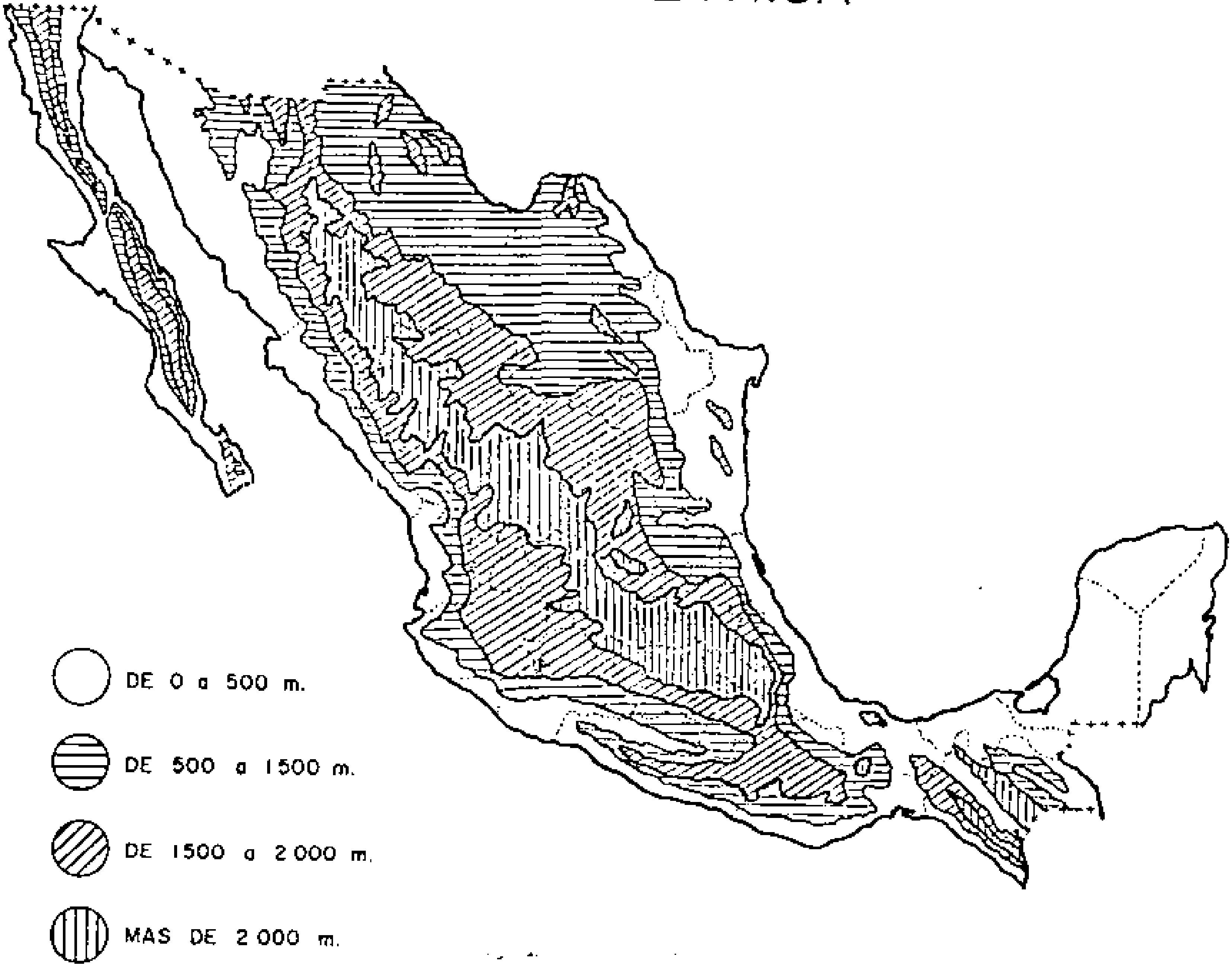

FIGURA 26

de este trabajo. Si bien su fluctuación durante el día (a alturas solares pequeñas) puede ser apreciable, sin embargo, es un valor bastante representativo del promedio de los valores que forman la curva diaria y por lo tanto confiable. Este valor de I_n es usado inclusive en las regiones templadas del planeta, no obstante su menor elevación y mayor latitud {25}.

En la tabla siguiente (II) se muestra la recopilación hecha por Vassy {26} del promedio de I_n en días despejados en varios lugares del mundo. Es interesante notar como aún cuando las diferencias latitudinales son notables, los valores de I_n son semejantes.

En la Tabla (III), aparecen los valores máximos registrados en Tacubaya {29} en condiciones de óptima transparencia atmosférica, aunque hay que tomar en cuenta que es una atmósfera urbana.

IV. RADIACION SOLAR DIRECTA SOBRE LOS PLANOS VERTICALES.

Considerando primero al plano horizontal, se tiene que la radiación directa recibida durante el día estará limitada por los valores del ángulo horario ω de salida y puesta del sol. De la Ecuación (9) se tiene:

$$\operatorname{sen} h = \operatorname{sen} \phi \operatorname{sen} \delta + \cos \phi \cos \delta \cos \omega$$

para los instantes de salida y ocultamiento del sol, $h = 0^\circ$, TABLA [illegible]

Localidad	Latitud	Longitud	Altitud	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC	[illegible]
Leningrado, URSS	59°56'	[illegible]	5	[illegible]	[illegible]	[illegible]	941.5	942.5	914.0	893.1	[illegible]	896.1	823.3	690.7	455.4	[illegible]
Slutzk, URSS	59°41'	30°23'E	40	537.0	767.5	868.7	900.0	921.0	927.9	900.0	858.2	823.5	768.4	655.6	565.0	795.5
Ekaterinburgo, URSS	56°50'	60°39'E	290	-	686.2	976.8	963.8	966.6	879.1	875.0	927.9	656.0	875.1	665.1	-	[illegible]
Halde	55°23'	9°15'E	75	502.3	614.0	607.6	-	753.5	767.5	921.0	927.9	837.2	851.2	558.2	541.9	[illegible]
Eskdalemuir, Ing.	55°19'	3°12'W	244	621.0	711.7	802.4	815.3	879.1	837.2	872.1	827.2	830.3	755.4	621.0	533.0	[illegible]
Varsovia, Pol.	52°15'	21°07'E	120	607.0	711.7	802.4	851.2	851.7	830.3	830.3	830.3	830.3	760.5	655.6	544.2	[illegible]
Kew, [illegible]	51°28'	0°18'W	6	486.4	537.2	680.7	704.7	725.6	753.5	711.7	739.6	683.7	607.0	523.9	467.5	[illegible]
Saint Maur, Fr.	48°49'	2°29'E	50	607.0	732.6	809.3	837.2	844.2	805.3	830.3	844.2	830.3	746.6	669.6	544.2	[illegible]
Lausanne, Sui.	46°31'	6°38'E	315	551.2	593.0	627.9	834.9	800.0	593.0	600.0	614.0	600.0	600.0	572.1	523.3	[illegible]
Florencia, It.	43°46'	11°13'E	73	725.6	781.4	900.0	844.2	844.2	844.2	837.2	802.4	795.4	774.5	718.6	704.7	[illegible]
Modena, It.	43°39'	10°56'E	54	767.5	704.7	858.7	923.3	865.1	809.4	530.3	858.2	795.4	951.2	802.4	732.5	[illegible]
Montpellier, Fr.	43°36'	3°52'E	43	865.1	837.2	934.9	934.9	865.1	751.4	837.2	-	837.2	879.1	802.4	[illegible]	[illegible]
Antibes, Fr.	43°34'	7°07'E	35	934.9	976.7	927.8	941.9	943.9	546.9	983.8	934.9	943.9	914.0	914.0	879.1	[illegible]
Tiflis, URSS	41°[illegible]	44°48'E	420	879.0	940.1	[illegible]	921.0	990.7	946.9	921.0	934.6	907.0	866.2	856.1	[illegible]	[illegible]
Madrid, Esp.	40°24'	3°41'E	655	956.2	979.1	934.9	948.9	927.9	907.0	900.0	979.1	893.1	866.1	860.2	[illegible]	[illegible]
Simla, URSS	31°07'	[illegible]	2204	1039.6	1032.6	1046.6	1025.6	990.7	900.0	900.0	962.8	997.7	1025.6	1039.6	1046.5	[illegible]
Tacubaya, Mex.	19°24'	99°12'W	2325	983.6	1016.6	976.9	965.8	993.7	1011.7	969.8	1004.7	1011.7	1011.7	997.7	1004.7	997.7

TABLA III

VALORES MENSUALES MAXIMOS DE LA RADIACION SOLAR DIRECTA
REGISTRADA EN TACUBAYA, MEX. (1911-16, 1927-28)

MES	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC	ANUAL
In(watt m^{-2})	1137	1158	1074	1088	1060	1074	1033	1067	1095	1116	1095	1137	1088

en consecuencia:

$$\operatorname{sen} \phi \operatorname{sen} \delta + \cos \phi \cos\delta \cos \omega = 0$$

y $$\cos \omega = - \tan \phi \tan \delta \qquad (33)$$

Esta expresión es válida solamente para aquellas latitudes comprendidas en el intervalo:

$$-1 \leq \tan \phi \tan \delta \leq + 1.$$

Al amanecer se tiene:

$$\omega_1 = - \cos^{-1} (-\tan \phi \tan \delta)$$

y al ocultarse el sol:

$$\omega_2 = - \cos^{-1} (\tan \phi \tan \delta)$$

En un plano horizontal las componentes n_x y n_y son paralelas al plano horizontal por lo que la única que contribuye es n_z, por lo que al integrar la Ecuación (12) obtenemos:

$$Q = I_n \{n_x (\operatorname{sen} \omega \operatorname{sen} \phi \cos \delta - \omega \operatorname{sen} \delta \cos \phi) -$$

$$n_y (\cos \delta \cos \omega) + n_z (\operatorname{sen} \omega \cos \phi \cos \delta + \omega \operatorname{sen}\phi \operatorname{sen}\delta)\}\Big|_{\omega_1}^{\omega_2} \quad (35)$$

entonces al considerar únicamente a n_z, se tiene que para el plano horizontal, la energía Q_H recibida durante el día en Kw h. m^{-2} día, es:

$$Q_H = \frac{24}{\pi} (\cos \phi \cos \delta \operatorname{sen}\omega - \omega \operatorname{sen} \phi \operatorname{sen} \delta)\Big|_{\omega_1}^{\omega_2} \quad (36)$$

Para tratar los casos de los planos verticales conviene reexaminar las trayectorias solares de las Figuras (4) a la (8). Podemos ver que tanto el acimut de salida o puesta del sol como la inclinación i de los planos de las trayectorias del sol sobre el horizonte, limitarán la insolación directa. En la pared sur ésta perdurará todo el día durante el Otoño e Invierno (sol al sur de la pared), sin embargo, el resto del año la iluminación directa estará limitada por el paso del sol por el acimut equivalente a los 90°. De esta manera, en el primer caso los ángulos horarios correspondientes a la mañana y tarde, se obtienen de las mismas condiciones expresadas en (34), mientras que en el segundo caso, la insolación directa estará parcialmente limitada durante el día por: $a = 90°$. Introduciendo esta condición en la Ecuación (10) se tiene que:

$$\text{sen}\,\phi\ \ \text{sen}\,\delta\cos\omega - \text{sen}\,\delta\cos\phi = \cos h\cos(\pi/2)$$

$$\text{y} \qquad \cos\omega = \tan\delta\cot\phi \qquad (37)$$

por lo que, por la mañana: $\omega_1 = -\cos^{-1}(-\tan\delta\cot\phi)$

y por la tarde: $\omega_2 = \cos^{-1}(-\tan\delta\cot\phi)$ (38)

La única componente que contribuye a la insolación directa de la pared sur es n_x, ya que n_y y n_z son tangentes a ella y por lo tanto nulas. Recurriendo a la expresión (35), la insolación directa sobre el plano vertical sur Q_s resulta ser:

$$Q_s = \frac{24}{\pi}\{\cos\delta\ \text{sen}\,\phi\ \text{sen}\,\omega - \text{co}\ \text{sen}\,\delta\cos\phi\} \quad (39)$$

donde:

$$\omega = \cos^{-1}(\tan\delta \cot\phi), \text{ para: } \delta \geq o \text{ y } \phi \geq 23°27'$$

y $$\omega = \cos^{-1}(-\tan\delta \cot\phi), \text{ para: } \delta < o \text{ y } \phi < 23°27' \quad (40)$$

Simétricamente, para la pared norte solamente resta considerar que cuando el acimut de salida de ocultamiento de sol es mayor que 90°, termina la insolación directa sobre la pared sur y empieza por su parte posterior, ó sea sobre la pared norte, por lo que:

$$Q_n = \frac{24}{\pi}\left[(\omega_1 - \omega_2)\,\text{sen}\delta\,\cos\phi + (\text{sen}\omega_2 - \text{sen}\omega_1)\cos\delta\,\text{sen}\phi\right] \quad (41)$$

donde:

$$\omega_1 = \cos^{-1}(\tan\delta \cot\phi)$$

$$\omega_2 = \cos^{-1}(-\tan\phi \tan\delta) \quad (42)$$

Para las paredes orientadas verticalmente hacia el Este u Oeste, recurrimos a la condición (33), solamente que en este caso, la componente que interviene en la insolación directa es n_y en sentido negativo (ver Figura 9). Sustituyendo la condición (33) en (35) se tiene que por la simetría de ambas paredes respecto a las trayectorias diarias del sol, la energía recibida durante el día por insolación directa será:

$$Q_E = Q_O = \frac{12}{\pi}(\cos\delta - \cos\delta\cos\omega) \quad (43)$$

donde:

$$\omega = \cos^{-1}(-\tan\phi \tan\delta)$$

V. RESULTADOS.

Con el objeto de ver la variación anual de las energías recibidas diariamente por incolación directa, tanto sobre el plano horizontal, como en los planos verticales, a partir de las Ecuaciones (36), (39), (41) y (43), se calcularon los resultados correspondientes, los cuales fueron directamente graficados por la computadora, grado por grado de latitud, como se muestra en las páginas siguientes. En cada gráfica las abscisas corresponden a los 36 períodos de 10 días en que se dividió el año, y en las ordenadas aparecen los valores de la energía recibida en Kw h. m^{-2}- día.

A la energía recibida sobre el plano horizontal, Q_H, se le asoció al graficar el número 1; a la pared Este u Oeste, ($Q_{E,O}$) el 2; a la pared Sur (Q_S), el 3; y a la pared Norte (Q_N), el 4.

VI. CONCLUSIONES.

Los resultados obtenidos en este estudio deben tomarse como representativos de la energía que puede ser recibida sobre los planos verticales considerados bajo condiciones de óptima transparencia atmosférica.

La situación geográfica de nuestro país hace que las características atmosféricas sean las de una atmósfera tropical sensiblemente modificada por la elevación continental del altiplano y relieve orográfico. Como ya se mencionó en el texto, el valor asignado I_n (1 kw. m^{-2}) viene a ser bastante representativo de las regiones de la altiplanicie.

El valor de I_n en las regiones bajas de nuestro país, principalmente en las subtropicales caracterizadas por una elevada humedad absoluta y turbidez atmosférica (polvos y aerosoles higroscópicos), puede ser hasta un 20% menor para alturas cenitales (comparar Figura (22) con la Figura(23). Sin embargo, la generalidad que en primera intención ha querido imprimirse a este estudio al describir la marcha anual de la insolación directa abarcando grado por grado de latitud, precisa de aproximaciones que si bien en muchos casos no ha sido posible verificar, si en cambio se encuentra cimentada en exhaustivos estudios pirheliométricos realizados en múltiples localidades, muchas de las cuales (a latitudes semejantes a las de México) presentan características climatológicas similares a las nuestras.

Puede decirse que los resultados aquí obtenidos, no pretenden ser definitivos sino deben ser considerados preliminares, ya que para conocer a fondo las características de la radiación solar incidente a nivel del suelo —ya no solamente la componente directa, sino también la difusa y la global — restan por hacerse muchas investigaciones tanto teóricas como piranométricas, las cuales es urgente realizar para poder lograr en un futuro inmediato el eficiente aprovechamiento de la energía solar en nuestro país.

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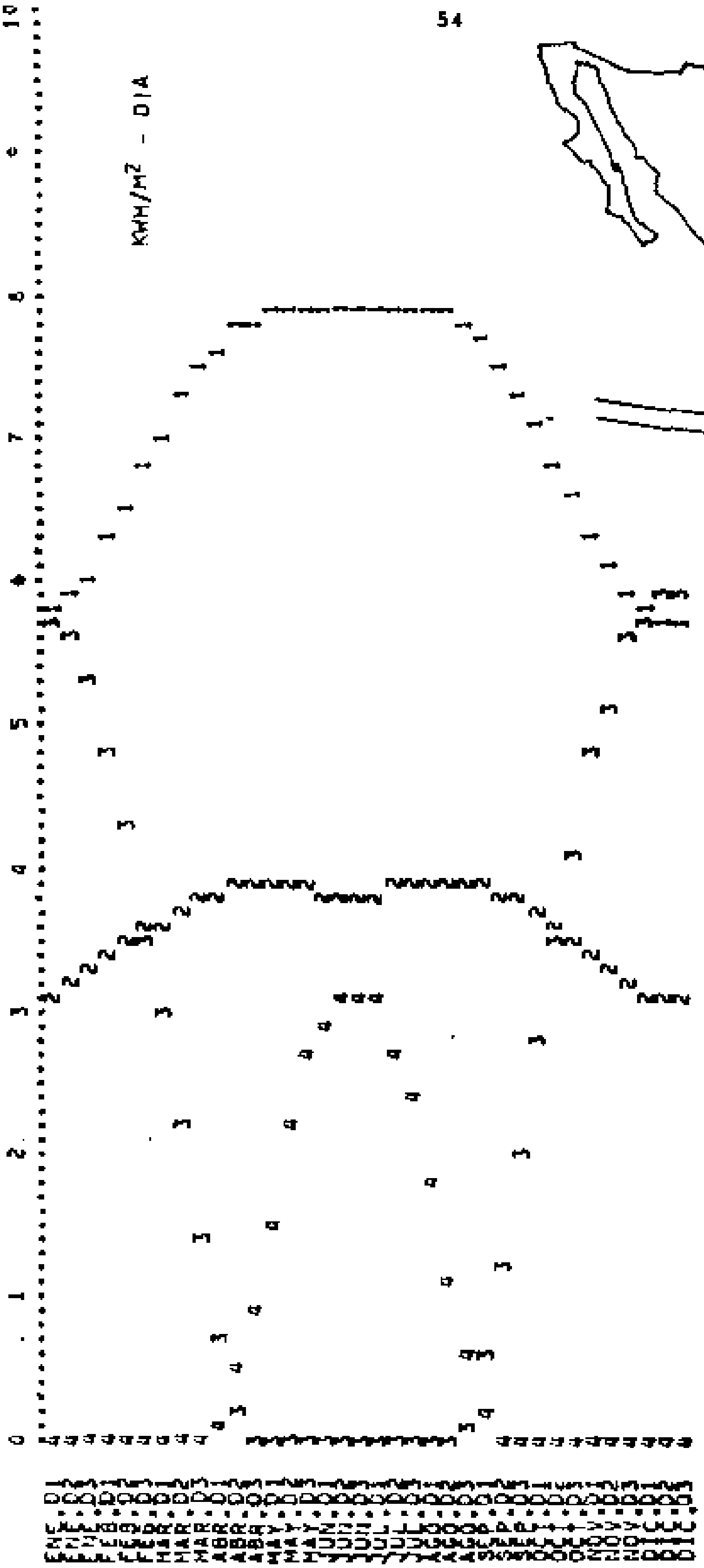
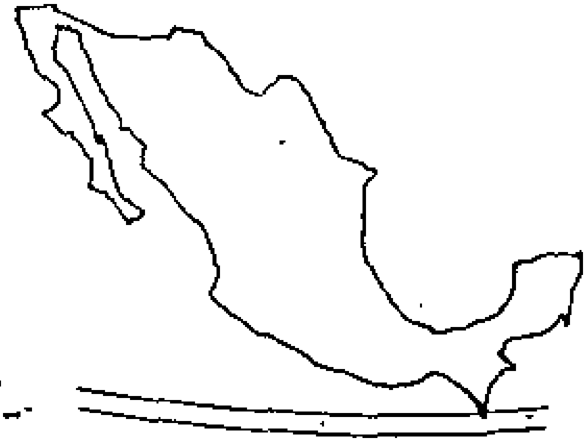
LATITUD 14° ± 0.5°



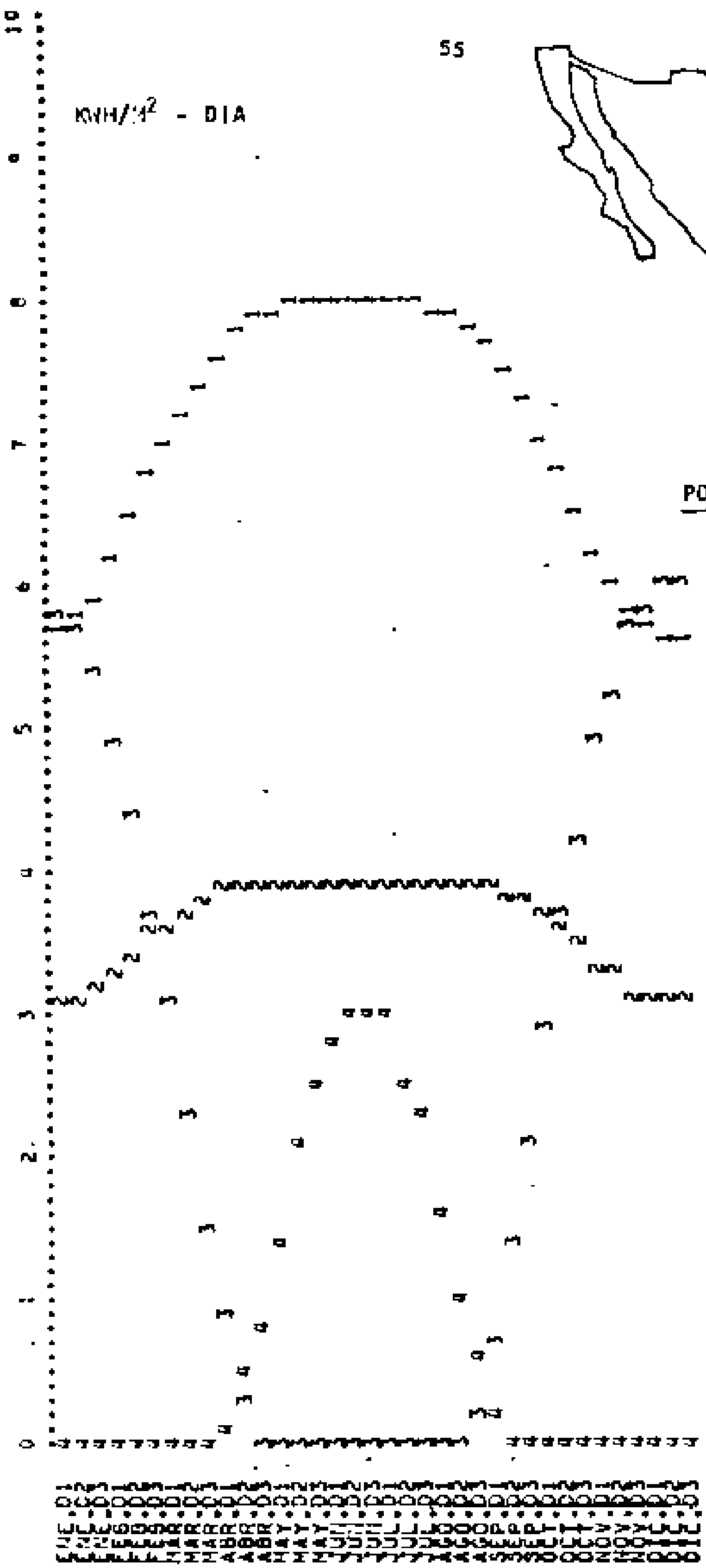


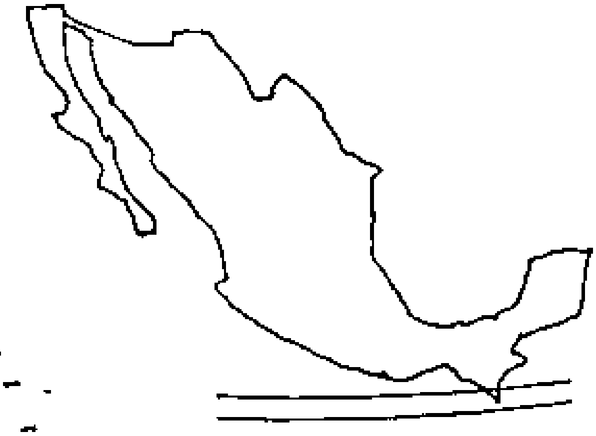
POBLACIONES :

Puerto Madero, Chis.

Cd. Hidálgo, Chis.

LATITUD 15° ± 0.5°





POBLACIONES :

Tapachula, Chis.

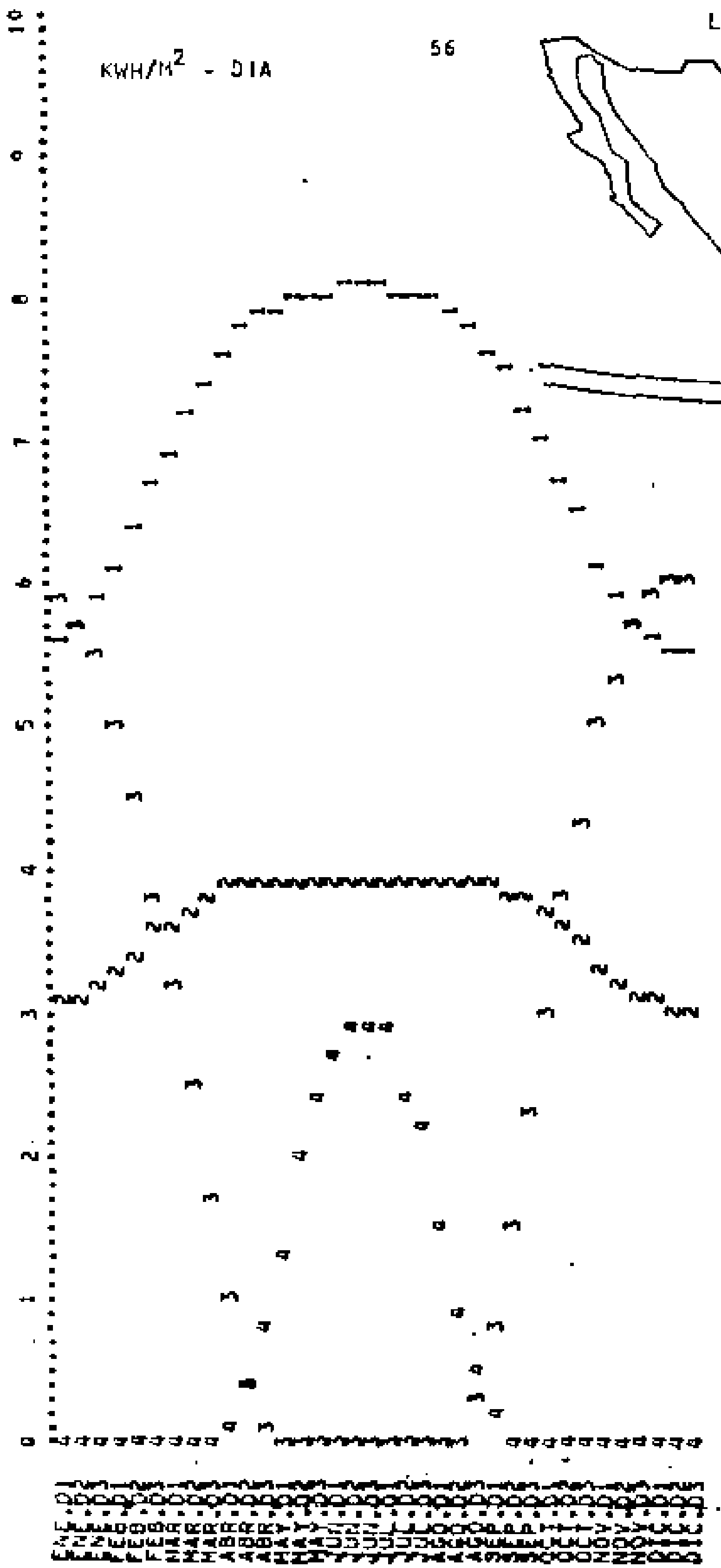
Tuxtla, Chis.

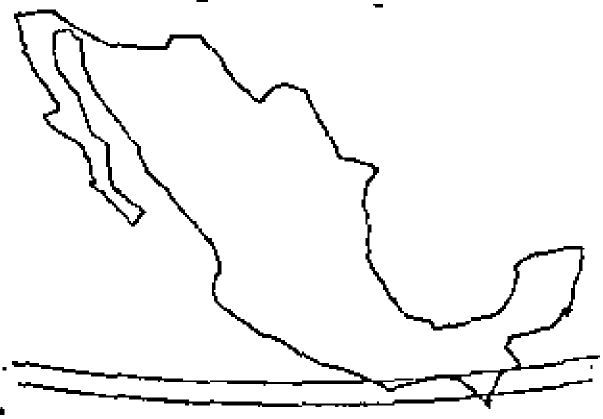
Huixtla, Chis.

La Gandeza, Chis.

Pto. Soconusco, Chis.

LATITUD 16° ± 0.5°

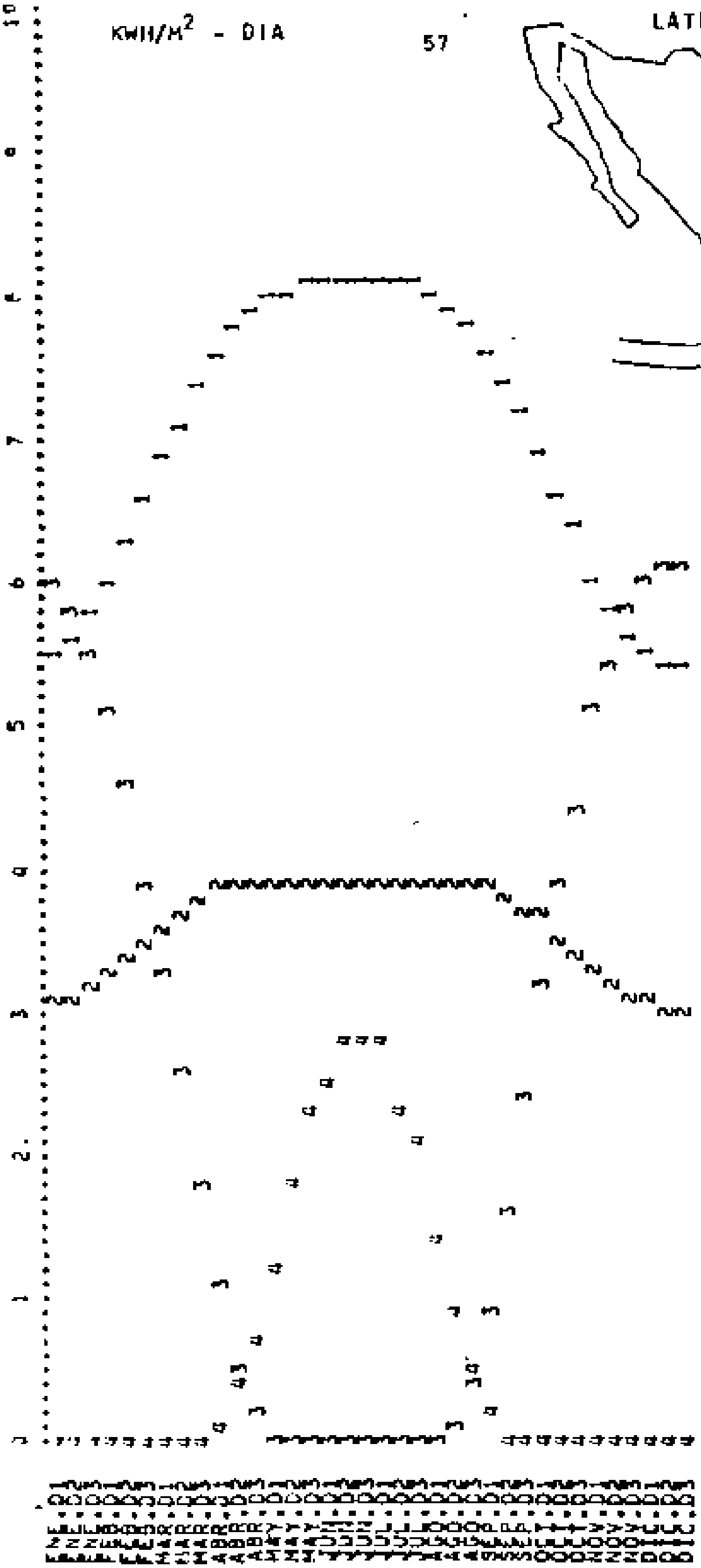


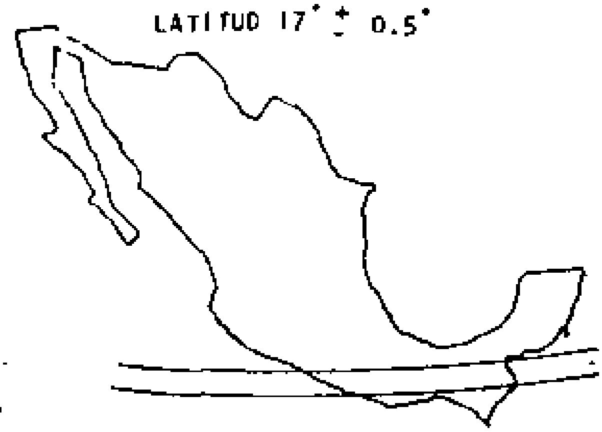


POBLACIONES:

Escuintla, Chis.
Mapastec, Chis.
Tonala, Chis.
Cd. Cuauhtémoc, Chis.
San Pedro, Chis.
Aurora, Chis.
Arriaga, Chis.
Pto. Angel, Oax.
Pochutla, Oax.
Chacalapa, Oax.
Pluma Hidalgo
Pto. Escondido, Oax.
Juchitan, Oax.
Mixtepec, Oax.
Salina Cruz, Oax.
Tehuantepec, Oax.
Atoyac, Oax.
Juchitan, Guerrero
Ometepec, Gro.
Copala, Gro.

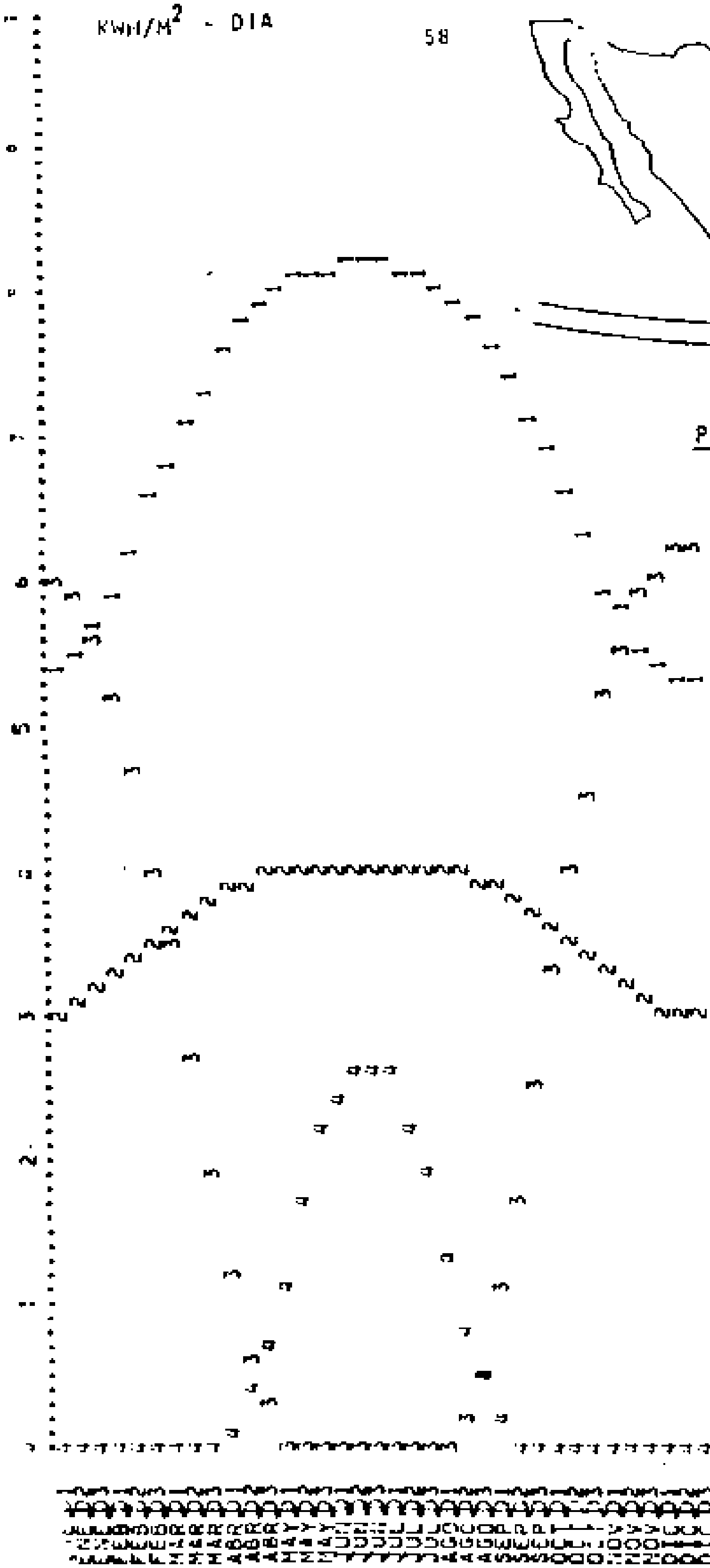
LATITUD 17° ± 0.5°

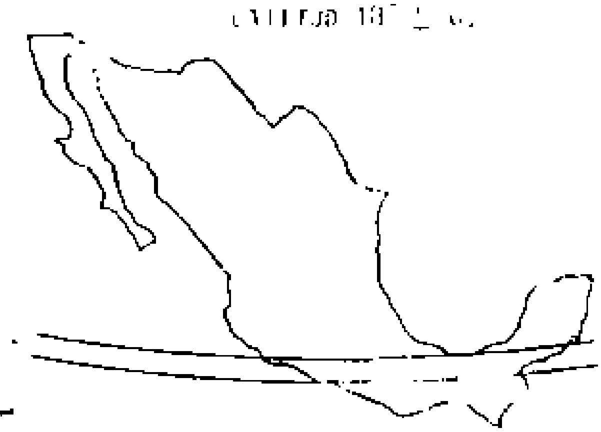




POBLACIONES :

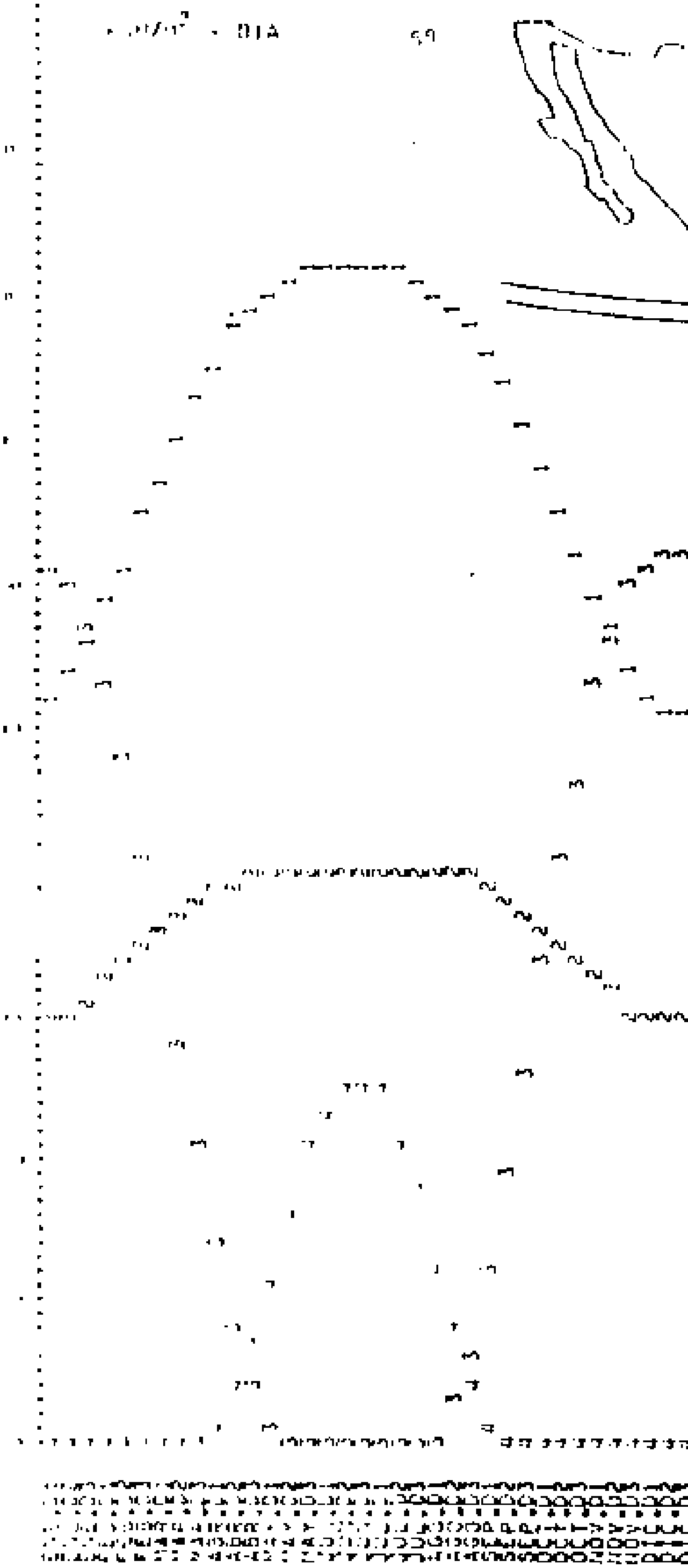
Tuxtla Gtz., Chis.
S.C. Las Casas, Chis.
Bonampak, Chis.
Tecpatan, Chis.
Bochil, Chis.
Matías Romero, Oax.
Ixcatlán, Oax..
Villa Alta, Oax.
Teposcolula, Oax.
Tlaxiaco, Oax.
Alotepec, Oax.
Acapulco, Gro.
Tulancingo, Gro.
Zapotitlan, Gro.
Tepetixtla, Gro.
Atoyac, Gro.
Cacalutla, Gro.

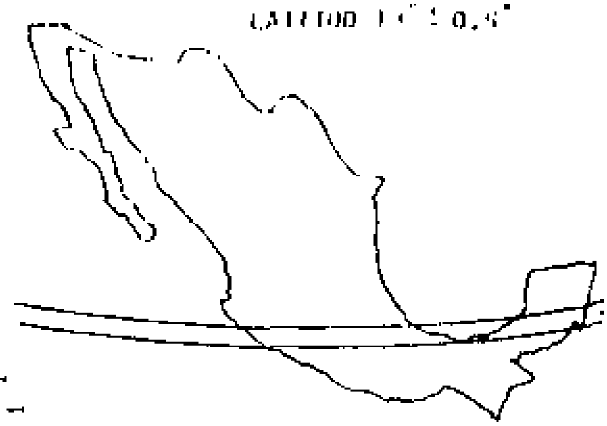




POBLACIONES :

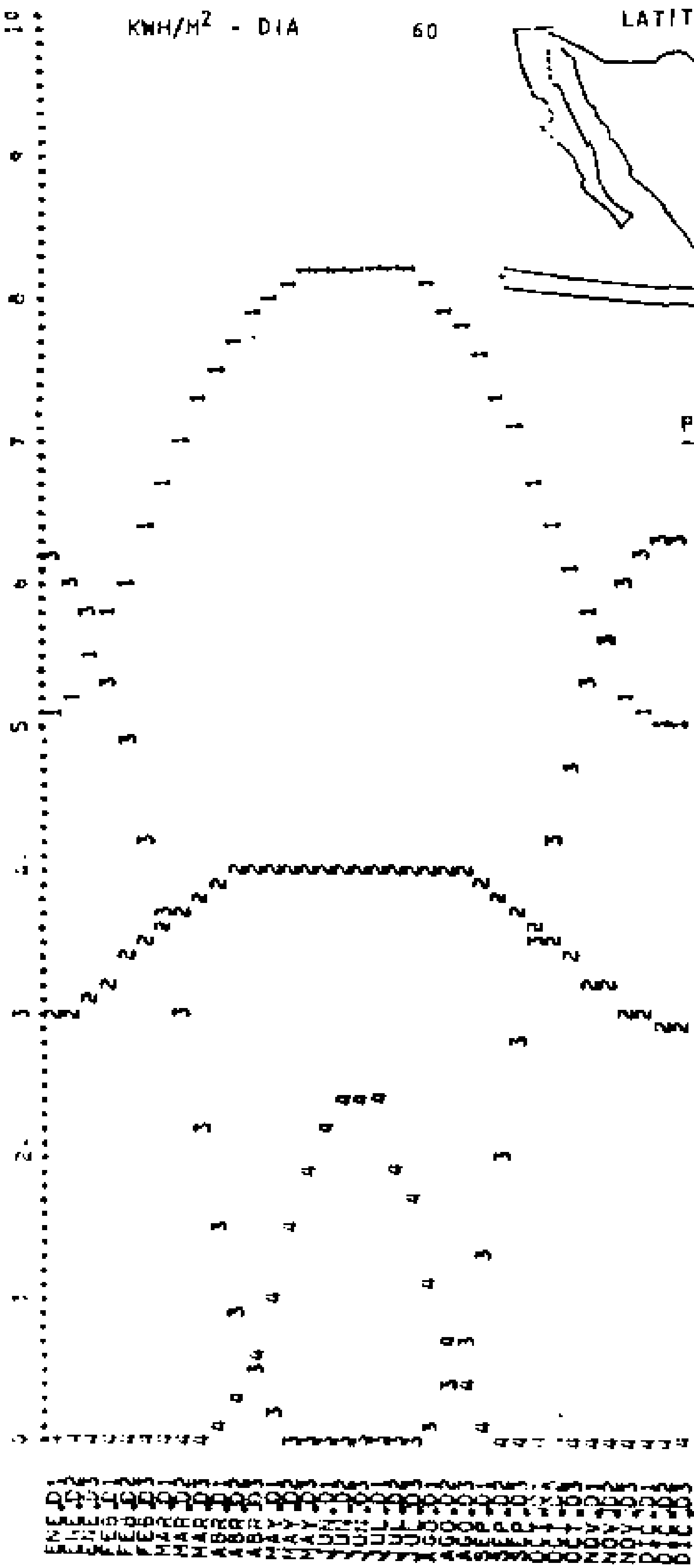
Chetumal, Q. R.
Santa Cruz, Q. R.
La Ahuada, Q. R.
Sn. Felipe, Camp.
Concepción, Camp.
Galerón, Camp.
Palijada, Camp.
Balancán, Tabasco
Triunfo, Tabasco
Cárdenas, Tabasco
Frontera, Tabasco
Chiltepec, Tabasco
Minatitlán, Ver.
Catemaco, Ver.
Cosamaloapan, Ver.
Papaloapan, Ver.
Sayula, Ver.
S.J. Evangelista, Ver.
Valle Nacional, Oax.
Tuxtepec, Oax.
Cieneguilla, Oax.
Miltepec, Oax.
Huautla, Oax.
Teopaxco, Oax.
Zapotitlán, Pbla.
Tulcingo, Pbla.
Ajolpan, Pbla.
Chitac, Pbla.
Coxcatlán, Pbla.
Zihuatanejo, Gro.
Lagunillas, Gro.
La Unión, Gro.
Coyuca, Gro.
Balsas, Gro.
Lázaro Cárdenas, Mich.
La Mira, Mich.
Turiscatio, Mich.
Ostula, Mich.
Maruata, Mich.
Playa Azul, Mich.



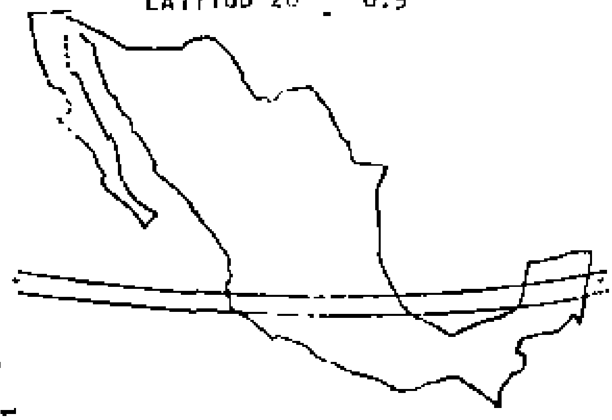


POBLACIONES :

Sta. Cruz Chico, Q. R.
Bacata, Q. R.
Placer, Q. R.
Aguada, Camp.
Morelos, Camp.
Juárez, Camp.
Pto. Real, Camp.
Cd. del Carmen, Camp.
Frontera, Tabasco
Tuxtla Gtz., Ver.
Veracruz, Ver.
Orizaba, Ver.
Córdoba, Ver.
Medellín, Ver.
Barra de Chachalacas, Ver.
Puebla, Pbla.
Tecamachalco, Pbla.
Atlixco, Pbla.
Cholula, Pbla.
Tehuacán, Pbla.
Amozoc, Pbla.
Tlaxcala, Tlax.
Huamanta, Tlax.
Cuernavaca, Morelos
Jojutla, Morelos
Puente de Ixtla, Morelos
Distrito Federal
Toluca, Edo.de México
Tenancingo, Edo. México
Victoria, Edo. de México
Uruapan, Mich.
Zitacuaro, Mich.
Apatzingan, Mich.
Patzcuaro, Mich.
Cuautitlán, Jalisco
Tuxpan, Jalisco
Ayotitlán, Jalisco
Tonila, Jalisco
Colima, Col.
Manzanillo, Col.
Tecomán, Col.

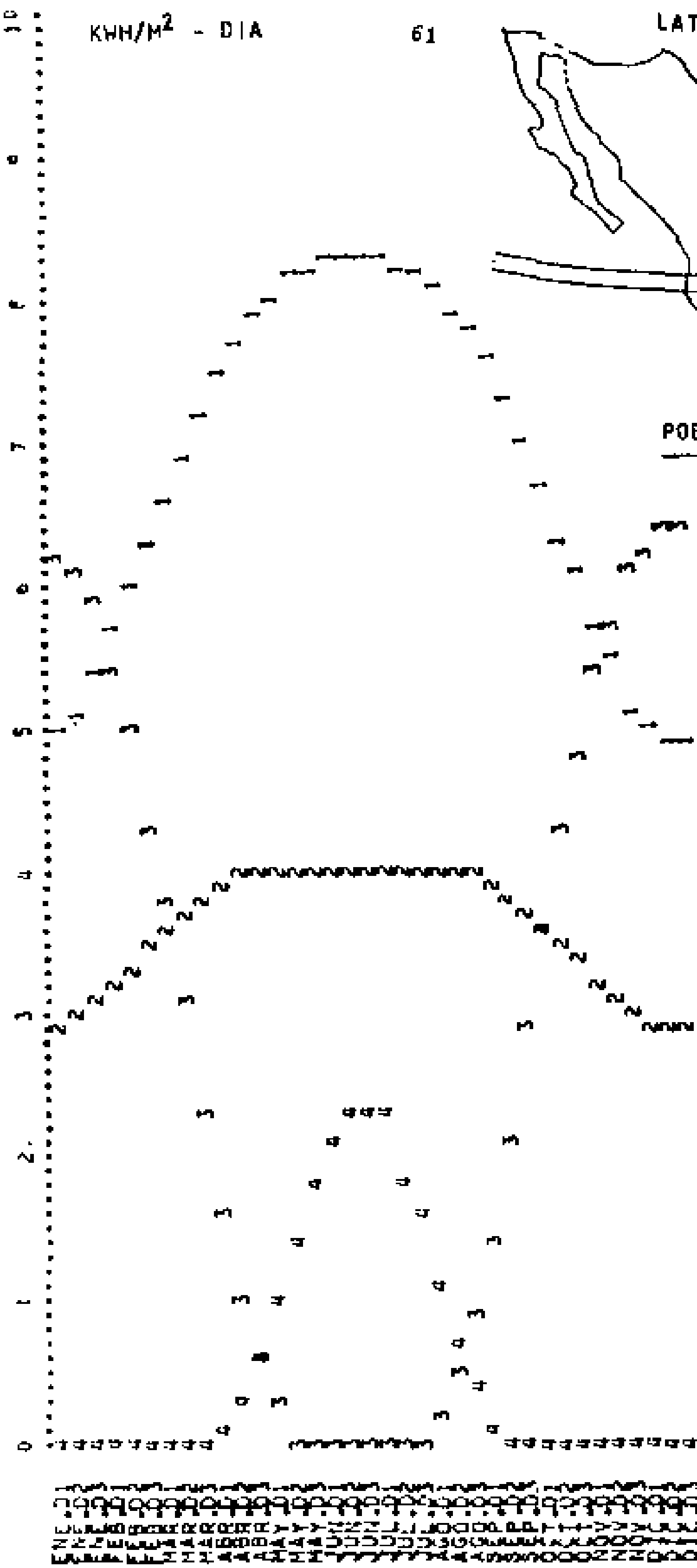


LATITUD 20° ± 0.5°



POBLACIONES :

Vigía Chico, Q. R.
Tulum, Q. R.
Cozumel, Q. R.
Uxmal, Yuc.
Peto, Yuc.
Ticul, Yuc.
Becanchen, Yuc.
Homul, Yuc.
Valladolid, Yuc.
Campeche, Camp.
Bolonchenticul, Camp.
China, Camp.
Iturbide, Camp.
Jalapa, Ver.
Tecolutla, Ver.
Papantla, Ver.
Poza Rica, Ver.
Tezuitlán, Pbla.
Tetela, Pbla.
Jalpan, Pbla.
Pachuca, Hidalgo
Tula, Hidalgo
Actópan, Hidalgo
Tulancingo, Hidalgo
Sn. Juan del Río, Qro.
Querétaro, Qro.
Salvatierra, Gto.
Muro León, Gto.
Pénjamo, Gto.
Celaya, Gto.
Tlanepantla, Edo. México
El Oro, Edo. de México
Jilotepec, Edo. de México
Otumba, Edo. de México
Pueblo Nuevo, Edo. de Méx.
Morelia, Mich.
Zamora, Mich.
Paracho, Mich.
Cd. Guzmán, Jalisco
Cocula, Jalisco
Tizapán, Jalisco
Jocotepec, Jalisco



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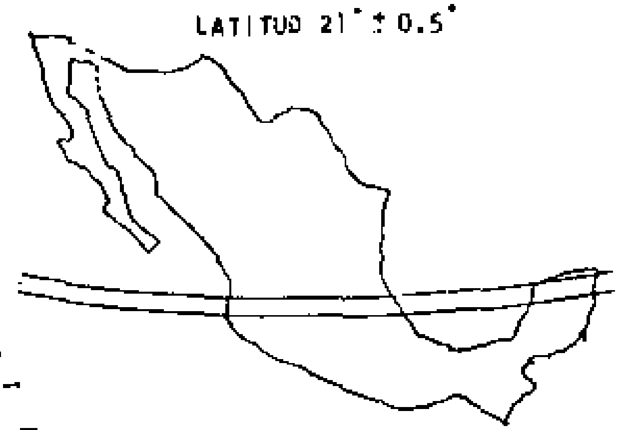
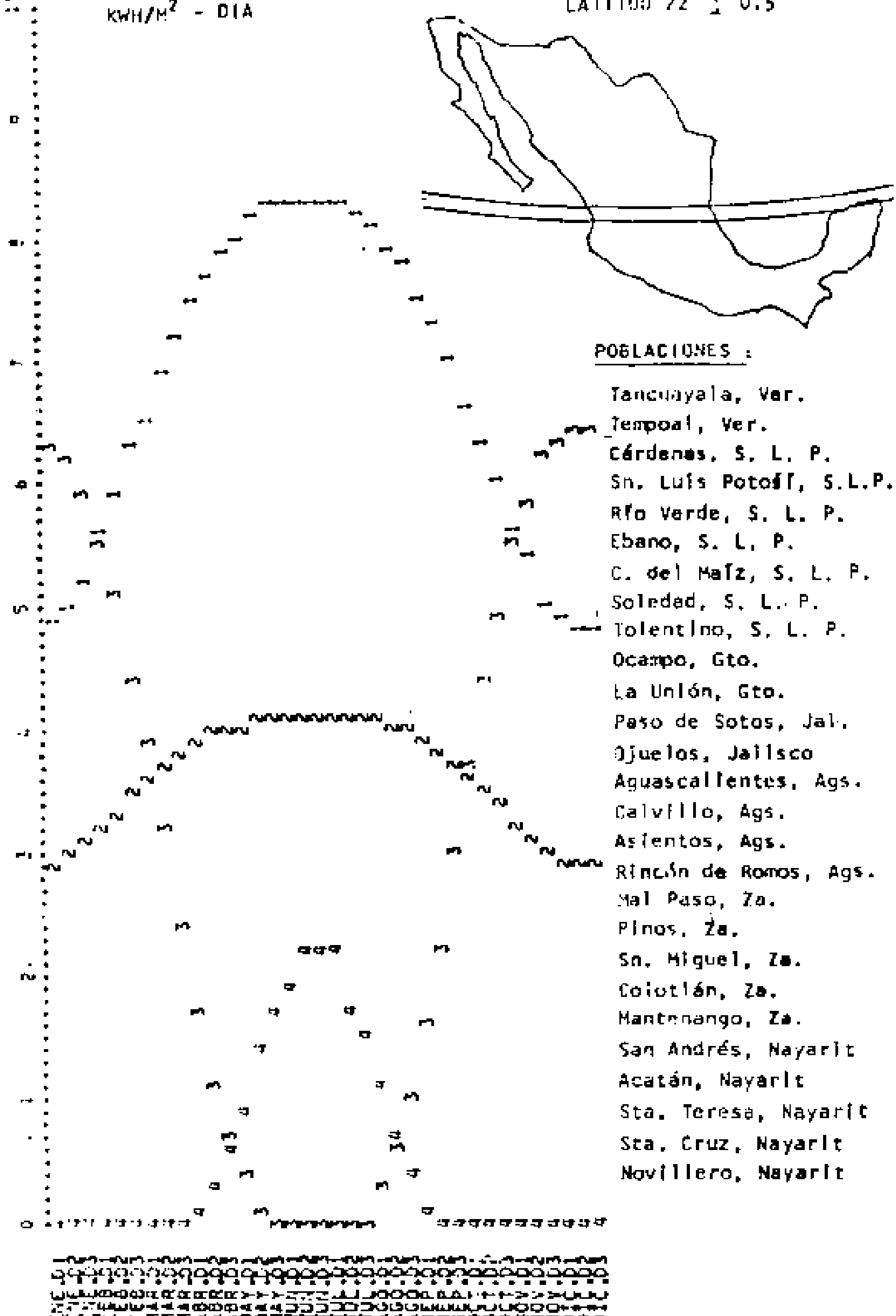
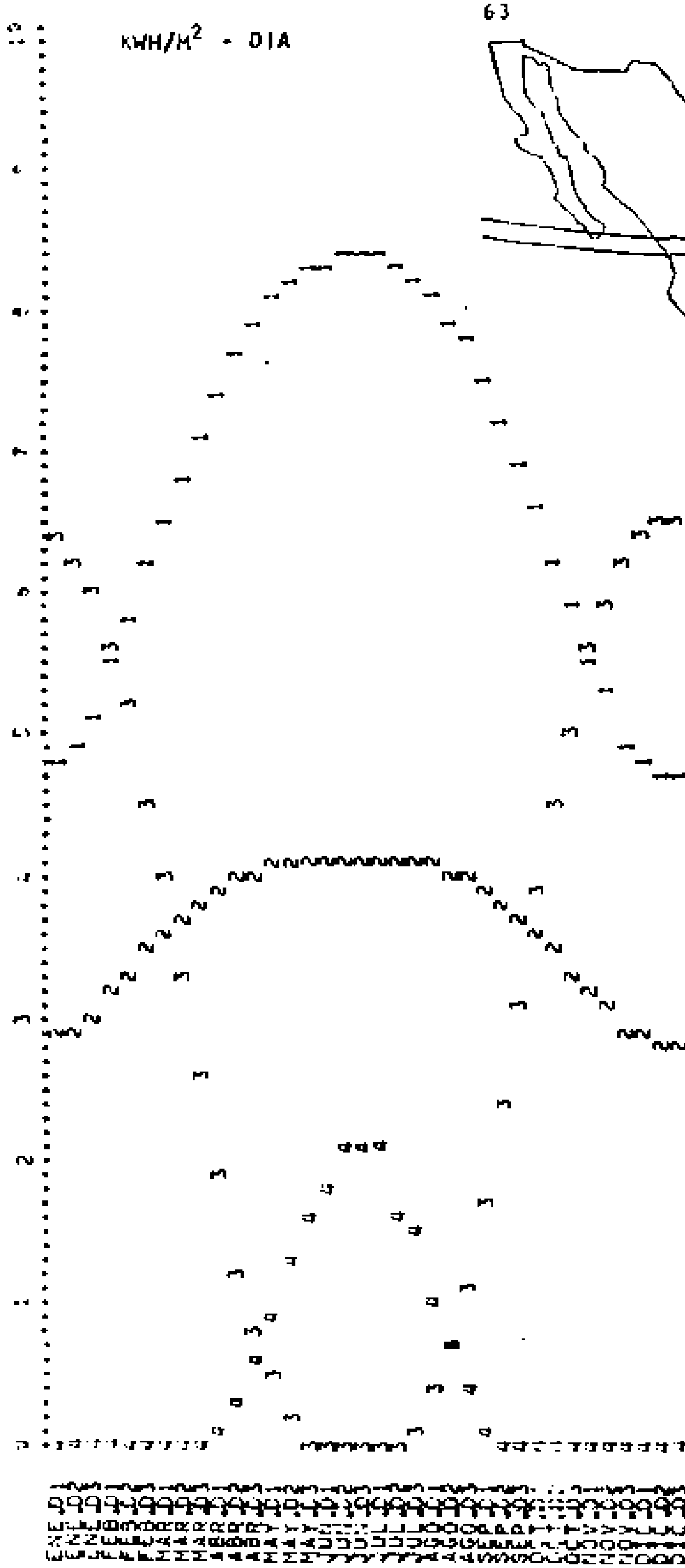
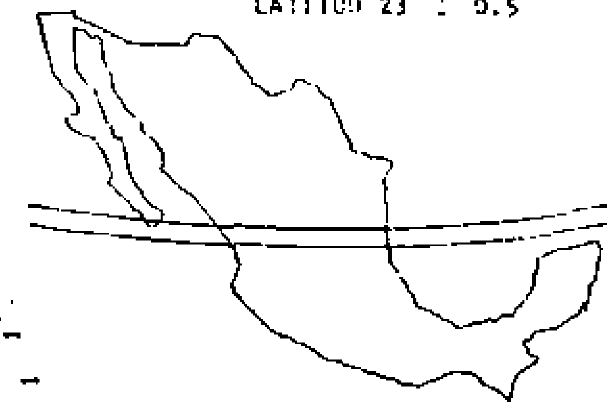


POBLACIONES :

Can Cun, Q. R.
Pto. Morelos, Q. R.
Pto. Juárez, Q. R.
Leona Vicario, Q. R.
Islas Mujeres, Q. R.
Mérida, Yuc.
Progreso, Yuc.
Motul, Yuc.
Izamal, Yuc.
Tizimín, Yuc.
Tuxpán, Ver.
Alamo, Ver.
Tantoyuca, Ver.
Barra de Tuxpán, Ver.
Cobos, Ver.
Huayacobos, Ver.
Jalpan, Pbla.
Molango, Hidalgo
Zacoaltipán, Hidalgo
Zulapán, Hidalgo
Huejutla, Hidalgo
Tlaxco, Hidalgo
Colón, Qro.
Jalpan, Qro.
Guanajuato, Gto.
Silao, Gto.
S. Miguel Allende, Gto.
Providencia, Gto.
Irapuato, Gto.
Guadalajara, Jal.
Pto. Vallarta, Jal.
Lagos, Jal.
Juchitán, Jal.
Arandas, Jal.
Tepic, Nayarit
Ixtapa, Nayarit
Valle de Banderas, Nayarit
Compostela, Nayarit
La Yesca, Nayarit
Sn. Marcos, Nayarit
Camotlán, Nayarit

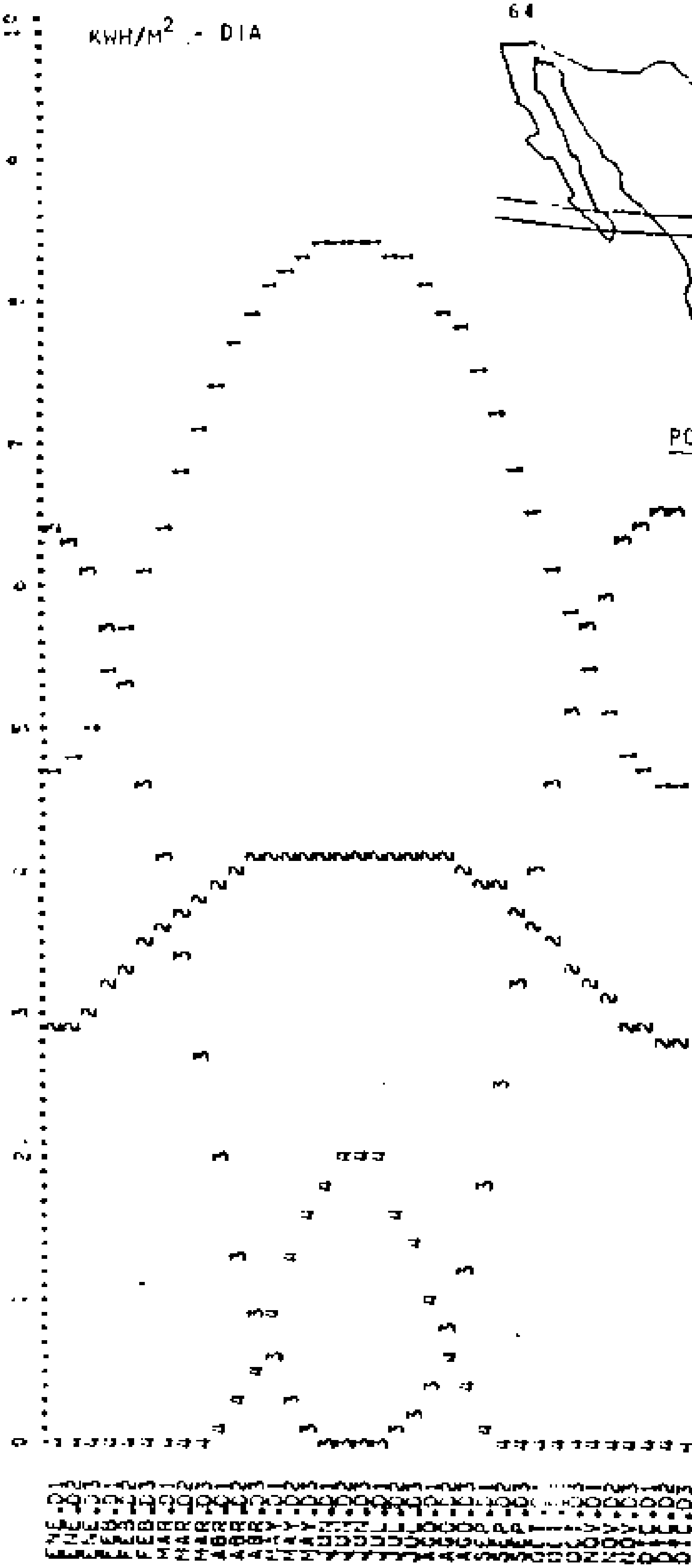

KWH/M² - DIA
LATITUD 22° ± 0.5°
POBLACIONES :
Tancuayala, Ver.
Tempoal, Ver.
Cárdenas, S. L. P.
Sn. Luis Potosí, S.L.P.
Río Verde, S. L. P.
Ebano, S. L. P.
C. del Maíz, S. L. P.
Soledad, S. L. P.
Tolentino, S. L. P.
Ocampo, Gto.
La Unión, Gto.
Paso de Sotos, Jal.
Ojuelos, Jalisco
Aguascalientes, Ags.
Calvillo, Ags.
Asientos, Ags.
Rincón de Romos, Ags.
Mal Paso, Za.
Pinos, Za.
Sn. Miguel, Za.
Colotlán, Za.
Mantenango, Za.
San Andrés, Nayarit
Acatán, Nayarit
Sta. Teresa, Nayarit
Sta. Cruz, Nayarit
Novillero, Nayarit





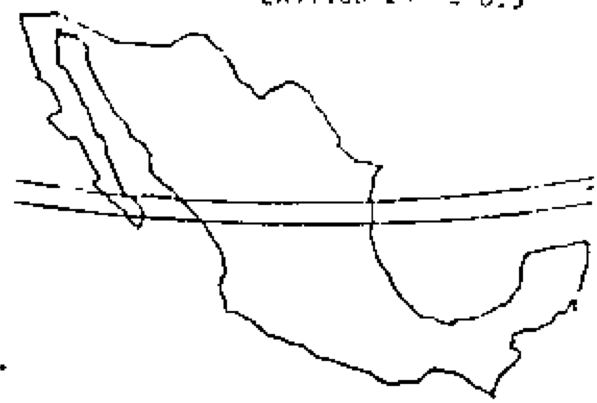
POBLACIONES :

Cd. Mante, Tamps.
Ignacio Zaragoza, Tamps.
Gomez Farías, Tamps.
Tula, Tamps.
Aldama, Tamps.
Moctezuma, S. L. P.
Arista, S. L. P.
Guadalcazar, S. L. P.
Sn. José, S. L. P.
Carmen, S. L. P.
Vallejo, S. L. P.
Zacatecas, Za.
Guadalupe, Za.
Jerez, Za.
Calera, Za.
La Bafa, Za.
Llano Grande, Dgo.
Pueblo Nuevo, Dgo.
Sn. Francisca, Dgo.
Teneraca, Dgo.
Milpillas, Dgo.
Buena Vista, Nayarit
Huajicori, Nayarit
Escuinapa, Sinaloa
Rosario, Sinaloa
B. Unión, Sinaloa
Mazatlán, Sinaloa
Concordia, Sinaloa
Pánuco, Sinaloa
Sn. Lucas, B.C.S.
Plutarco Elías C., B.C.S.
Mira Flores, B.C. S.
Sta. Catarina, B.C.S.
El Pescadero, B. C.S.



64

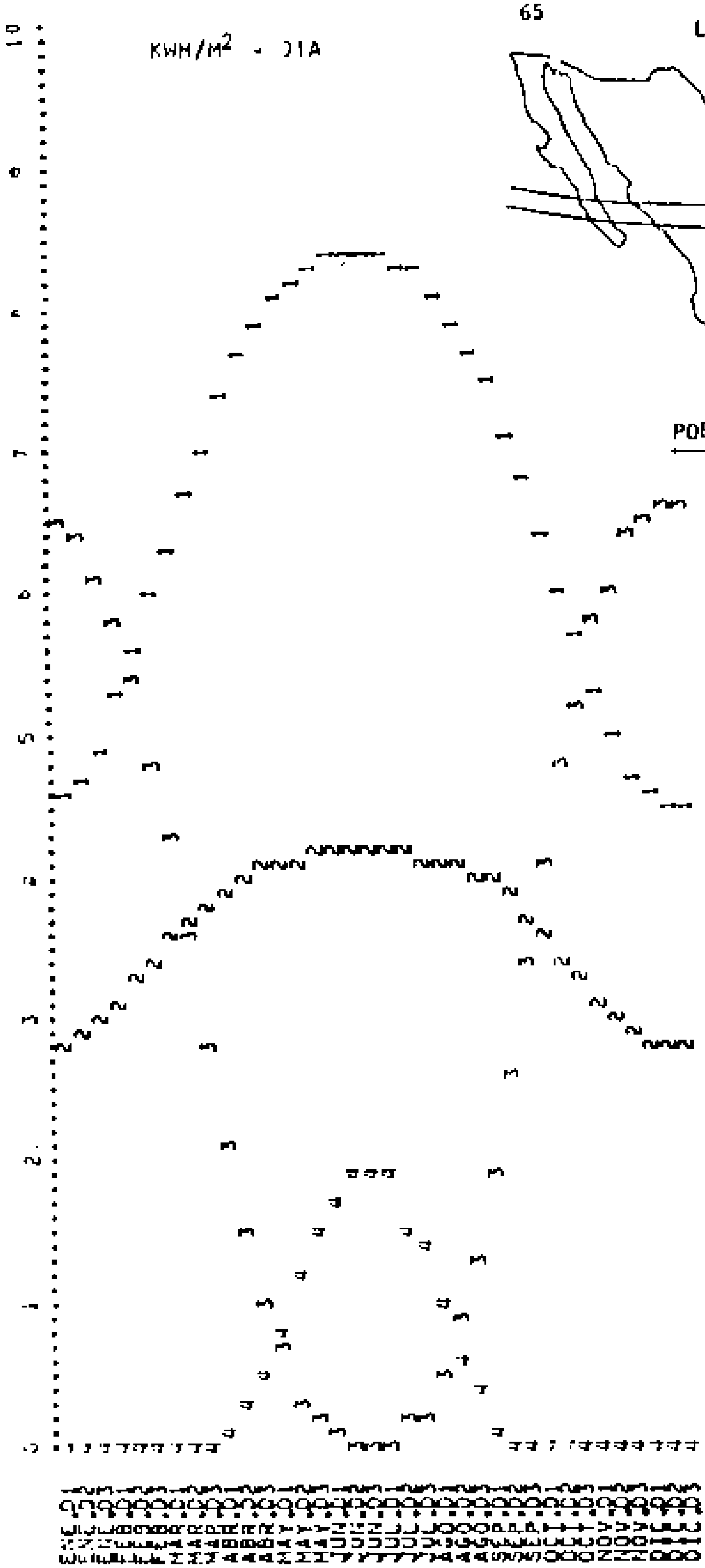
LATITUD 24° ± 0.5°

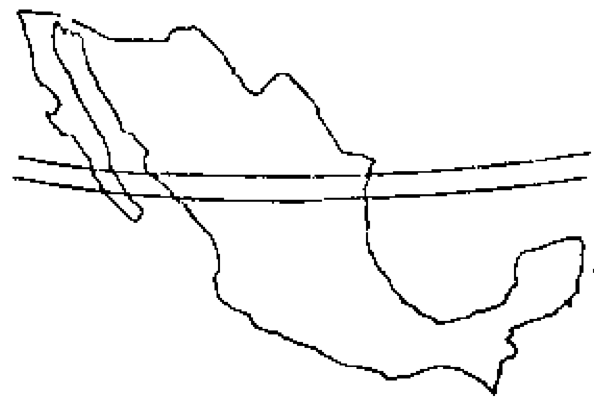


POBLACIONES :

Cd. Victoria, Tamps.
La Pesca, Tamps.
Barretal, Tamps.
Padilla, Tamps.
Carrizos, Tamps.
Villagran, Tamps.
Union Morales, Tamps.
Canela, N. L.
Miguel, N. L.
Dr. Arrollo, N. L.
Zaragoza, N. L.
Sn. Juan, N.L.
Tinajas, N. L.
Majomal, Zacatecas
Sta. Eugenia, Za.
Sn Andrés, Za.
El Sombrerete, Za.
El Arenal, Za.
Pacheco, Za.
Camacho, Za.
Juan Aldama, Za.
Nieves, Za.
Madero, Dgo.
Gavilanes, Dgo.
Jiborillas, Dgo.
V. Guerrero, Dgo.
Morcillo, Dgo.
Panuco, Dgo.
El Limón, Sin.
Elota, Sin.
Sn. Juan, Sin.
Conitaco, Sin.
La Paz, B. C. S.
Santiago, B. C. S.
Los Barriles, B. C. S.
Conejo, B. C. S.
L. Ana, B. C. S.

LATITUD 25° ± 0.5°



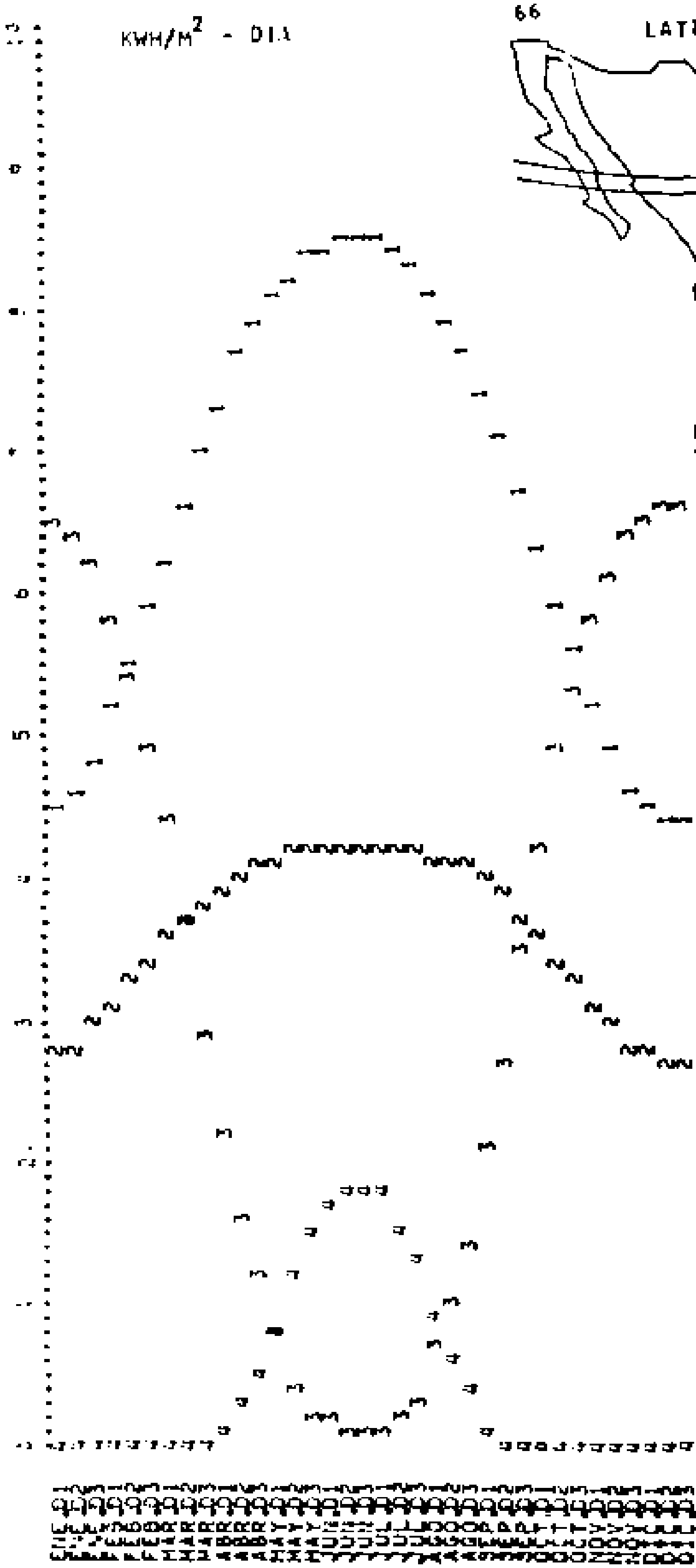


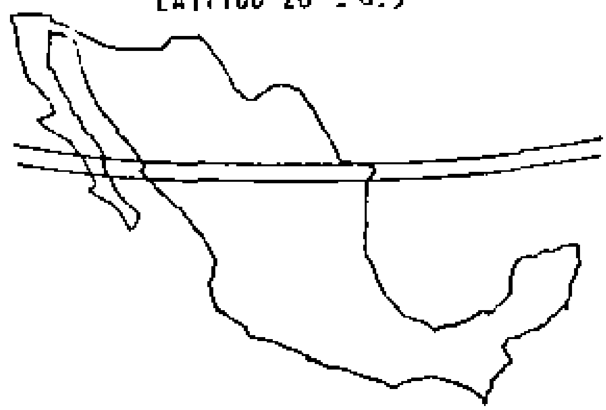
POBLACIONES:

Burgos, Tamps.
Mendez, Tamps.
Soldadito, Tamps.
Corral, Tamps.
Nicolás, Tamps.
Sn. Antonio, NL.
Rayones, N.L.
Sn. Rafael, N. L.
Pastor, N. L.
Monte Morelos, N. L.
Caderita, N. L.
El Cercado, N. L.
Saltillo, Coahuila
Parras, Coahuila
Torreón, Coahuila
Viesca, Coahuila
Matamoros, Coahuila
La Rosa, Coahuila
Gómez Palacios, Dgo.
Atotonilco, Dgo.
Rodeo, Dgo.
Tongo, Dgo.
Corrales, Dgo.
Topia, Dgo.
Angostura, Sin.
Culiacán, Sin.
Huamuchil, Sin.
La Rastra, Sin.
Pericos, Sin.
Guasave, Sin.
Sn. Carlos, B. C. S.
El Refugio, B. C. S.
Villa Constitucion, B.C.S.
Queretaro, Qro.

66

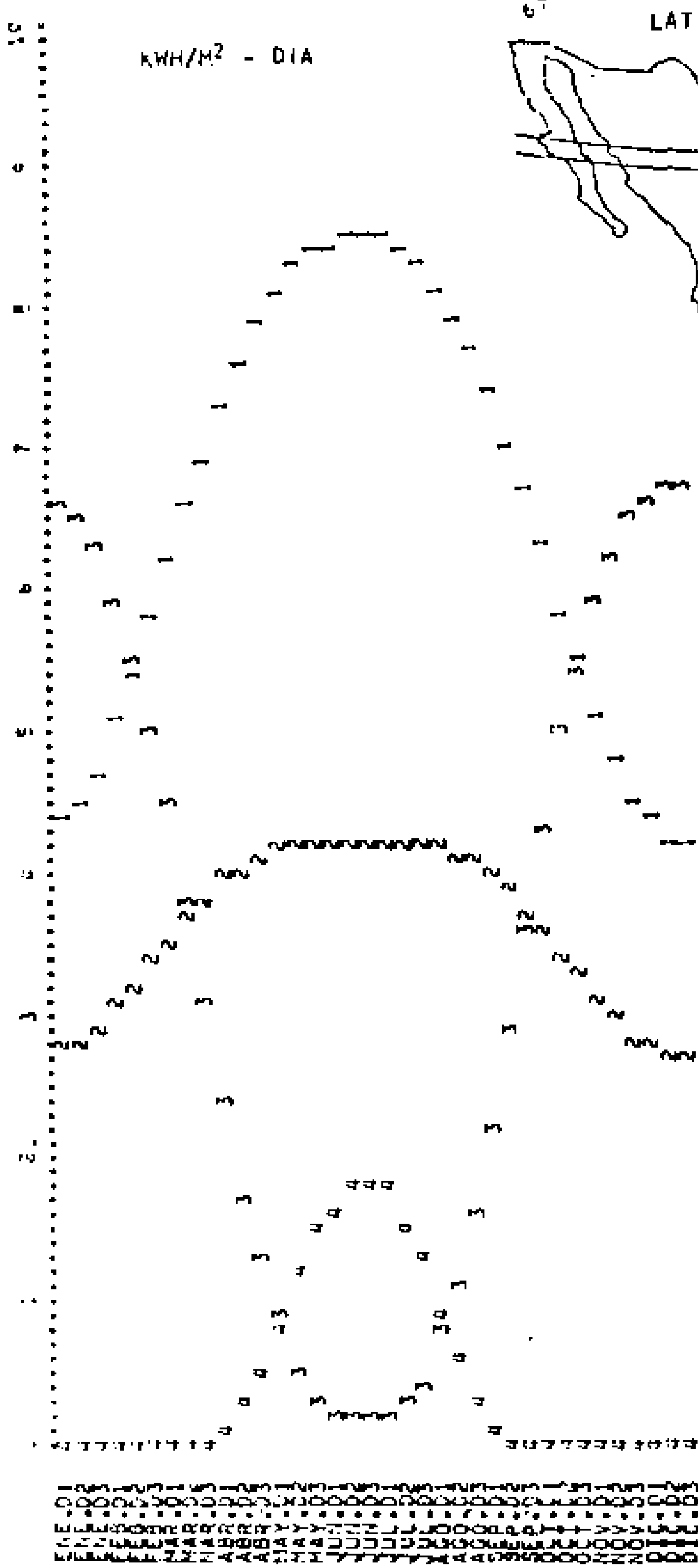
LATITUD 26° ± 0.5°





POBLACIONES :

Matamoros, Tamps.
Bagdad, Tamps.
Laguna Barril, Tamps.
Reynosa, Tamps.
Dr. Coss, N. L.
Los Herrera, N. L.
Abasolo, N. L.
García, N. L.
Monterrey, N.L.
Australia, Coahuila
Colorado, Coahuila
Guadalupe, Coahuila
Las Delicias, Coahuila
Charco de Risa, Coahuila
Mapimí, Dgo.
Zape, Dgo.
Jarolito, Dgo.
Conejos, Dgo.
Yermo, Dgo.
Villa Hidalgo, Dgo.
Redondeado, Chih.
Babrigane, Chih.
El Vergel, Chih.
Real la Dura, Chih.
Sn. Miguel, Sin.
Sn. Blass, Sin.
Chinobampo, Sin.
Ocorini, Sin.
Sn. José, Sin.
Pozo Grande, B.C.S.
El Pabellón, B. C.S.
La Purísima, B. D. S.
Sta. Isabel, B. C. S.



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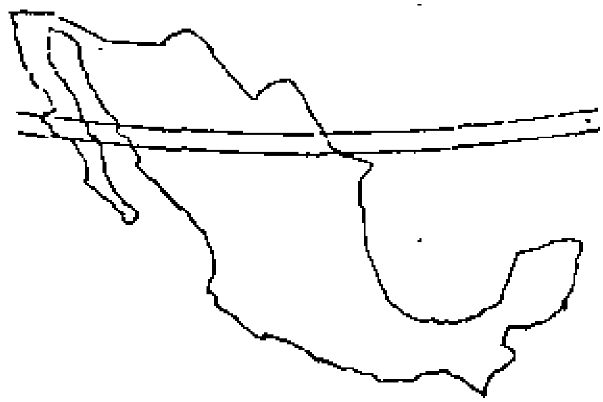
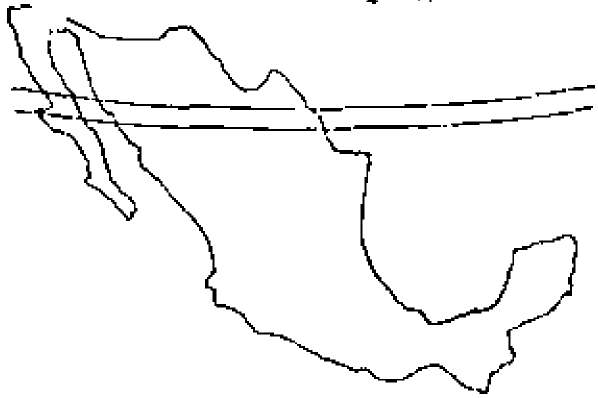


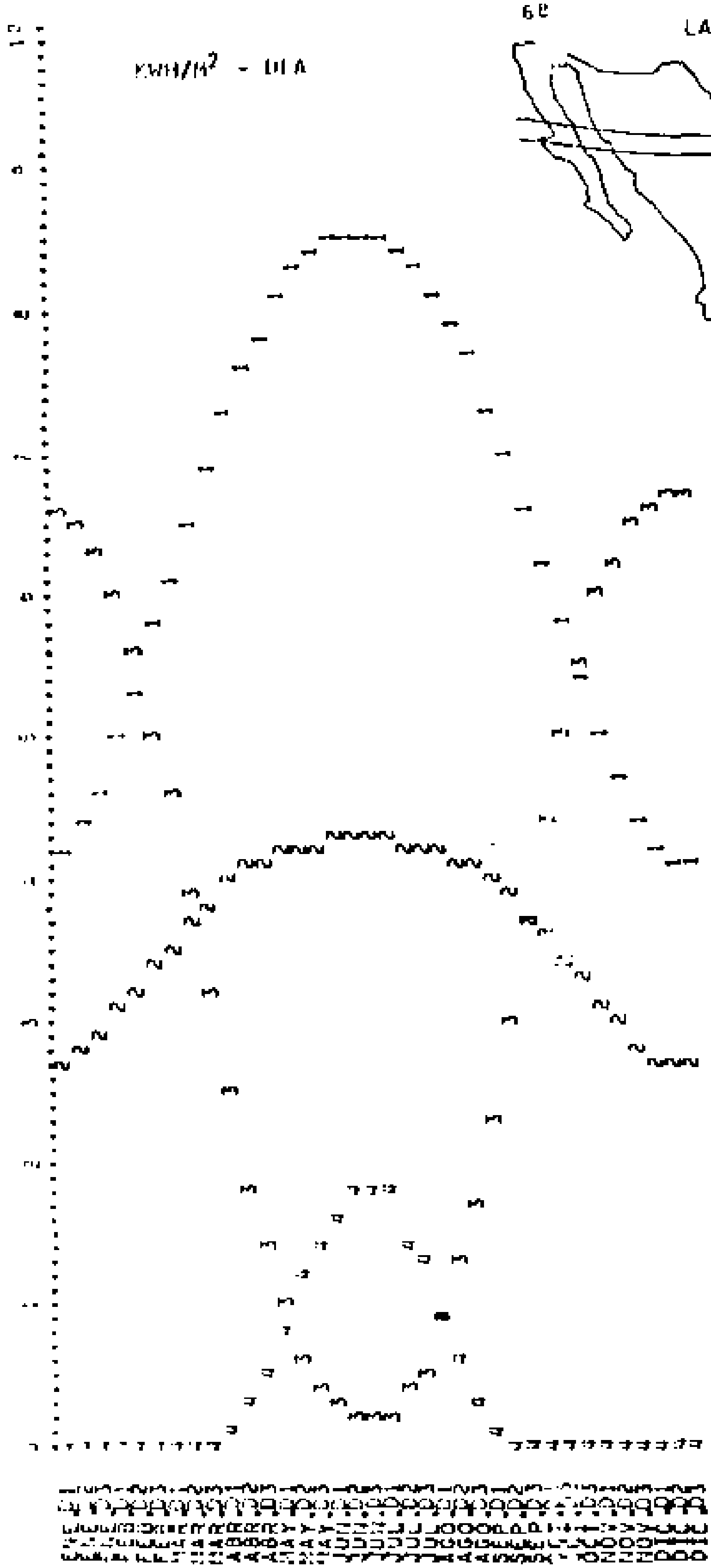
POBLACIONES :

- Las Tortillas, Tamps.
- Mier, Tamps.
- Monclova, Coahuila
- Romero, Coahuila
- Progreso, Coahuila
- Sardinas, Coahuila
- Ocampo, Coahuila
- El Buxido, Coahuila
- Jimenéz, Chih.
- Jacales, Chih.
- Maravillas, Chih.
- El Tule, Chih.
- Piedras Verdes, Chih.
- Navajoa, Son.
- Alamos, Son.
- Camoa, Son.
- San Bernardino, Son.
- Cd. Obregón, Son.
- Sta. Rosalía, B. C. S.
- Bruno, B. C. S.
- Querente, B. C. S.
- Muleje, B. C. S.
- Zacatoso, B. C. S.

6B

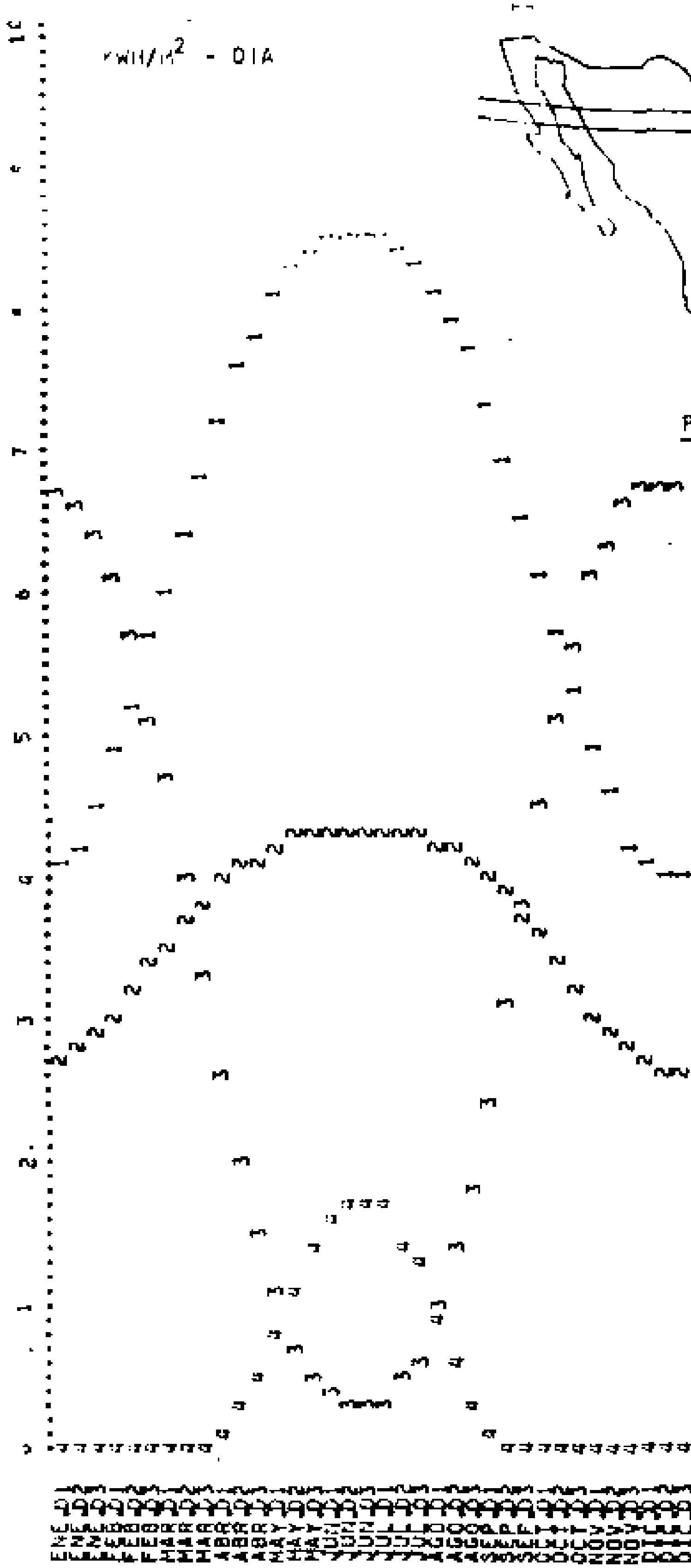
LATITUD 28° ± 0.5°



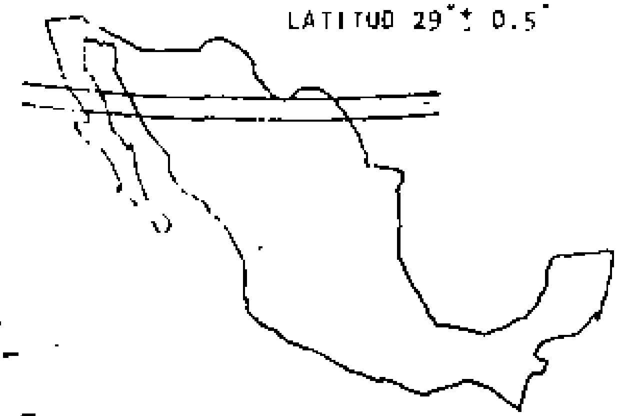


POBLACIONES :

N. Laredo, Tamps.
Colombia, NL
Nueva Rosita, Coahuila
Sabinas, Coahuila
Tanque, Coahuila
Muzquiz. Coahuila
Sta. Ana, Coahuila
Sn. Lucas, Coahuila
Camargo, Chih.
Delicias, Chih.
Naica, Chih.
La Cruz, Chih.
La Perla, Chih.
La Morita, Chih.
Guaymas, Son.
Nuri, Son.
Empalme, Son.
Trinidad, Son.
Mulatos, Son.
Ojo de Liebre, B.C.S.
Mexquital, B. C. S.
La Laguna, B. C. S.
Guerrero Negro, B. C. S.
Rosarito, B. C. N.
Sto. Domingo, B. C. N.
El Arco, B. C. N.
Sta. Gertrudis, B. C. N.



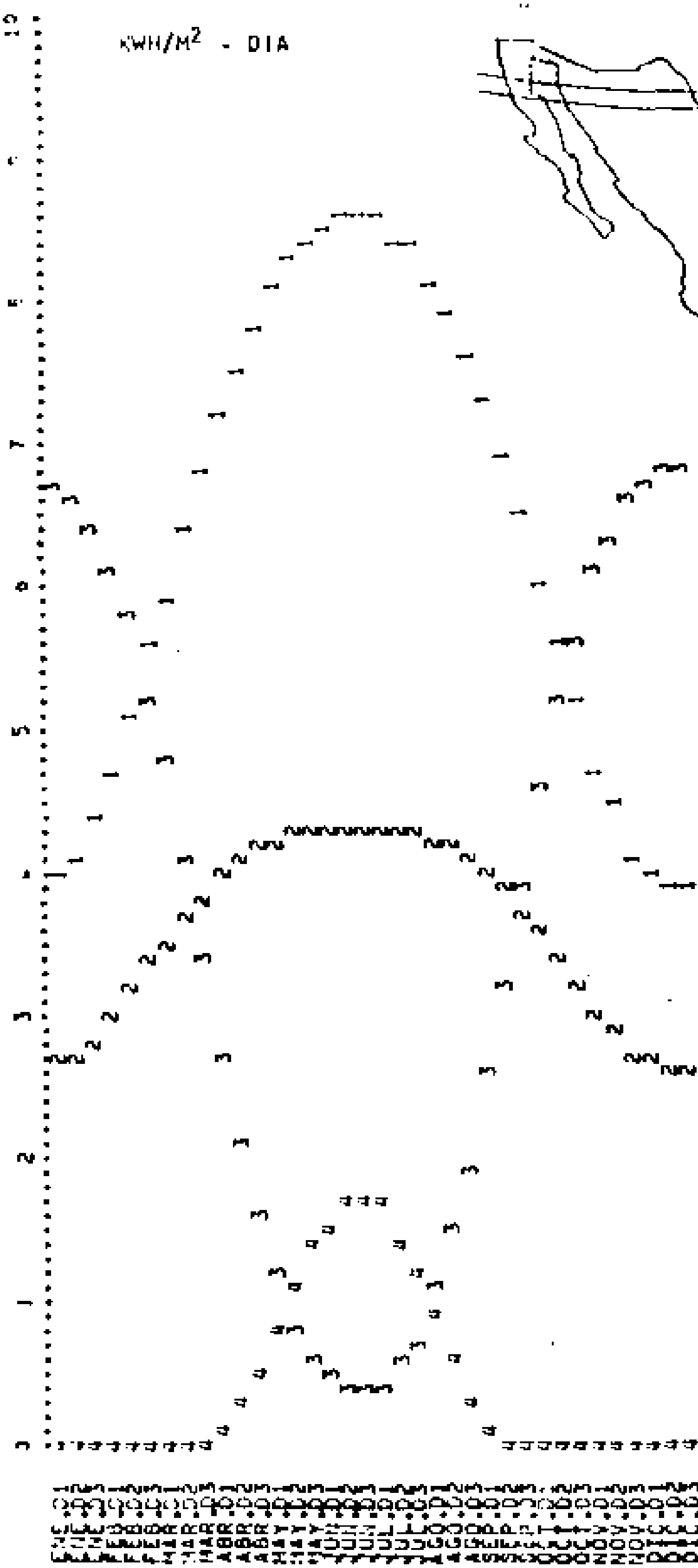
LATITUD 29° ± 0.5°

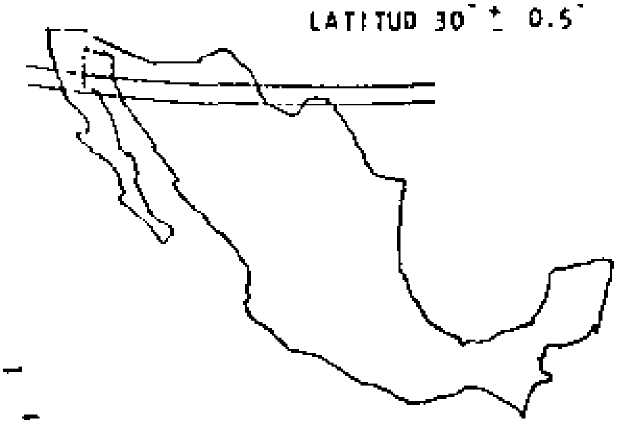


POBLACIONES :

Piedras Negras, Coahuila
Cd. Acuña, Coahuila
Sto. Domingo, Coahuila
El Chupadero, Coahuila
La Cabecera, Coahuila
El Moral, Coahuila
Chihuahua, Chih.
La Mula, Chih.
Sacramento, Chih.
El Mulato, Chih.
Sta. Clara, Chih.
Aldama, Chih.
Quino, Son.
Tepache, Son.
La Colorada, Son.
Mulatos, Son.
Masatán, Son.
Batuc, Son.
Prieta, B.C.N.
Isla Angel, B.C.N.

LATITUD 30° ± 0.5°





POBLACIONES :

Juárez, Chih.

Conchos, Chih.

Pilares, Chih.

Los Fresnos, Chih.

El Sueco, Chih.

Ojo Caliente, Chih.

Nacosari, Son.

Aconchi, Son.

Cucurpe, Son.

Carbo, Son.

El Burro, Son.

Puerto Lobos, Son.

Molino Lasi, B.C.N.

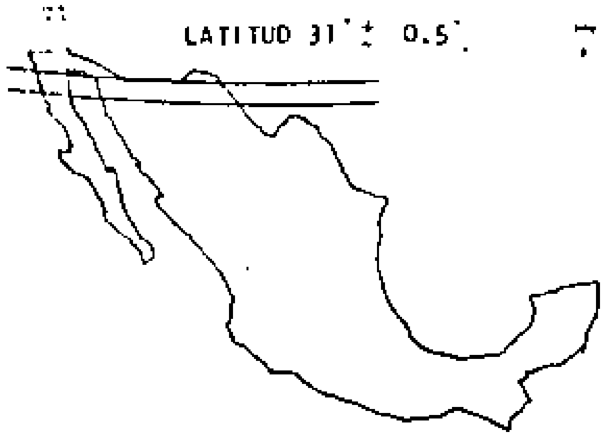
Rosario, B. C. N.

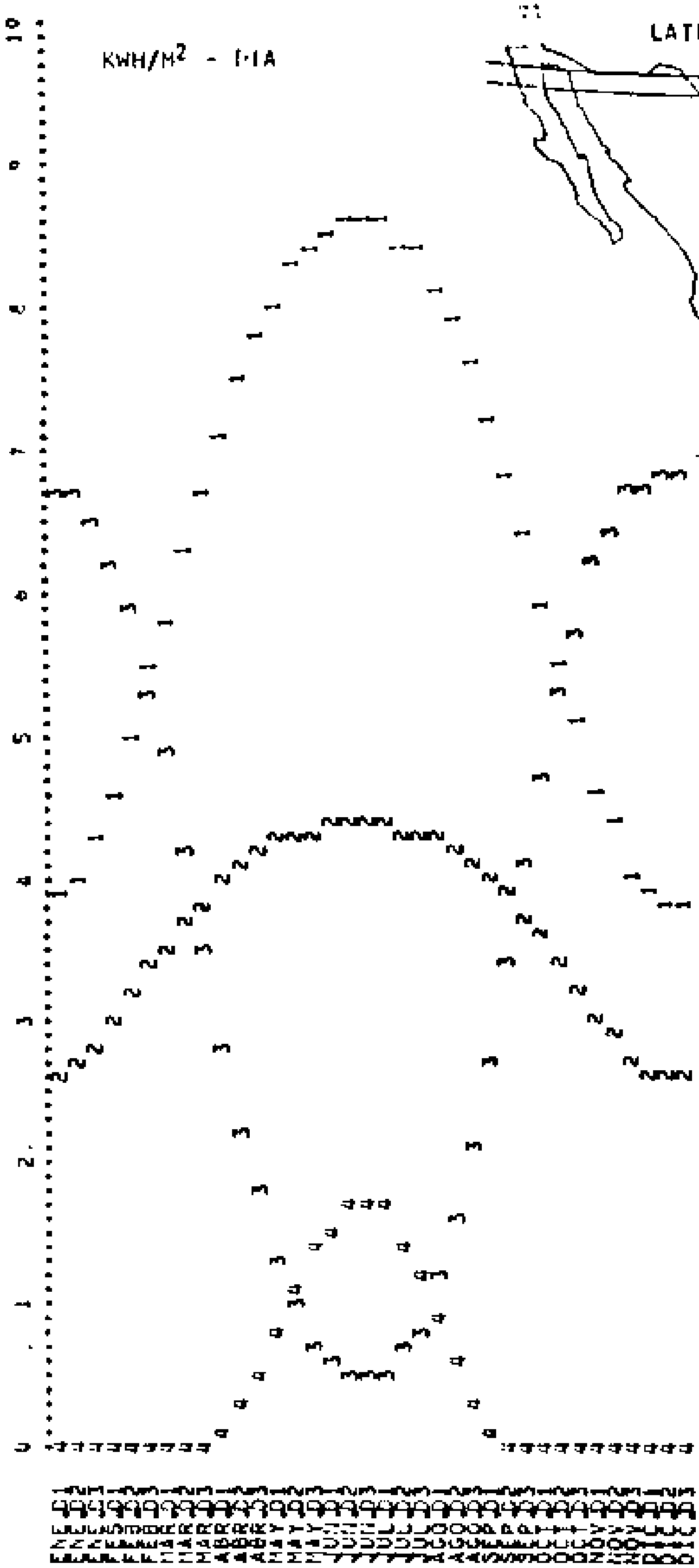
Sta. Catarina, B.C.N.

Jaraguacito, B.C.N.

Sn. Agustín., B.C.N.

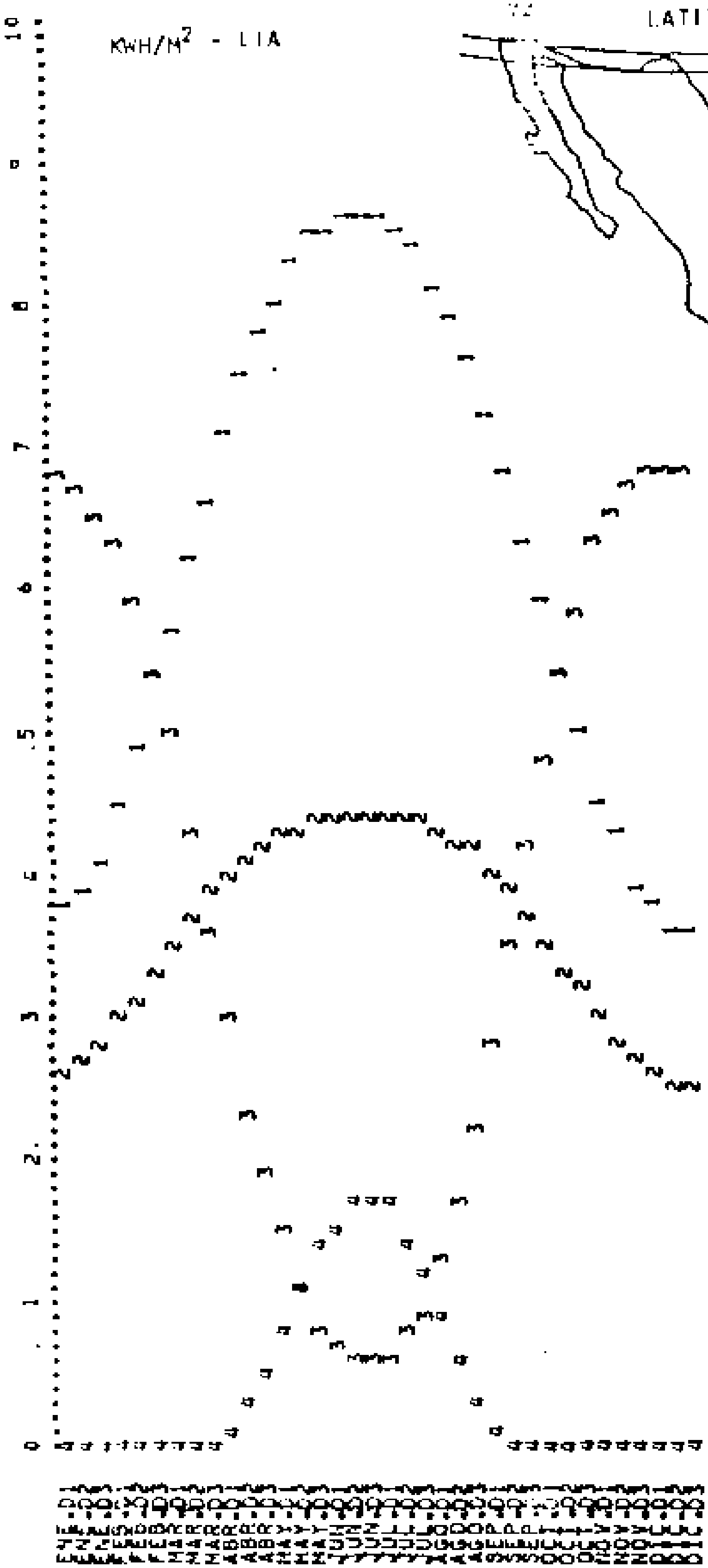
LATITUD 31° ± 0.5°

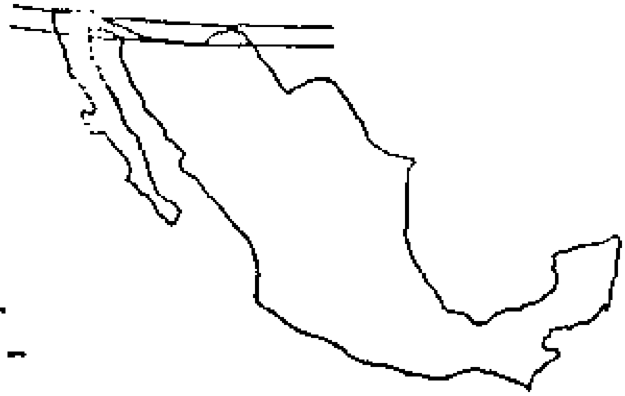




POBLACIONES :

El Barreal, Chih.
Corralitos, Chih.
Lucero, Chih.
Sn. Pedro, Chih.
Cananea, Sonora
Agua Prieta, Son.
Nogales, Son.
Fronteras, Son.
Magdalena, Son.
San Quintín, B.C.N.
Villa Hidalgo, B.C.N.
Sn. Felipe, B.C.N.
Sn. Telmo, B.C.N.
Arroyo Seco, B.C.N.
Col. Guerrero, B.C.N.





POBLACIONES:

Cd. Juárez, Chih.

El Paso, Chih.

Las Palomas, Chih.

Vado de Piedra, Chih.

Sonoyta, Chih.

Est. Doctor, Chih.

Los Vidrios, Chih.

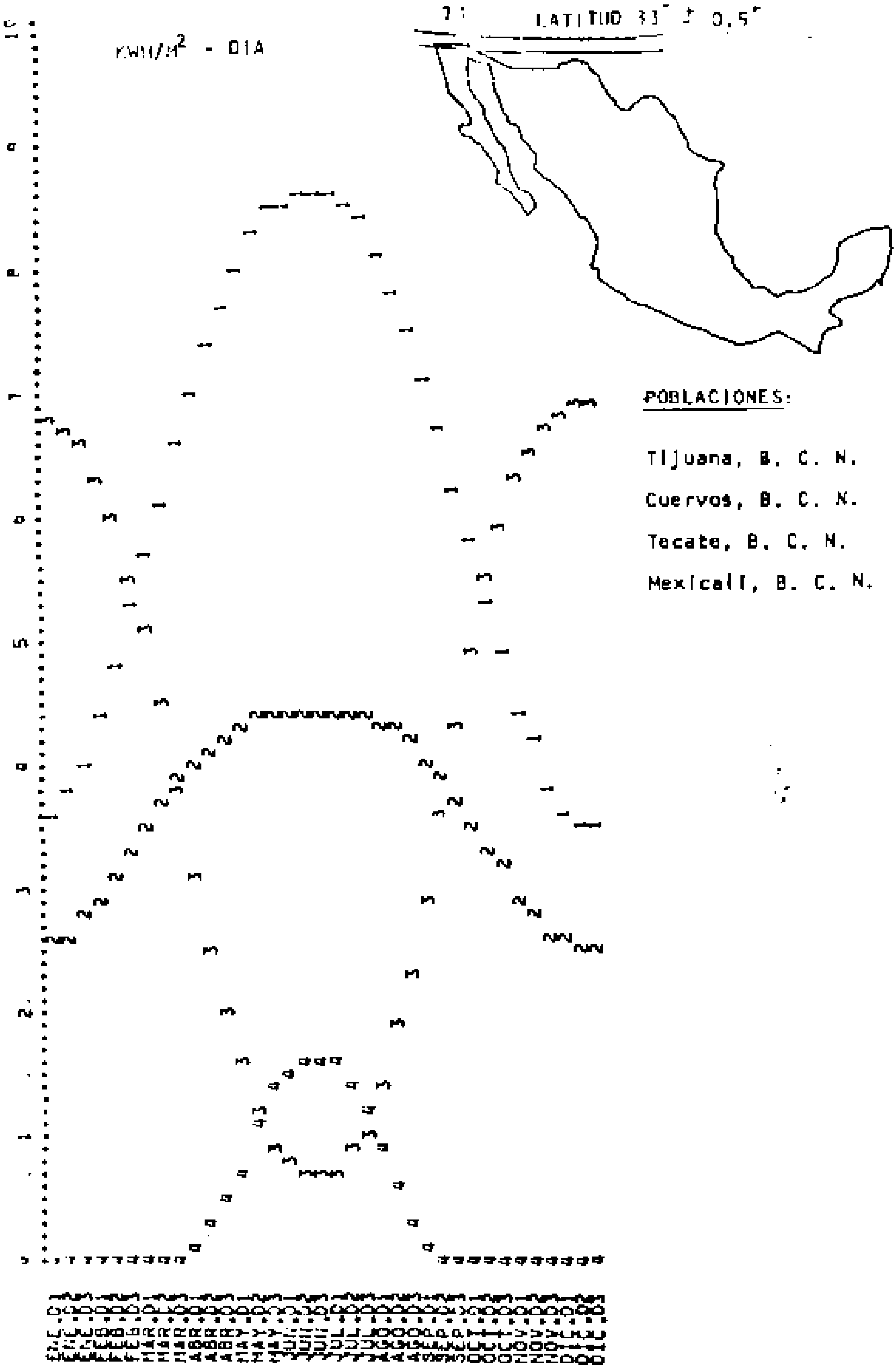
Sausal, B.C.N.

Real del Castillo, B.C.N.

Ensenada, B. C. N.

Descauso, B.C.N.

La Rumorosa, B.C.N.


KWH/M² - DIA
LATITUD 33° ± 0.5°
POBLACIONES:
Tijuana, B. C. N.
Cuervos, B. C. N.
Tecate, B. C. N.
Mexicali, B. C. N.

Agradecimientos:

Los autores agradecen la colaboración del Grupo de Energía Solar del Centro de Investigación de Materiales de la U.N.A.M., muy especialmente al Dr. Eric R. Mayer por sus valiosos comentarios; al Sr. Hernando Cortés por el magnífico entinte de las figuras; a la Srita. Mercedes J. Spíndola por la transcripción del manuscrito; así mismo a la Sra. Rosalva Verástegui y a los Sres. Rodolfo Verástegui y Efraín Regalado por su cooperación en la elaboración de los diagramas.

(1) Hernández, E. 1976, "On the Numerical Computation of Solar Radiation Parameters from Satellite Cloud Cover Data", Proceedings of the UNESCO/World Meteorological Organization - Solar Energy Symposium, Ginebra, Suiza.

(2) Hernández, E. 1976, "The Seasonal Distribution of the Incoming Solar Radiation in Mexico", Proceedings of the "Sharing the Sun 76 Solar Technology" International Solar Energy Society, Winnipeg, Canada, Vol. 10.

(3) Hans, R. 1964, "Solar Energy". The Mac Millan Company. New York Collier-Mac Millan Limited, London.

(4) Hernández, E. 1977, "Las Coordenadas Horarias de la Trayectoria Diaria del Sol sobre el Horizonte y su Representación Polar en la República Mexicana". Publicación del Centro de Investigación de Materiales, U.N.A.M.

(5) Smart, W. 1971, "Spherical Astronomy". Cambridge University Press, London.

(6) Hess, L. 1959, "Introduction to Theoretical Meteorology", Holt Rinehart and Winston. New York.

(7) Johnson, F. 1954, "The Solar Constant". Journal of Meteorology, Vol. 11 No. 6, p.431-439.

(8) Drummond, A., Thekaekara A. 1971, "Standard Values for the Solar Constant and its Spectral Components", Nature, Physical Sciences, No. 229, p.p. 6-9.

{ 9} Thekaekara, A. 1973, "Solar Energy Outside the Earth's Atmosphere". Solar Energy, Vol. 14, p.p. 109-127.

{10} Ångström, A. 1929, "On the Atmospheric Transmission of Sun Radiation and on Dust in the Atmosphere", Geografiska Annaler. Stockholm, Vol. 11, p.p. 156-166.

{11} Robinson, N. 1966, "Solar Radiation", Elsevier Publishing Co. Delft Holland.

{12} Schüepp, W. 1964, "Rayonnement et Trouble Atmosphérique en régions équatoriales. Annals of the IGY, Vol. 32. Meteorology.

{13} Moon, P. 1954, "Proposed Standard Solar Radiation Curves for Engineering Use", J. Franklin Institute. Vol. 230, No. 1379-23, p.p. 583-617.

{14} Fowle, F. 1917, "Water Vapor Transparency to Low Temperature Radiation", Smithsonian Miscellaneous Collections. Vol. 68, No. 8.

{15} Thekaekara, A. Thomas, P. 1976, "Experimental and Theoretical Studies on Solar Energy for Energy Conversion", Proceedings of the "Sharing the Sun-Solar Technology", International Solar Energy Society, Winnipeg, Canada. Vol. 1.

{16} Gates, M. 1966, "Spectral Distribution of Solar Radiation at the Earth's Surface", Vol. 151, No. 3710, p.p. 523-529.

{17} Linke, F. 1942, "Die Sonnestrahlung und ihre Schwächung in der Atmosphäre, Handbuch der Geophysik, Bornträger, Berlin, Vol. 8, p.p. 239-332.

{18} Flügge, S. 1957, Hancbuch der Physik, Band XIVIII, Vol. XLVIII, Geophysik II, Springer - Verlag., Berlin - Gottingen - Heidelberg.

{19} Hernández, E. Martínez, R. 1976, Mediciones Actinométricas, Reportes internos, Centro de Investigación de Materiales, U.N.A.M.

{20} ASHRAE 1974, Handbook of Fundamentals American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York.

{21} Tricaud, J. 1976, "Contribution á l'Estimation des Ressources Energétiques Solaires Ebauche d'un Atlas du Rayonnement pour la France" These Doctoral. Université Paris VII.

{22} Perrin de Brichambaut. 1963, "Rayonnement Solaire et Echanges Radiatifs Naturels", Gauthier Villard, Paris VI^e^.

{23} Van Hull, L. 1977, "Methods for Estimating Total Flux in the Direct Solar Beam at any Time", Proceedings of the "Sharing the Sun 76- Solar Technology", International Solar Energy Society. Winnipeg, Canada, Vol. 1.

{24} Page, K. 1964, "The Estimation of Monthly Mean Values of Daily Total Short Wave Radiation on Vertical and Inclined Surfaces from Sunshine Records for Latitudes 40° N- 40°S". New Sources of Energy Proceedings of the Conference of Rome, 21-31 August 1961. Vol. 4 United Nations, New York.

{25} Remenieras G. 1959, "Elements D'Hydrologie Applique", Collection Armand Colin, No. 343, Paris V^e^.

{26} Vassy, E. 1966, "Physique de L'Atmosphere", Gauthier-Villard Editeurs, Paris V^e^.

8ó

(27) Laue, E. G., 1970, Solar Energy. Vol. 13
Pergamon Press, London.

(28) Hand, I. F., 1954, "Insolation on Cloudless Days at the time of Solstices and Equinoxes". Heating and Ventilating. February.

(29) Gorczyński, L., 1932, "Radiación Solar en Tacubaya, según las mediciones pirheliométricas desde 1911". Servicio Meteorológico Mexicano, SAG, México, D. F.

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

INFORMES TECNICOS

AGOSTO, 1979

Palacio de Minería Calle de Tacuba 5, primer piso. México 1, D. F. Tel: 521-40-20

energéticos
BOLETIN INFORMATIVO DEL SECTOR ENERGETICO
año 2 No. 7 Julio 1978

La demanda de energía

Introducción

por Wolf Häfele

Desde la reciente crisis de energía, se han propuesto diversos planes energéticos: casi todos ellos preconizan alguna forma de adaptación de la demanda de energía o de medidas de conservación de los recursos, con la esperanza de evitar así los temidos problemas de abastecimiento de energía. Sin embargo, no parece existir una explicación clara de la forma en que podríamos mitigar nuestros futuros y previsibles problemas energéticos. En realidad, una primera tentativa de definir con exactitud la demanda de energía y sus interacciones con otros objetivos, por ejemplo los económicos, muestra que se trata de un concepto sumamente complejo, que todavía entendemos mal. Convendría pues explicar en detalle por qué es tan difícil interpretar debidamente la demanda de energía.

Esquemas de flujo de la energía

LA FIGURA 1 muestra el flujo de la energía dentro del sistema económico de la República Federal de Alemania en 1975, en millones de toneladas de carbón equivalente* o en gigavatios/año. La parte más importante de la energía se somete a procesos de conversión para obtener formas energéticas más prácticas y fáciles de manejar, llamadas energía secundaria. La electricidad y la gasolina —los ejemplos más destacados—, se transportan hasta el consumidor. El mayor sector de consumo lo constituyen los usos domésticos y las actividades comerciales, que absorben el 45% de toda la energía secundaria; después vienen la industria, con el 36% y el transporte, con el 14%. El uso de energía secundaria implica igualmente pérdidas de conversión, que se elevan hasta el 56%.

Aparte de los cauces principales de flujo de la energía indicados en la Figura 1, existen otros cauces y ramificaciones menores que no cabe desconocer simplemente en un examen de la demanda de energía y de su evolución futura. La calefacción municipal, por ejemplo, se piensa que representará un importante papel en el porvenir, posiblemente como resultado de la producción combinada de electricidad y calor. La parte de energía secundaria que corresponde actualmente a este uso es de sólo 4 millones de toneladas equivalentes de carbón, aunque puede aumentar significativamente en el futuro. La complejidad del problema se hace evidente al considerar todos los cauces y conexiones del esquema de la Figura 1, y resulta necesario utilizar categorías y términos bien definidos. En la Figura 2 hemos tratado de hacerlo así. Tenemos en primer lugar la energía primaria. Puede consistir en carbón, petróleo crudo, uranio y otros recursos. La conversión en otra forma de energía da origen a lo que llamamos energía secundaria y a las

* Una tonelada equivalente de carbón = 5 x 10^6 Kcal.

El Dr. Häfele es Director Adjunto del International Institute For Applied Systems Analysis (IIASA) de, Laxenburg (Austria).

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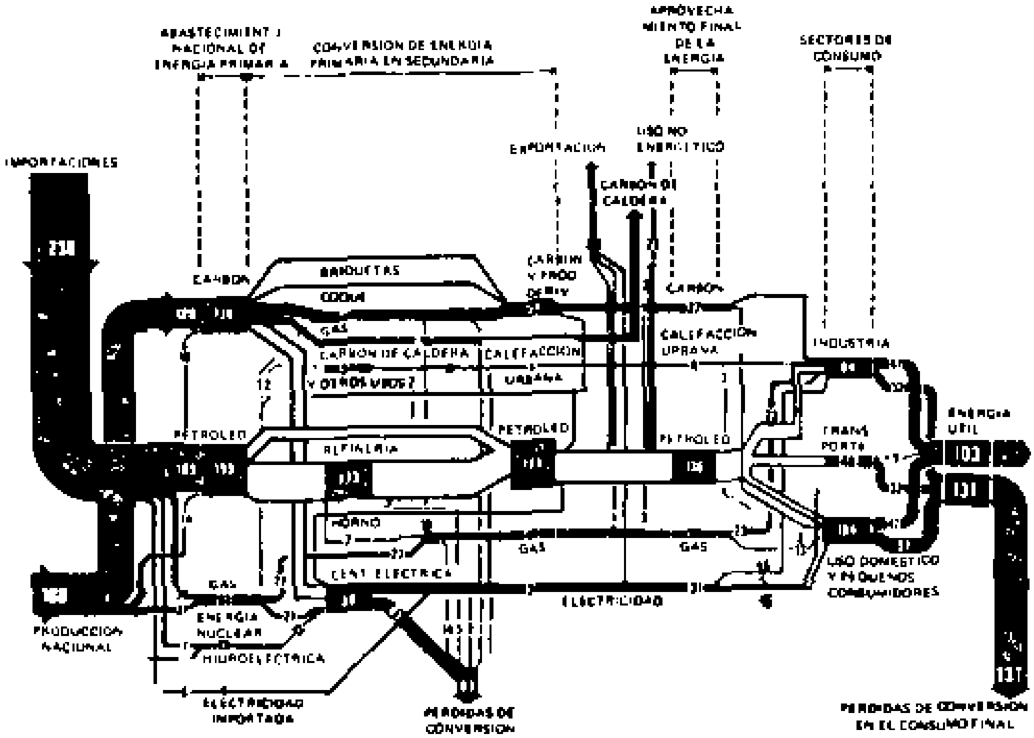

Figura 1. Flujo de la energía por el sistema económico de la República Federal de Alemania en 1975 (en millones de toneladas de carbón equivalente o gigavatios/año). Dividiendo las respectivas cantidades por 33,6 se obtienen "quads" ($Q = 10^{15}$ Btu). La energía primaria disponible fue de 406 millones de toneladas de carbón equivalente o Gigavatios/año, o sea 12 Q, suma de 238 (importaciones) y 168 (producción nacional). Las importaciones se elevaron al 59%, consistiendo sobre todo en crudos de petróleo (45%) y cierta cantidad de gas natural (7,3%). La producción nacional de carbón representó el 31,5%. La contribución de todas las demás fuentes no alcanzó gran importancia en 1975. Con mucho, la mayor parte de la energía primaria se convirtió en formas de energía más fáciles y convenientes de manejar, llamadas de energía secundaria. Los ejemplos más conocidos son la electricidad y la gasolina, que se transportan del centro de producción al consumidor. Las pérdidas de conversión y de transporte se elevaron a 91 millones de toneladas de carbón lo que representa el 22% del consumo primario. El mayor sector de consumo correspondió a las actividades comerciales y la utilización doméstica, que absorbieron el 46% de la energía secundaria; seguía en importancia el consumo industrial con el 33% y el del transporte con el 14%. La utilización de la energía secundaria produjo también pérdidas de conversión, que llegaron al 56%. En consecuencia, de 406 millones de toneladas de carbón equivalente sólo se utilizaron productivamente 103, o sea aproximadamente el 26%, que fueron transformadas en movimiento mecánico o en iluminación, o dedicadas a otros usos

correspondientes pérdidas. Tras la conversión y el transporte, se obtiene la energía útil suministrada a los consumidores locales. La energía útil es la destinada a asegurar un servicio que puede consistir, por ejemplo, en la calefacción de un cuarto, en luz para la lectura o en el funcionamiento de un automóvil.

Como veremos después, estos servicios no se sitúan en el mismo nivel conceptual que la energía, por lo que en nuestra figura están inscritos en un círculo y no en un rectángulo.

Eficiencia de la conversión

¿Cómo se puede economizar energía? Se ve en la Figura 1 que, de una manera u otra, se pierde aproximadamente el 75% de la energía primaria. ¿Es esto inevitable? Consideremos las diferentes etapas del flujo de la energía y examinemos la cuestión. Para la conversión de energía primaria en energía secundaria (Figura 3), el proceso más conocido es la generación de electricidad en centrales eléctricas. En realidad, la energía térmica se convierte primero en energía mecánica y después en energía eléctrica. La energía térmica en este caso es la suma de todas las energías cinéticas de las moléculas de un gas o de un líquido, cuyas direcciones de movimiento tienen una distribución aleatoria. Pero, a causa de la inflexibilidad de las leyes de la física, existe un límite superior para la conversión de energía térmica en formas no aleatorias. Ese límite es bien conocido bajo la denominación de "rendimiento de Carnot", que es siempre inferior a la unidad. Cuando la temperatura de salida del líquido o del gas de trabajo es de 500°C, el rendimiento de Carnot se aproxima al 63% ; sin embargo, las centrales eléctricas nunca alcanzan tales rendimientos a causa de las pérdidas técnicas que se producen. Estas se pueden reducir, pero es imposible anularlas. Para mejorar el rendimiento se requiere experiencia técnica y capital. La Figura 4 muestra la evolución a largo plazo de las ganancias en rendimiento en el caso de las centrales eléctricas.

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* Una tonelada equivalente de carbón = 5 x 10^9 Kcal.

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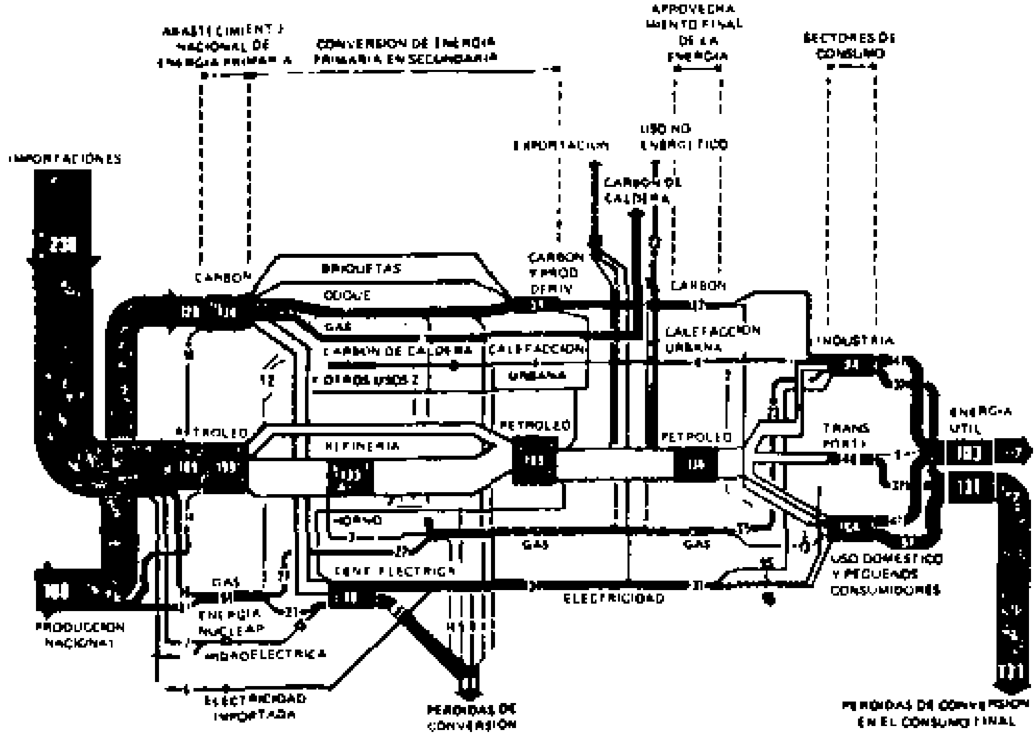


Figura 1. Flujo de la energía por el sistema económico de la República Federal de Alemania en 1975 (en millones de toneladas de carbón equivalente o gigavatios/año). Dividiendo las respectivas cantidades por 33,5 se obtienen "quads" ($Q = 10^{15}$ Btu). La energía primaria disponible fue de 406 millones de toneladas de carbón equivalente o Gigavatios/año, o sea 12 Q, suma de 238 (importaciones) y 168 (producción nacional). Las importaciones se elevaron al 59 %, consistiendo sobre todo en crudos de petróleo (45 %) y cierta cantidad de gas natural (7,3 %). La producción nacional de carbón representó el 31,5 %. La contribución de todas las demás fuentes no alcanzó gran importancia en 1975. Con mucho, la mayor parte de la energía primaria se convirtió en formas de energía más fáciles y convenientes de manejar, llamadas de energía secundaria. Los ejemplos más conocidos son la electricidad y la gasolina, que se transportan del centro de producción al consumidor. Las pérdidas de conversión y de transporte se elevaron a 91 millones de toneladas de carbón lo que representa el 22 % del consumo primario. El mayor sector de consumo correspondió a las actividades comerciales y la utilización doméstica, que absorbieron el 45 % de la energía secundaria; seguía en importancia el consumo industrial con el 33 % y el del transporte con el 14 %. La utilización de la energía secundaria produjo también pérdidas de conversión, que llegaron al 56 %. En consecuencia, de 406 millones de toneladas de carbón equivalente sólo se utilizaron productivamente 103, o sea aproximadamente el 25 %, que fueron transformadas en movimiento mecánico o en iluminación, o dedicadas a otros usos.

correspondientes pérdidas. Tras la conversión y el transporte, se obtiene la energía útil suministrada a los consumidores locales. La energía útil es la destinada a asegurar un servicio que puede consistir, por ejemplo, en la calefacción de un cuarto, en luz para la lectura o en el funcionamiento de un automóvil.

Como veremos después, estos servicios no se sitúan en el mismo nivel conceptual que la energía, por lo que en nuestra figura están inscritos en un círculo y no en un rectángulo.

Eficiencia de la conversión

¿Cómo se puede economizar energía? Se ve en la Figura 1 que, de una manera u otra, se pierde aproximadamente el 75% de la energía primaria. ¿Es esto inevitable? Consideremos las diferentes etapas del flujo de la energía y examinemos la cuestión. Para la conversión de energía primaria en energía secundaria (Figura 3), el proceso más conocido es la generación de electricidad en centrales eléctricas. En realidad, la energía térmica se convierte primero en energía mecánica y después en energía eléctrica. La energía térmica en este caso es la suma de todas las energías cinéticas de las moléculas de un gas o de un líquido, cuyas direcciones de movimiento tienen una distribución aleatoria. Pero, a causa de la inflexibilidad de las leyes de la física, existe un límite superior para la conversión de energía térmica en formas no aleatorias. Ese límite es bien conocido bajo la denominación de "rendimiento de Carnot", que es siempre inferior a la unidad. Cuando la temperatura de salida del líquido o del gas de trabajo es de 500°C, el rendimiento de Carnot se aproxima al 63% ; sin embargo, las centrales eléctricas nunca alcanzan tales rendimientos a causa de las pérdidas técnicas que se producen. Estas se pueden reducir, pero es imposible anularlas. Para mejorar el rendimiento se requiere experiencia técnica y capital. La Figura 4 muestra la evolución a largo plazo de las ganancias en rendimiento en el caso de las centrales eléctricas.

Abriendo ahora un breve paréntesis, parémonos un momento a examinar algo más a fondo esta evolución. En la Figura 4 se ha trazado la curva logística como si fuera una recta. En un gráfico normal, la curva logística tiene forma de S, con lo que describe el crecimiento diferencial en un medio ambiente limitado (véase la Figura 5). La curva en S implica una transición de un límite bajo a un límite elevado y está regida por una constante de tiempo. Como veremos, un número sorprendentemente grande de procesos presenta este comportamiento, de manera que es interesante comparar los intervalos de tiempo para pasar de un punto a otro de la curva.

La Figura 4 muestra que el rendimiento de las centrales eléctricas ha seguido siempre una tendencia ascendente. Si se considera un período de tiempo suficientemente largo, es de esperar que, en general, la tendencia ascendente continúe. Esta ganancia en rendimiento ahorra energía, porque significa un consumo menor de energía primaria para obtener una cantidad igual de energía secundaria. Pero también existen tendencias opuestas. Antes, cuando se utilizaba directamente la leña y el carbón, no había pérdidas de conversión. Pero sí había grandes pérdidas en el aprovechamiento de la energía útil. La conversión se hizo necesaria sólo cuando la economía moderna exigió formas de energía más fáciles de manejar.

En el futuro, con formas de energía primaria que no se podrán emplear directamente, esa conversión será cada vez más indispensable, aunque la facilidad de manejo sea una cuestión sin importancia. La Figura 6 ilustra este concepto. La energía nuclear y la solar son casos típicos a este respecto. Su futuro empleo (des-

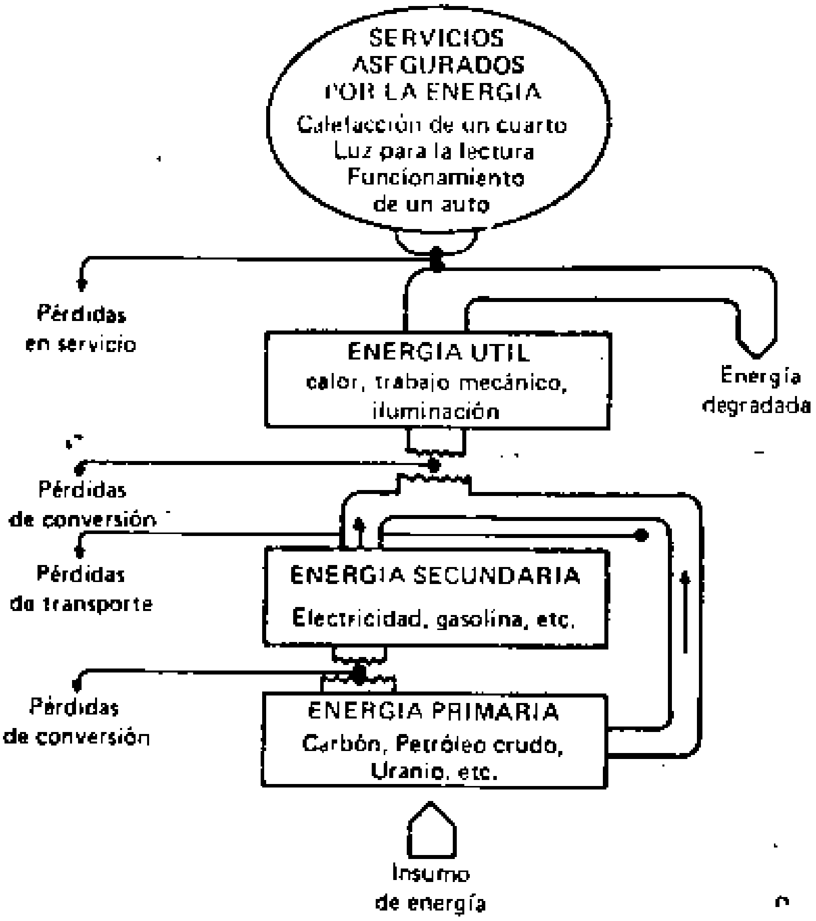


Figura 2. Esquema simplificado del flujo de energía y de los servicios por ella prestados.

pués del año 2000) en gran escala hará aumentar considerablemente las pérdidas de conversión, en tanto que hoy día disfrutamos aún de una situación favorable, pues el gas natural no tiene pérdidas de conversión y las del petróleo son pequeñas. Debe tenerse presente que el futuro consumo de carbón en gran escala conducirá también a grandes pérdidas de conversión, ya que el mercado tiende a rechazar los combustibles sólidos y será necesaria la conversión del carbón en líquido o gas, como muestra la Figura 7. En el año 1950, todavía un 80% de la energía secundaria se presentaba en forma de combustibles sólidos, pero después fue aumentando la demanda de combustibles líquidos, que llegó al máximo a principios de los años 70. También ha crecido rápidamente el consumo de gas, lo mismo que el de electricidad. De toda la energía secundaria, la proporción que corresponde actualmente a la electricidad se sitúa entre el 10 y el 12%, y muchas previsiones realizadas para el año 2000 pronostican una proporción del 20 al 25%.

En este punto hay que hacer una observación bastante importante acerca de la energía nuclear. Hasta ahora la energía nuclear se ha desarrollado y utilido que en la India, mientras que la densidad de población de los dos países es muy parecida. Es importante no pasar por alto la relación de la infraestructura energética con la infraestructura económica general. Se ha recomendado con frecuencia a los países en desarrollo que procuren diversificar las fuentes energéticas necesarias para su evolución. Así, se ha mencionado la aplicación de tecnologías sencillas, tales como el aprovechamiento de la fuerza del viento y el empleo local de la energía solar, especialmente de manera descentralizada, es decir, en las zonas rurales. Cabe observar sin embargo que no es en estas zonas donde se plantea el problema.

La relación de la infraestructura energética con la infraestructura económica en general —esto es: el complejo esquema de utilización de la energía— requiere un detenido análisis cuantitativo. Un enfoque inicial consiste en estudiar la interdependencia entre el consumo energético y los costes de la energía, mediante la aplicación de métodos econométricos establecidos y utilizados en los Estados Unidos. En este dominio se destacan los nombres Jorgenson, Houthakker, Nordhaus y Manne. Sus datos iniciales fundamentales son las diversas elasticidades, entendiéndose por ese término el cambio de porcentaje de consumo de energía por cambio de porcentaje de otra variable, por ejemplo, el PNB. Se establecen las elasticidades de numerosos datos estadísticos relativos a una serie de años, lo que significa una referencia implícita a una infraestructura económico-energética existente. Dentro de ese marco se considera entonces posible estudiar el consumo energético probable durante un período medio de 10 años, por ejemplo. La Figura 15 reproduce las características de este enfoque econométrico. Por ejemplo, se interpretan las funciones de la demanda mediante elasticidades que relacionan el consumo energético neto per cápita, el precio neto relativo de la energía y el PIB real per cápita.

Chapman, Slesser y otros autores han propuesto otro enfoque, denominado análisis energético. Es un método más tecnológico que engloba el estudio del contenido energético de mercancías y servicios. La Figura 16 ilustra algunos resultados obtenidos con este procedimiento. Presenta valores expresados en kilovatios/hora térmicos por dólar del producto económico final de diversos sectores de la economía francesa en el año 1971. Las cifras correspondientes a los renglones del acero y de metales no ferrosos son altas, así como las de la energía consumida indirectamente para el trabajo en metales, que son igualmente bastante altas en los renglones de la construcción y de la industria del vidrio. Es evidente la excelencia con que este método refleja la infraestructura y la tecnología actuales.

Los suministros de energía y la información

La utilización de la energía no constituye una finalidad en sí misma. Hemos observado que la mano de obra y la energía mueven el capital existente para la producción del PNB, que se mide en dólares y no en kilovatios/hora. ¿Qué sucede cuando los kilovatios/hora contribuyen a producir dólares? La utilización de

$$\text{ELASTICIDAD } (\beta, \gamma) = \frac{\text{PORCENTAJE DE CAMBIO DE DEMANDA}}{\text{PORCENTAJE DE CAMBIO DE PRECIO O DE INGRESOS}}$$

$$\boxed{Q_t = \text{const} \cdot \prod_{\theta=0}^{n} P_{t-\theta}^{\frac{\beta}{n}} \cdot \prod_{\theta=0}^{m} Y_{t-\theta}^{\frac{\gamma}{m}}}$$

Q_t = Consumo neto de energía per capita
P_t = Precio neto relativo de energía
Y_t = Producto bruto local real per capita
β = Elasticidad de precio
γ = Elasticidad de ingreso

Figura 15. El enfoque econométrico para determinar la interdependencia entre el consumo de energía y los precios de la energía implica el uso del concepto de "elasticidad": el porcentaje de cambio de la demanda de energía en función del porcentaje de cambio de otra magnitud, tal como el precio, el ingreso, etc.

Sector industrial	Total de energía consumida en función del producto	Consumo directo de energía	Consumo indirecto de energía
Alimentación	2.20	1.72	0.48
Construcción	16.07	13.98	2.09
Vidrio	16.03	14.54	1.49
Acero	34.85	28.28	6.57
Metales no ferrosos	33.16	31.33	1.83
Metales fabricados	11.44	1.32	10.12
Electromecánica	6.01	1.59	4.42
Química	11.41	9.40	2.01
Vestimenta	2.92	2.09	0.83
Papel	5.62	4.44	1.18
Otros	4.93	3.00	1.93

Figura 16. En este cuadro se indica el total de la energía consumida en kilovatios/horas KWH (térmicos) por dólar de producto económico final con respecto a diversos sectores de la economía de Francia en 1971. La elevada suma de los sectores del acero, de metales no ferrosos, del vidrio y de la construcción reflejan la infraestructura y tecnología existentes (Fuente: referencia 2).

"INFORMACION" SIGNIFICA LOS INSUMOS NECESARIOS PARA EL ESTABLECIMIENTO DE UNA PAUTA DESEADA

EL ALFARERO NECESITA UN SUMINISTRO DE ENERGIA E INVERSIONES Y HABILIDAD PARA PRODUCIR ALFARERIA

LA CALEFACCION DE UNA CASA REQUIERE UN SUMINISTRO DE ENERGIA GRANDE O PEQUEÑO, DE ACUERDO CON LA CALIDAD DE LA AISLACION Y LA EFICIENCIA DE SU EMPLEO

LA DISPONIBILIDAD, FIABILIDAD, VERSATILIDAD Y LIMPIEZA DE LOS SUMINISTROS DE ENERGIA SON TAMBIEN INSUMOS DE "INFORMACION"

II SUMINISTRO DE ENERGIA SIGNIFICA TRASPONER LA UTILIZACION DE ENERGIA AL NIVEL DE "INFORMACION"

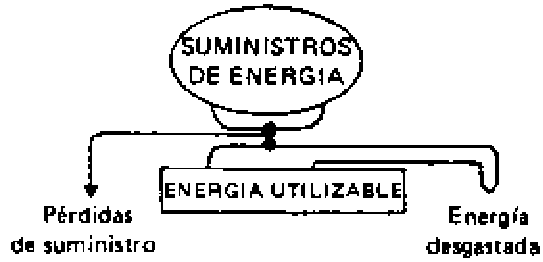


Figura 17. Los suministros de energía y la "información".

energía presta un servicio, que no es el único (véase la Figura 17). Podría aclararse este concepto con el siguiente ejemplo. En el caso de un taller de alfarería, se necesita energía para hacer girar la rueda de alfarero, pero es indispensable también la habilidad de éste para la fabricación de sus productos sin desperdicio de material ni de tiempo. El alfarero necesita también contar con capital. Cuanto mayor sea su habilidad y más adecuadas las inversiones, menor será la demanda de energía necesaria para producir una cantidad determinada de productos. Si le falta habilidad, los errores de fabricación le obligarán a empezar de nuevo muchas veces antes de terminar el trabajo y la cantidad de energía consumida por pieza será alta. Igualmente, cuanto más claro y preciso sea el concepto de su trabajo, tanto mayor será el PNB producido. Examinemos otro ejemplo referente a lo que se necesita para caldear una vivienda. La cantidad de energía requerida puede variar mucho de acuerdo con las características de la aislación térmica y de la efectividad del sistema, o del hecho que las puertas y ventanas están cerradas o no, y en todo caso interesa para el cálculo saber que se dispone de energía oportunamente cuando sea necesario.

Otra cuestión de capital importancia es que los suministros energéticos sean limpios desde el punto de vista ecológico. Muchos tipos de industrias requieren alimentación eléctrica en vez de otra forma de energía, ya que aquélla se puede controlar y manejar con facilidad y limpieza, cualidad que S.H. Schurr llama "la gran eficiencia económica de la electricidad". Todos estos factores sirven para indicar que conviene estudiar comparativamente los suministros energéticos junto con otros servicios que, considerados globalmente, se integran en la suma de la pauta deseada, tal como en el ejemplo de la alfarería o de la calefacción de una habitación. Existe una importante diferencia entre una habitación caldeada y la acción de calentarla. El primer concepto es una pauta y el segundo implica el empleo de instrumentos, por ejemplo la utilización de energía. En el primer caso, el nivel relativo a la formación de las pautas es más abstracto que el nivel de los instrumentos.

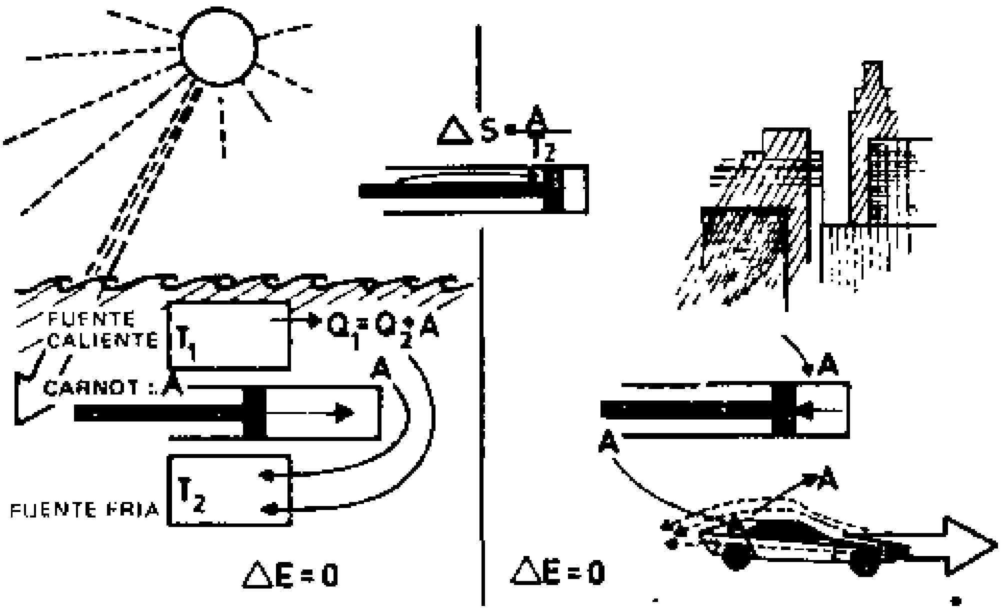
Por consiguiente, suministro de energía significa transponer la utilización de la energía en ese nivel más abstracto, que llamamos nivel de "información". Haciendo una vaga referencia a la teoría oficial de la información de Shanon y al concepto de la entropía y de la entropía negativa, cabe admitir que la ciencia contemporánea no permite todavía considerar en una sola teoría unificada la habilidad, el capital y los suministros de energía. Esta es ciertamente la razón definitiva que explica por qué es tan difícil de comprender realmente la demanda de energía y ése es el problema tantas veces aludido cuando se habla de la necesidad de tener en cuenta la calidad de la utilización de energía.

La relación entre la utilización de energía y la información es de carácter no restringido. Teóricamente y en condiciones ideales, se puede suministrar servicios de energía sin consumo de energía. Se podría demostrar esta teoría muy efectivamente mediante el experimento conceptual Gedanken-experiment (véase la Figura 18). Consideremos una región oceánica determinada; el calentamiento solar produce un gradiente de temperatura en las capas superiores del agua. Este gradiente puede aprovecharse de manera clásica mediante el motor de Carnot. El motor toma calor de la capa superior del océano a la temperatura T_2 y transforma el aporte calórico en trabajo mecánico y cede el resto del calor a las capas inferiores oceánicas a la temperatura T_1. Si se utiliza el trabajo mecánico para comprimir aire, éste se calienta en condiciones isotérmicas y la energía del trabajo mecánico se restituye a la capa superior oceánica de la cual se había obtenido. Se da por supuesto que no hay consumo de energía en el transporte del aire comprimido a la ciudad. La energía interna de un gas (ideal) depende únicamente de la temperatura y no de la presión, y en este caso se supone que la temperatura es invariablemente T_2. El contenido energético del océano permanece sin cambio, pero aumenta la entropía de esa determinada región oceánica, fenómeno conocido con el nombre de entropía de mezcla. La misma cantidad de entropía, con signo negativo, es decir la denominada "negentropía", ha sido transportada a la ciudad en forma de aire comprimido. Si se invierte el proceso, la negentropía creada será igual a la entropía producida localmente. En la infraestructura urbana, la expansión ofrece la energía necesaria que puede servir para hacer funcionar un automóvil, por ejemplo. Se debe recordar que en nuestra terminología, un automóvil en marcha representa un suministro de energía, e implica un esquema de información. El aire se enfría al dilatarse y la atmósfera ambiente aporta la cantidad necesaria de calor en tanto que un insumo de energía del motor de expansión. Cuando el automóvil está en movimiento, la fricción resultante disipa parte de la energía mecánica en forma de calor de fricción, con lo cual se restituye a la atmósfera el calor que había cedido y el contenido energético urbano continúa también sin cambio.

Con la perturbación creada en la pauta natural de la fuente oceánica habremos creado una pauta de información que se utiliza en una economía; en otros términos, la economía funciona sin consumir energía. El Gedanken-experiment termina con la restauración gradual del gradiente oceánico y repitiendo el ejercicio sería posible hacer funcionar la economía de esta manera. Este experimento revela que el consumo de energía es una expresión cuando menos ambigua, puesto que se ha demostrado que se puede hacer funcionar una economía sin consumo de energía. Lo que se ha consumido es información .

Este experimento pone de relieve la diferencia fundamental que existe entre la utilización de energía y el suministro de energía o de información . Existe, cierto es, una ley de la conservación de energía como también hay una ley aplicable a la masa o al funcionamiento, pero que no hay ninguna referente a la entropía y a la información. La entropía permanece constante o en aumento. En consecuencia, se pueden liberar cantidades indefinidas de negentropía o de información. Expresada en otros términos, la relación de la utilización de energía y de la información dependen de las pautas de esa utilización y en ese sentido, es una relación no limitada.

Esta es precisamente la razón por la cual es tan difícil com-



(A: TRABAJO, E: ENERGIA, Q: CALOR, S. ENTROPIA, T: TEMPERATURA)

Figura 18 Gedanken-experiment de negentropía urbana que presenta el ejemplo de una economía que funciona sin consumo de energía. A la izquierda de la figura, el calor del Sol produce un gradiente de temperatura en las capas superiores del agua oceánica. Se toma la cantidad de calor Q_1 de la capa superior del océano a la temperatura T_1 y se aplica al motor de Carnot, que transforma el aporte de calor en trabajo mecánico al mismo tiempo que se cede el aporte calórico Q_1 a las capas inferiores oceánicas a la temperatura T_2. Si se utiliza el trabajo mecánico para comprimir aire, éste se calienta en condiciones isotérmicas y la energía del trabajo mecánico se restituye a la capa superior oceánica de la cual se había obtenido. Se da por supuesto que no hay consumo de energía en el transporte del aire comprimido a la ciudad. La energía interna de un gas (ideal) depende únicamente de la temperatura y no de la presión, y en este caso se supone que la temperatura es invariablemente T_2. En efecto, si bien en el océano solo se ha transferido la cantidad de calor Q_1 de la temperatura T_1 a la temperatura T_2, el contenido energético de la zona oceánica permanece invariable. En cambio ha aumentado la entropía de esa determinada zona oceánica, fenómeno conocido con el nombre de entropía de mezcla. La misma cantidad de entropía, pero con signo negativo, es decir la denominada "negentropía", ha sido transportada a la ciudad en forma de aire comprimido. Si se invierte el proceso, la negentropía creada será igual a la entropía producida localmente. En la infraestructura urbana, la expansión aporta la energía necesaria para hacer funcionar un automóvil, por ejemplo. El aire se enfría al dilatarse y la atmósfera ambiente suministra la cantidad necesaria de calor en tanto que un insumo de energía del motor de expansión. Cuando el automóvil está en movimiento, la fricción resultante disipa parte de la energía mecánica en forma de calor de fricción A. Este proceso de degradación de la calidad de energía restituye a la atmósfera el calor que había cedido, con lo cual el contenido energético urbano continúa también sin cambio. (Referencia 10).

prender la demanda de energía. Se ha podido observar que es la infraestructura de la economía la que establece la relación entre la utilización de energía y el PNB. El PNB es uno de los indicadores más eficaces para medir la información en el sentido empleado en el presente estudio. Pero esto conduce a observar que el desarrollo posible de una economía es básicamente un proceso lineal no limitado, es decir, que no existen leyes naturales que impongan límites al crecimiento. Esta es una afirmación de carácter bastante general y antes de aceptarla conviene tener presente el nivel de complejidad al que conduce el análisis de un proceso no limitado de este tipo. La orientación de una evolución económica sólo puede conducir a actividades de un género cada vez más abstracto. Y cuando se destaca la creciente importancia del sector de servicios en una economía, no se hace otra cosa sino señalar ese fenómeno. Ello puede conducir a disminuir los servicios de energía por un valor determinado del PNB.

Será útil ilustrar lo que antecede con un ejemplo práctico que, aunque represente un caso extremo, es real. Las primeras computadoras digitales que aparecieron en los años 50, tales como el modelo IBM 650, consumían varios kilovatios de energía eléctrica y un período apreciable de tiempo para el tratamiento de datos. Hoy en día, en cambio, bastan unos pocos milivatios de energía y mucho menos tiempo para prestar el mismo servicio, la diferencia del consumo de energía se sitúa en cuatro o cinco órdenes de magnitud. Para lograr este adelanto se necesitaba una mejor comprensión de la física del estado sólido y la creación de una industria especializada. Fue preciso desarrollar un nuevo cuerpo de conocimientos y realizar progresos científicos. La economía de energía así lograda es sólo una de las numerosas consecuencias de importancia. Para modificar la infraestructura que relaciona la utilización de energía y los servicios de la misma, será probablemente necesario utilizar una vasta y variada masa de riquezas en materia científica, tecnológica y administrativa, que a su vez podrán modificar también la demanda de energía.

Dar tiempo a la evolución

Una evolución de esa índole exige tiempo. El tiempo es la clave de las estrategias modernas. Parece pues conveniente concluir considerando las características cronológicas de la evolución de la demanda de energía. Existen tres componentes (véase la Figura 19). Uno de ellos es el crecimiento demográfico, aunque es verdad que este factor no aumenta la demanda de energía de manera inmediata. Si no va acompañado de capital o de infraestructura, el crecimiento demográfico no implica una mayor demanda de energía; este era el caso cuando comparábamos la India con la República Federal de Alemania. No obstante, el crecimiento demográfico afectará a la larga la demanda de energía. En los países industrializados el crecimiento demográfico produce una correlación inmediata con la demanda de energía, por lo que dentro de los 40 a 60 años venideros, la posible duplicación de la población mundial ha de influenciar ciertamente en la demanda global de energía.

El segundo elemento que influye en la evolución de la demanda de energía es el crecimiento económico. Una tasa de crecimiento económico del orden del 5% anual equivale a una duplicación del PNB en 15 años, lo cual también puede duplicar la demanda de energía si no se produce un cambio significativo en la infraestructura. Sólo la intervención de un tercer elemento representa un cambio de la infraestructura; es el cambio de las pautas de la utilización de servicios y, en particular, de los servicios de energía. Ya se ha visto que los cambios de este tipo siguen de manera bastante determinista una curva logística, y los datos correspondientes nos hacen observar que habrán de transcurrir probablemente de 50 a 100 años para que se produzca un cambio significativo que permita reducir en la mitad la demanda de energía.

• DUPLICACION DE LA POBLACION	≈ 40	60 AÑOS
• DUPLICACION DEL CRECIMIENTO ECONOMICO DEL 5%		15 AÑOS
• CAMBIO DE LA PAUTA EN USO DE "INFORMACION"	MAS DE 50 AÑOS	

Figura 19. Características cronológicas de la evolución de la demanda de energía.

Observaciones finales

Era el propósito de este estudio mostrar la gran complejidad de la demanda de energía. En contraste las características del aprovisionamiento de energía, como en el pasado, son mucho más sencillas. La producción de energía se hace en grandes instalaciones técnicas centralizadas, y han progresado mucho las ciencias y las técnicas de su ingeniería. En ella se aplican, leyes naturales muy bien conocidas, como por ejemplo, las de la energía del momento y de la conservación de masa. En consecuencia, no es extraño que, en el pasado, los análisis se centren casi exclusivamente en los aspectos del aprovisionamiento.

Los problemas de la demanda de energía tienen también en parte, índole tecnológica, pero la diversidad y variedad de las utilizaciones de la energía y, en especial, la diferencia básica entre la utilización de energía y los servicios de energía, nos llevan a consideraciones de carácter no restringido, a las que no es práctico aplicar las leyes científicas de la conservación. Aun en el plano de la investigación fundamental queda todavía mucho por hacer, antes de que se pueda comprender claramente la demanda de energía.

Hemos visto también que sólo de manera muy gradual se pueden introducir perfeccionamientos en la eficiencia de la utilización de la energía, mediante la modificación de la infraestructura. Si bien cabe esperar mucho en ese aspecto a largo plazo, es necesario ser prudente en cuanto al calendario de las mejoras concomitantes, que probablemente han de exigir el esfuerzo de varias generaciones.

La conclusión general es que se debe observar cautela en materia de afirmaciones relativas a la demanda de energía. No se resolverán los problemas energéticos de la sociedad privándose del uso de energía. Solamente pueden aportar una solución a estos problemas, los cambios de pautas que comprendan la evolución de los aspectos sociales, económicos, técnicos y científicos en este dominio abstracto, y ello exige tiempo, mucho tiempo.

AGRADECIMIENTO

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Referencias y obras afines

[1] *Chapman, P., A Review of Methods and Applications, OMEGA, The International Journal of Management Science, 4, 1, 1976.*

[2] *Charpentier, J.-P., y Beaujean, J.-M., Toward a Better Understanding of Energy Consumption –III, Energy, 2 pp. 213–282, 1977.*

[3] *Fisher, J.C., y Pry, R.H., A Simple Substitution Model of Technological Change, Report 70-C-215. General Electric Company, Research and Development Center, Schenectady N.Y., Technical Information Series, Junio, 1970; véase igualmente Technological Forecasting and Social Change, 3, 1971.*

[4] *Georgescu, N.R., The Entropy Law and the Economic Process, Harvard University Press, 1971.*

[5] *Häfele, W., y Sassin, W., Applications of Nuclear Power other than for Electricity Generation, RP-75-40, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 1975.*

[6] *Häfele, W., Energy Systems, Global Options and Strategies, en la Conferencia de IIASA 1976, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 10–13 Mayo, Vol. 1, 1976.*

[7] *Häfele, W., y colaboradores, Second Status Report of the IIASA Project on Energy Systems 1975, RR-76-1, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 1976.*

[8] *Häfele, W., Die Bedeutung der Energie für den Lebensstandard, die wirtschaftliche Entwicklung und die Umwelt, publicado en Vorträge des Internationalen Kongresses Energie und Umwelt de 8.2 a 10.2.1977, Düsseldorf, Vulkan-Verlag Essen, República Federal de Alemania, 1977.*

[9] *Hildebrandt, R., Schiling, H.-D., y Peters, W., Der Verbrauch an Primärenergieträgern in der Welt, den USA und der Bundesrepublik Deutschland, Reihe Rohstoffwirtschaft International, Verlag Glückauf, Essen, (Se publicará).*

[10] *Marchetti, C., Primary Substitution Models, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 1975.*

[11] *Nordhaus, W.D., The Demand for Energy: An International Perspectives CP-76-1, Actas de cursillos sobre demanda de energía, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 1976.*

[12] *Schurr, S.H., y Darmstadter, J., Some Observations on Energy and Economic Growth, Symposium on Future Stretegies for Energy Development, Oak Ridge, Tennessee, 1977.*

[13] *Slesser, M., Energy Analysis in Technology Assessment, University of Strathclyde, Reino Unido, 1973.*

[14] *Thoma, J., Energy, Entropy, and Information, RM-77-32, Instituto Internacional de Análisis Aplicado de Sistemas, Laxenburg, Austria, 1977.*

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Reservas y recursos mundiales de uranio

RECURSOS RAZONABLEMENTE ASEGURADOS

(1,000 tons. U)

PAIS	Datos disponibles al 1o. de enero de 1975: MENORES DE 15 $/lb U_3O_8 (RESERVAS)	Datos disponibles al 1o. de enero de 1975: 15–30 $/lb U_3O_8	Datos disponibles al 1o. de enero de 1977: MENOR DE 80 $US/kg U, MENOR DE 30 $/lb U_3O_8 (RESERVAS)	Datos disponibles al 1o. de enero de 1977: 80–130 US$/kg U, 30–50 $/lb U_3O_8
Argelia	28	–	28.	–
Argentina	9.3	11.3	17.8	24
Australia	243	– a)	237 *	–
Austria	–	–	1.8	–
Brasil	9.7	0.7	9.7	0.7
Camerún	–	–	–	–
Canadá b)	144	22 c)	167 g)	15 h)
República Central Africana	8	–	8	–
Chile	–	6	–	–
Dinamarca	–	–	–	5.8
Finlandia	–	1.9	–	1.9
Francia	37	18	37	14.8
Gabón	20		20	–
República Federal de Alemania	0.5	0.5	1.5	0.5
India	3.4	25.8	3.4	25.8
Italia	–	1.2	1.2	–
Japón	1.1	6.6	7.7	–
Corea	–	2.4	–	2.4
México	5	1	5.5	–
Nigeria	40	10	40	10
Portugal	6.9	– a)	6.8	1.0
Sudáfrica f)	186	90	306	42
España e)	10	93.5	6.8	–
Sudán	–	–	–	–
Suecia	–	300	1	300
Turquía	2.6	0.5	4.1	–
Reino Unido	–	1.8	1.8	0.4
Estados Unidos d)	320	134	523	120
Yugoslavia	4.2	2.3	4.2	2.3
Zaire	1.8	–	1.8	–
Total (redondeado)	1 080	730	1 441	567

a) El cálculo de los recursos en este rango no se ha hecho y por lo tanto se desconoce. La exploración a la fecha se ha concentrado en probar recursos de alta ley.
b) Las categorías se refieren al precio.
c) La estimación en este rango de precio es preliminar, limitada solo a los depósitos principales y muy conservadora.

d) Los siguientes recursos potenciales adicionales de gran incertidumbre se indican por E.U.

Recursos posibles	30 $/lb: 1 030.$10^3$ t U
Recursos especulativos	30 $/lb: 310.$10^3$ t U

* Necesita actualizarse

RECURSOS ADICIONALES ESTIMADOS

(1,000 tons. U)

	Datos disponibles al 1o. de enero de 1975		Datos disponibles al 1o. de enero de 1977	
RANGO DE COSTOS	MENOR DE 15 \$/lb U_3O_8	15–30 \$/lb U_3O_8	MENOR DE 80 \$US/kg U MENOR DE 30 \$/lb U_3O_8	80–130 \$US/kg U 30–50 \$/lb U_3O_8
PAIS	RESERVAS			
Angola	–	–	50	–
Argentina	15	24	–	27
Australia	80	– a)	42	–
Austria	–	–		–
Brasil	8.8	–	8.8	–
Camerún	–	–	–	–
Canadá	324	95 c)	392 g)	264 h)
República Central Africana	– 8	–	8	–
Chile	–	–	5.1	–
Dinamarca	–	10	–	8.7
Finlandia	–	–	–	–
Francia	25	15	24.1	20.0
Gabón	5	5	5	5
República Federal de Alemania	1	3	3	0.5
India	0.8	22.5	0.8	22.5
Italia	–	1	1	–
Japón	–	–	–	–
Corea	–	–	–	–
México	–	–	2.8	
Nigeria	20	10	20.	10
Portugal	– a)	– a)	0.9	–
Sudáfrica	6	68	34	38
España	8.8	98	8.5	–
Sudán	–	–	–	–
Suecia		–	3	–
Turquía	0.4	–	–	–
Reino Unido	–	4	4	1.2
Estados Unidos	500	312	838	215
Yugoslavia	–	15.2	–	15.2
Zaire	1.7	–	1.7	
Total (redondeado)	1 000	680	1 453	627

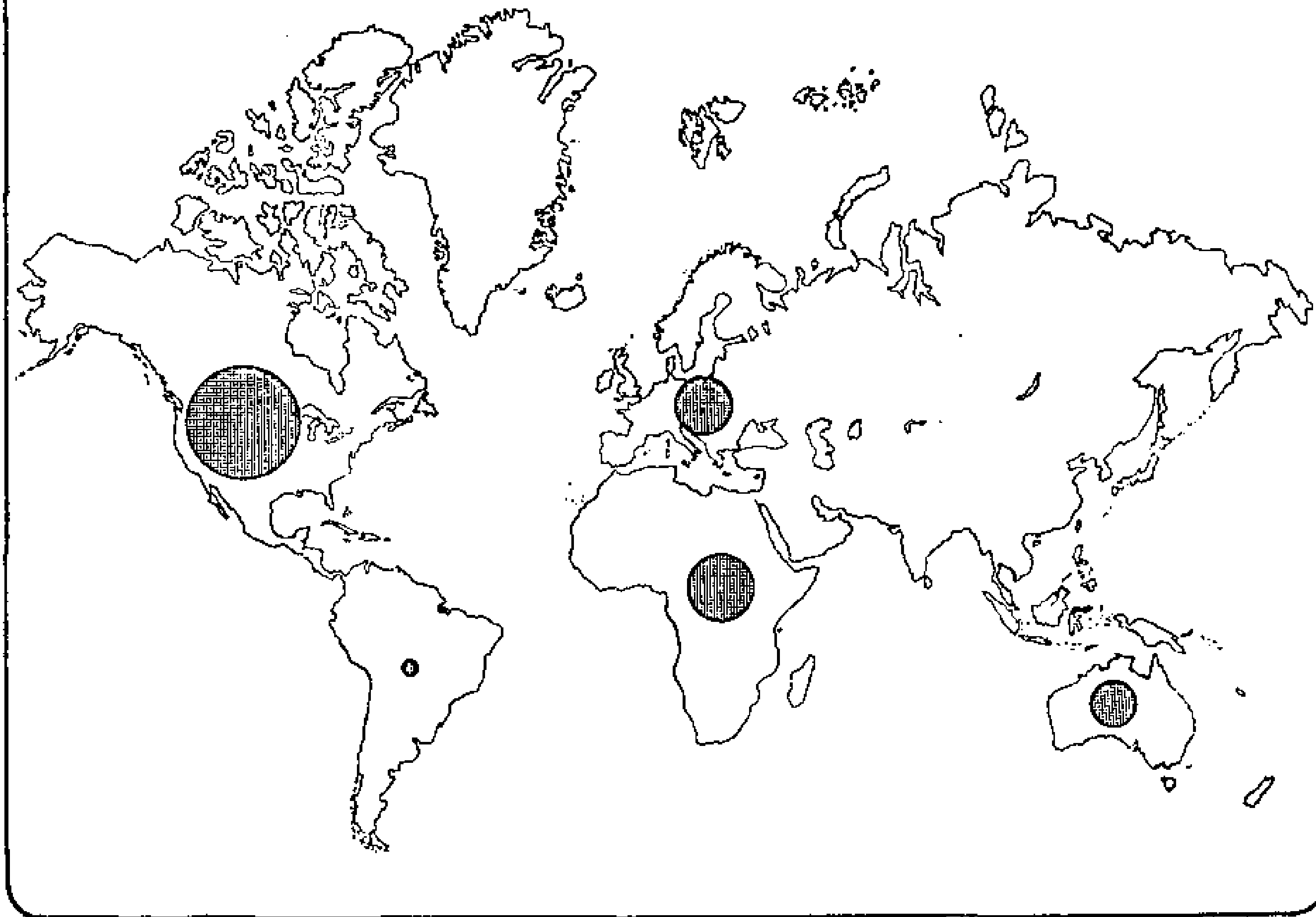
e) Incluye 63,800 toneladas de U de recursos estimados adicionales en lignito, en el rango de costos de \$15-30 U.S./lb U_3O_8 cuya disponibilidad es incierta.

f) Las 350,000 toneladas de recursos totales de uranio para Sudáfrica se han suministrado, como el mejor estimado de varias categorías de recursos.

g) Minable a precios hasta \$104 US/kg: U. (\$40 US/lb U_3O_8)

h) Minable a precios entre \$104-156 US/kg: U. (\$40-60 US/lb U_3O_8)

RESERVAS MUNDIALES DE URANIO



Reservas y recursos mundiales de uranio

Desde 1975 a la fecha, los precios del uranio han seguido la tendencia ascendente manifestada por todas las fuentes de energía; la inflación resentida por los costos de recuperación del uranio ha sido un factor significativo. De esta forma, a pesar de que el Grupo de Trabajo de la NEA (Nuclear Energy Agency) ha mantenido el concepto de "categorías-costo" y no el de "categorías-precio" en sus definiciones de los recursos de uranio, se hace nuevamente necesario revisar la amplitud de estas categorías. Los parámetros de costo adoptados se sitúan actualmente en $\leq$ US$80 / Kg. U. (US$30 / lb U_3O_8) y US$80 - US$130 / Kg de U. (US$30 - US$50 / lb U_3O_8) lo que implica un cambio considerable frente a los rangos de 1975 ($\leq$ US$15 / lb U_3O_8 y US$15 - US$30 / lb U_3O_8). Considerando los efectos de la inflación antes señalados, el rango actual y el de 1975 no resultarían comparables en términos de costo, aunque sí lo son en términos de volumen.

Aún cuando las bases para calcular los costos a fin de estimar los recursos son similares de país a país, existen algunas diferencias. El Grupo de Trabajo ha concluído que estas diferencias no afectan significativamente la comparabilidad de las cifras de los recursos; por lo demás, para los propósitos de este informe, se complementarán las cifras respectivas a fin de proporcionar una estimación adecuada de la magnitud de los recursos mundiales. Generalmente, sin embargo, la mayoría de las bases de costos incluyen no sólo los costos directos de minería y procesamiento, sino también los gastos de capital erogados en el mantenimiento de la unidad de producción. Los costos efectuados de exploración, comunmente no se incluyen.

El valor del dólar empleado a lo largo de este reporte corresponde al dólar norteamericano, a las tasas de cambio del 1o. de enero de 1977. No se incluye información de la URSS, Europa Oriental ni de China, por no haber datos disponibles; por lo mismo, la expresión "mundo" queda circunscrita a los demás países. Por último, cada rango de costo del uranio se subdivide en este informe, a su vez, en dos categorías.

El término **recursos razonablemente asegurados** se refiere a uranio, localizado en yacimientos de minerales conocidos, de cierta ley y cantidad que puede ser recuperada dentro del rango de costos y precios vigentes al explotarse, así como a los métodos y sistemas de extracción aplicables. Las estimaciones de tonelaje y ley se basan en datos específicos de muestras, así como en dimensiones y características conocidas del yacimiento. Los **recursos razonablemente asegurados** ofrecen un alto grado de certeza; si se sitúan en un rango de costos inferior a US$80 / Kg U. (US$30 / lb U_3O_8) se consideran como **reservas** para el propósito de este análisis.

El término **recursos adicionales estimados** alude al uranio que se espera encontrar adyacente a los **recursos razonablemente asegurados**, principalmente con base en una evidencia geológica directa, ya sea:

- en extensiones de depósitos bien explorados;
- en yacimientos poco explorados;
- en yacimientos no descubiertos que se supone existen a lo largo de características geológicas bien definidas y provistas de depósitos conocidos.

Si se enmarcan dentro del rango de costos dado, estos depósitos pueden ser identificados y delineados y, subsecuentemente podrá recuperarse el uranio. La estimación del tonelaje y la ley de los recursos adicionales se deduce primordialmente, de las características de las partes mejor conocidas del yacimiento o de depósitos similares. En consecuencia, la evaluación de los **recursos adicionales estimados** resulta menos confiable que la correspondiente a la categoría de **razonablemente asegurados.**

Los recursos estimados se expresan en términos de las cantidades de uranio recuperable del yacimiento, considerando la dilución permitida y las pérdidas resultantes de los trabajos de minería y molienda. Las cantidades se expresan en toneladas métricas de mineral de uranio (toneladas de uranio), correspondiendo cada una de dichas unidades aproximadamente a 1.3 toneladas cortas de U_3O_8; los rangos de costos se expresan en US$/Kg U y en US$/lb U_3O_8 (US$ 1.00/lb U_3O_8 corresponde a US$2.60/Kg U.)

Las estimaciones disponibles son incompletas por lo que los esfuerzos se dirigen comunmente a evaluar los recursos potencialmente previstos, así como a determinar las regiones en que se deberá concentrar la exploración para identificarlos. Estas evaluaciones deberán orientarse, razonablemente, hacia otras categorías de recursos de menor certeza que la de los recursos adicionales estimados.

Las diferencias observadas entre **recursos razonablemente asegurados, recursos adicionales estimados** y una posible categoría futura se basan en los diversos grados de evidencia geológica y exigen que cada categoría se considere como una entidad discontinua. De ahí que se deba ser muy riguroso en la clasificación de los recursos estimados (por ejemplo, no deben sumarse las estimaciones de las diferentes categorías para obtener los "recursos totales") En el nivel de **recursos adicionales estimados** hay que considerar un potencial para su conversión posterior a **recursos razonablemente asegurados**, como posible resultado de esfuerzos detallados de exploración.

Fuente: *Uranium, Resources, Production and Demand. Diciembre de 1975, OECD Nuclear Energy Agency e International Atomic Energy Agency.*
Steering Comitee for Nuclear Energy
Study Group on the Long Term Role for Nuclear Energy
París, junio 13 de 1977.

UN NUEVO ANALISIS DE PRODUCCION MUESTRA ELEVACION EN EL PRECIO DEL URANIO HASTA 1990.

La investigación efectuada por "Collieries Management Corp." de Filadelfia, indica que no se presentará estancamiento en el precio del uranio entre 1978 y 1990, sino por el contrario, los resultados del estudio indican que el precio del concentrado amarillo (U_3O_8), en dólares de 1978, estará en años futuros en los siguientes rangos:

1980 - 49.20 a 60.80 Dls/lb.
1985 - 70.20 a 100.80 " "
1990 - 86.70 a 110.20 " "

El enfoque del análisis se concentra en la extracción del mineral y el proceso de beneficio para producción del U_3O_8. En apoyo de aquellos que predicen una baja en el precio del uranio por abundancia del mineral, el estudio supone que existen recursos adecuados y que serán descubiertos oportunamente. Además, para determinar la demanda se ha tomado la estimación "baja" del Departamento de Energía respecto a capacidad de unidades nucleoeléctricas en los Estados Unidos.

1985 - 110 GW con utilización de 65%
1990 - 180 " " " " "
2000 - 330 " " " " "

Aún con estas suposiciones las conclusiones centrales del análisis que inciden en el precio siguen siendo:

1) Los reactores actualmente en construcción implican un incremento en demanda de combustible que excede el suministro disponible.
2) La industria de suministro de combustible nuclear debe incrementar considerablemente su capacidad durante los siguientes 10 a 20 años aún considerando el plan más pesimista de colocación de órdenes de unidades nucleares.

De acuerdo con el estudio existen factores que hacen prever escasez significativa de uranio en el período 1985-1990, a menos que se tenga un desarrollo intensivo de la producción entre 1978 y 1985. Los principales factores son:

1) Tiempos largos de exploraciones, de desarrollo de minas y en los procesos de beneficio.
2) Declinamiento confirmado en la ley de los minerales extraídos.
3) Constante empobrecimiento de las minas en explotación, tanto antiguas como nuevas.

Las leyes de minerales extraídos han decaído en los últimos años de un promedio de 0.2% a un promedio de 0.15% y se espera que durante el período considerado por el estudio de ley promedio bajará de 0.1% a menos.

Para abastecer la demanda de combustible nuclear en el caso de "bajo crecimiento" de la capacidad nuclear, se requieren las siguientes capacidades de tratamiento de mineral de uranio:
1985-39 millones de toneladas por año
1990-55 " " " " "
2000-95 " " " " "

El estudio calcula que se requerirá invertir 8,000 millones de dólares en las dos décadas siguientes en el desarrollo de nuevas minas de uranio, sin incluir los gastos de exploración. 3,000 millones de dólares adicionales deberán invertirse en plantas de beneficio del mineral para una inversión total de 11,000 millones de dólares en el período 1980 - 2000.

Fuente: *Nucleonics Week, Vol. 19 No. 11 Marzo, 1978.* INEN

EL PRESIDENTE DE LOS E.U.A. FIRMO EL DECRETO CONTRA LA PROLIFERACION NUCLEAR.

El Presidente Carter incorporó a las leyes de los E.U.A. una serie de medidas tendientes a limitar la proliferación de armas nucleares en el mundo. A partir de la firma del decreto empiezan a contar los plazos para que las medidas entren en vigor. Como consecuencia Euratom tendrá que renegociar sus acuerdos de cooperación con los E.U.A. en un plazo de 30 días o enfrentarse a la suspensión del suministro de combustible nuclear norteamericano.

En la ceremonia de la firma del decreto el Presidente Carter mencionó "algunos de los países amigos tendrán que modificar sus políticas nucleares". También hizo notar que los E.U.A. seguirán apoyando el empleo intensivo de reactores de agua ligera, pero que no se considera que los reactores de cría son necesarios actualmente.

Fuente: *Nucleonics Week, Vol. 19, No. 11 Marzo de 1978. INEN.*

¿SOLUCION A LA PROLIFERACION NUCLEAR?

En la V Conferencia sobre Tecnología Energética que se llevó al cabo recientemente en Washington, se describió un sistema que permitiría la expansión mundial de la energía nuclear sin el riesgo de proliferación de las armas atómicas. El nuevo proceso se basa en el tratamiento químico del combustible usado en reactores de agua ligera (LWR) convirtiéndolo en combustible para reactores de cría de neutrones rápidos (FBR), bajo condiciones que son totalmente seguras contra terroristas y grupos subversivos, o la decisión súbita de un gobierno para disponer de plutonio para armas nucleares.

El Dr. Chauncey Starr, Presidente de EPRI, explicó que el nuevo proceso nombrado "Civex" parte de combustible irradiado descartado de reactores en operación y lo convierte en combustible refabricado, que es también altamente radioactivo y que es producido por aparatos automáticos controlados en forma remota y protegidos por gruesos blindajes de concreto.

En ningún punto del proceso se obtiene plutonio puro y nunca se le separa de una cantidad considerable de productos de fisión radioactivos.

Debido a los altos niveles inherentes de radiactividad todas las etapas del ciclo de combustible están autoprotegidas, por lo que el producto no es accesible físicamente, quedando protegido contra robo. Además, las concentraciones de plutonio durante el proceso Civex son demasiado bajas para ser usadas en armas nucleares. Pero, lo que es aún más importante, el proceso hace que sea físicamente imposible que mediante cualquier modificación del proceso o manipulación del mismo se puede obtener plutonio de grado bélico.

Todas las etapas individuales del proceso Civex han sido demostradas a escala de laboratorio, como partes de programas de investigación y desarrollo de combustible para reactores rápidos de cría en el ámbito mundial, durante las últimas dos décadas, especialmente en Argonne y en Oak Ridge National Laboratories en los Estados Unidos.

Una planta Civex totalmente operable, requeriría del desarrollo de un sistema de fabricación comercial basado en todas las etapas que han sido demostradas.

Fuente: *Electrical World - Abril, 1978. INEN.*

LONDRES, SEDE DE LA CONFERENCIA SOBRE VEHICULOS ELECTRICOS.

En octubre de 1980 se celebrará en el Centro de Conferencias de Wembley, Londres, una importante exposición y conferencia internacional sobre vehículos eléctricos. La conferencia, que tendrá como nombre "Tracción Eléctrica 1980", será patrocinada por la Asociación británica de Vehículos Eléctricos y el Consejo de Electricidad.

Para 1980 -afirman los organizadores- Gran Bretaña y el resto de la Comunidad Europea, Japón y los Estados Unidos habrán logrado un importante avance hacia la producción en serie de vehículos eléctricos.

En la conferencia, por consiguiente, se invitará a que los fabricantes y principales usuarios presenten una evaluación del progreso logrado, y a que expongan y debatan los futuros planes a seguir.

En otras sesiones de la conferencia se llevarán a cabo deliberaciones y se presentarán monografías. Los delegados podrán visitar las instalaciones técnicas de los principales centros británicos especializados en la producción de vehículos eléctricos.

Fuente: Cortesía de la Embajada Británica. Junio de 1978.

AHORRO DE CARBON EN LA FABRICACION DE LADRILLOS

La industria británica de fabricación de ladrillos para la construcción podría reducir un 50% la cantidad de carbón que utiliza anualmente sin ahorro de 500,000 toneladas adoptando técnicas de fabricación que conservan energía.

Esta es una de las principales conclusiones de un informe titulado "Energy Audit 2- The building brick industry" (Segunda revisión del uso de la energía) la industria de fabricación de ladrillos para la construcción, preparado en forma conjunta por los Ministerios de Energía e Industria de Gran Bretaña.

Dicho informe señala que en la fabricación de ladrillos se podría efectuar este ahorro recuperando una parte de la energía que se pierde en el gas de salida de los hornos, agregando desechos carbonosos a la arcilla y los esquistos y aumentando el nivel de las perforaciones de los ladrillos.

El informe manifiesta que algunas fábricas de ladrillos ya están aplicando fichas técnicas pero recomienda al gobierno promover y financiar investigaciones sobre proyectos de recuperación del calor residual, de inclusión de aditivos carbonosos y elevación de los niveles de perforación en la producción de ladrillos.

El informe sobre la industria de fabricación de ladrillos forma parte de una serie de estudios relativos al consumo y la conservación de energía en la industria británica, en los que participan el Departamento de Base Tecnológica de la Energía (ETSU), dependiente del Ministerio de Energía, y el Departamento de Energía del Ministerio de Industria.

El citado informe señala un posible ahorro de combustible del orden de los 28 millones de gigajoules (GJ) por año de energía de fuentes convencionales. Según se expone, el uso de energía es mucho mayor que el uso de combustible porque el carbon presente en la materia prima de algunos ladrillos se consume durante la cocción.

El promedio de la "cantidad normalmente necesaria de combustible" (excluyendo el carbon) es equivalente a 2.2 GJ/tonelada pero el informe indica que el consumo de diversas fábricas fluctúa de 0.8 GJ/tonelada a 6GJ/tonelada, según el tipo de ladrillo, su contenido de carbon, la escala de producción y la forma en que se utiliza la energía.

El informe apunta que se necesitará menos combustible para la cocción si se aumentan los niveles de carbon de la arcilla y los esquistos mezclándolos con desechos carbonosos que se obtienen al extraer la arcilla.

Entre el 80 y 90% de la energía total necesaria para la fabricación de ladrillos se utiliza en la etapa de cocción si los ladrillos son secados, como suele ocurrir, por aire caliente proveniente del horno. La cocción es, por consiguiente, la única etapa en la que se pueden efectuar grandes ahorros de energía.

El informe destaca que debe encomendarse a la Asociación Británica de Investigación de Productos Cerámicos la realización de experimentos destinados a producir ladrillos de nivel aceptable con mezcla de carbon, y al ETSU que aliente a las empresas para que ensayen en fábrica el uso de aditivos carbonosos.

Puede solicitarse "Energy Audit 2- the building brick industry" en forma gratuita del Department of Energy, Thames House South, Millbank, Londres, SW1P 4QJ, Inglaterra.

Fuente: Cortesía de la Embajada Británica. Junio de 1978.

FRANCIA BUSCA DIVERSIFICAR SUS FUENTES DE URANIO

De acuerdo con el Consejo de Política Exterior Nuclear, que comprende ministros y consejeros, el gobierno de Francia está buscando la manera de diversificar sus fuentes de abastecimiento de uranio, el Consejo está considerando también estrategias de almacenamiento de uranio.

Fuentes de París consideran que el anuncio del Consejo tiene dos objetivos: en primer lugar trata de convencer a la fracción de derecha Degaullista de que Francia no se está doblegando a la influencia de los Estados Unidos, en lo que a ciclo de combustible se refiere. El Consejo reiteró su preocupación de que la reunión Internacional de Evaluación del Ciclo de Combustible tenga una opinión prejuiciada. En segundo lugar, trata de mostrar a los actuales abastecedores, que Francia puede dirigirse a otros proveedores de uranio. Francia teme que si Canadá no le da garantía de abastecimiento a medio y largo plazo, Gabón y Nigeria pueden seguir los mismos pasos.

El único comentario del Gobierno Francés consistió en decir que la diversificación es perfectamente natural, así como el tener una reserva que garantice la seguridad de abastecimiento. Consideran que la reserva que tienen almacenada es adecuada para el corto plazo, pero que necesitan aumentarla para cubrir el plazo medio.

El abastecimiento de uranio parece ser el único punto débil en el programa nuclear francés, pues cuenta con todos los otros ingredientes necesarios para el éxito; cuenta con un fuerte apoyo gubernamental, tiene capacidad de enriquecimiento, sus técnicas de reprocesso y almacenamiento de desperdicios están bastante avanzadas, únicamente le falta la garantía de abastecimiento de uranio a medio y largo plazo.

No se sabe cuales son las fuentes a las que recurrirá Francia para diversificar su abastecimiento, pero el Comisariado de Energía Atómica estima que las empresas francesas, tanto privadas como públicas, tienen intereses mineros o de prospección en casi 20 países, el propio CEA participa activamente a través de subsidiarias en seis países: Nigeria, Gabón, Australia, Canadá, Estados Unidos e Indonesia.

Fuente: Nuclear Fuel, Enero, 1978, INEN.

COSTOS DE GENERACION COMPARABLES PARA PLANTAS NUCLEARES Y DE CARBON SEGUN ESTUDIO PATROCINADO POR LA EMPRESA ELECTRICA "WISCONSIN POWER & LIGHT"

El estudio fue realizado por la firma "Sargent & Landy" y de acuerdo con los resultados se estima un costo promedio de generación durante la vida útil de dos unidades nucleares de 900 MW cada una, en 0.0825 Dls/KWH y para tres unidades de carbón de 600 MW cada una en 0.0815 Dls/KWH.

Las dos unidades nucleares se consideran en el mismo sitio. La primera unidad entra en servicio en 1987 y la segunda en 1989. Los costos de instalación respectivos son 1309 y 1243 Dls/KW. El precio del uranio se hizo variar entre 28 y 43 Dls/libra.

Dos de las unidades de carbón se consideran en un sitio entrando en servicio en 1987 y 1989 con costos de 998 y 837 Dls/KW respectivamente. La tercera unidad en un sitio diferente por regulaciones ambientales, entra en servicio en 1989 con un costo de 998 Dls/KW. Se supone de carbón de bajo azufre procedente de Montana y Wyoming y no se consideran depuradores para los gases liberados a la atmósfera. El costo del carbón se estimó en 20.70 Dls/ton. incluyendo transporte.

Tanto para unidades nucleares como de carbón se consideraron: factor de planta de 70%; tasas anuales de inflación de 8% para materiales, de 10% para mano de obra y de 6% para combustibles.

El objetivo del estudio es convencer a la "Wisconsin Public Service Commission" de la conveniencia de programar una mezcla de plantas de carbón y nucleares ya que dicha Comisión respalda la idea de depender en forma exclusiva del carbón.

De los costos de generación nuclear 57.3% corresponden a cargos por capital y 30% a cargos por combustible. Para la generación de carbón 38.9% del costo corresponden a cargos por capital y 53.3% a cargos por combustible.

Se hace notar que en el caso de la generación nuclear si la tasa de inflación del combustible se considera de 8% anual, el costo de generación aumenta un 10.2%. En cambio si se considera un factor de planta de 80% el costo de generación disminuye un 12%.

Para las plantas de carbón el empleo de depuradores para los gases de combustión significaría un aumento de costos de generación de entre 10% y 20%.

Fuente: *Nucleonics Week, Vol. 18*, INEN.

EL PETROLEO DE ARABIA PARA 1984

Para 1984, la creciente demanda mundial de crudo requerirá de 14 MMBPD de los campos sauditas, que en 1977 producían 8.9 MMBPD. De acuerdo con estimaciones de la CIA, para 1985 se necesitarán 16 MMBPD ó más de Arabia Saudita. Sin embargo, los sauditas no tienen intenciones de realizar nuevas inversiones y para 1985, la capacidad será de entre 12 y 14 MMBPD.

Actualmente la producción saudita es de 10.5 millones de b/d.; con una inversión de 20 mil millones de dlls. podrían incrementarla a 16 MMBPD. La decisión de los sauditas se basará en gran medida en el valor del dólar, ya que la caída de éste hace más atractivo tener el petróleo bajo tierra que en notas de banco. Por otra parte, se observa que los sauditas necesitan del apoyo militar y político de los EUA, y éstos últimos de la influencia que Arabia Saudita ejerce sobre los países árabes y la OPEP.

Fuente: *Business Week, febrero 27, 1978.*

DEMANDA Y PRODUCCION DE PETROLEO EN LOS EUA

La demanda nortramericana de productos petroleros crecerá al 3.4% durante 1978, promediando 19.1 MMBPD. En 1977, esta demanda creció 6.1% sobre 1976. La producción interna de crudo será de 8.7 MMBPD, sólo 470,000 BPD, mayor que la de 1977, este incremento se debe a la producción de Alaska. Para satisfacer la demanda estimada, los EUA requerirán importar 8.5 MMBPD de crudo.

Fuente: *Chemical Engineering, febrero 13, 1978.*

IMPORTACIONES DE CRUDO EN LOS EUA

Un estudio desarrollado por Shell Oil Co. especifica que la dependencia norteamericana en crudo y gas natural importados será creciente durante los próximos 12 años.

Para 1990 los EUA importarán 11.3 MMBPD de gas natural (en términos equivalentes). En 1977 estas importaciones fueron de 8.6 MMBPD de crudo y 500 MBPD de gas natural.

Mientras tanto el crecimiento de la demanda energética promediará entre 2 y 2.5% anual y el del PNB será de 3.1%.

Bajo el Plan Nacional de Energía, el nivel de las importaciones es bastante menor, para 1985 sería en total de 7.2 MMBPD de crudo equivalente, contra 12.9 MMBPD proyectadas por Shell. Asimismo el Plan Nacional estima un crecimiento del PNB del 3.6% anual. Para 1990 el 73% de las importaciones de crudo, según Shell, provendrá de la Organización de Países Arabes Exportadores de Petroleo (OPAEP) mientras que el gas provendrá principalmente de México, conforme se reducen las exportaciones de Canadá.

La demanda total de energía en 1990 será de 50.6 MMBPD de crudo equivalente, contra 36.2 MMBPD en 1977.

Fuente: *The Oil and Gas Journal, febrero 20, 1978.*

INVERSIONES PETROLERAS EN LOS EUA

La industria petrolera norteamericana proyecta invertir 28,900 millones de dlls. en este año, en gastos de capital y de exploración. Esta cifra es 8.8% mayor que la de 1977.

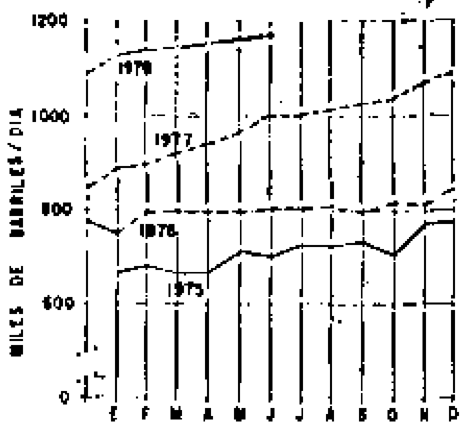
	Millones de dlls.
Exploración	10,544
Producción	6,735
Refinación	2,184
Petroquímica	1,782
Comercialización	998
Oleoductos	916
Gasoductos	946
Otros transportes	419
Diversos	4,403
T O T A L :	28,927

Los gastos de empresas nortramericanas en el exterior ascenderán a 8,526.3 millones, o sea 39.5% más que en 1977. El renglón principal de inversión en el exterior será la producción de crudo, pero el que presenta un crecimiento más fuerte es la petroquímica al pasar de 91.9 a 155.6 millones de dlls., o sea un incremento del 69.3%.

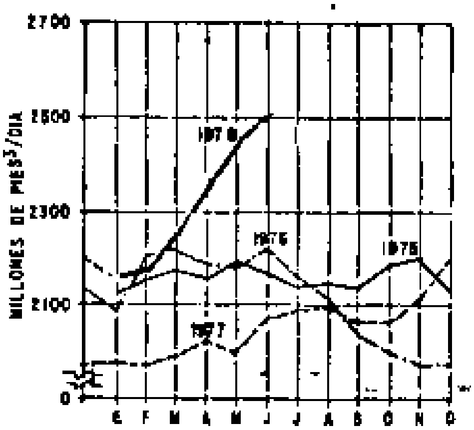
Fuente: *The Oil and Gas Journal, febrero 20, 1978.*

PRODUCCION NACIONAL DE HIDROCARBUROS

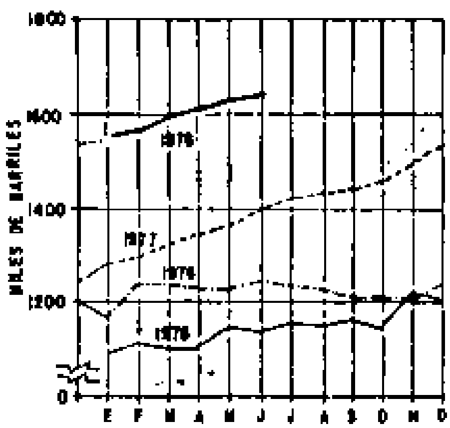
Crudo y Condensado



Gas Natural



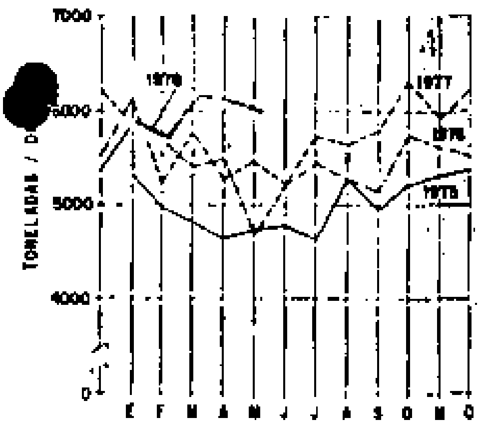
Hidrocarburos Totales*



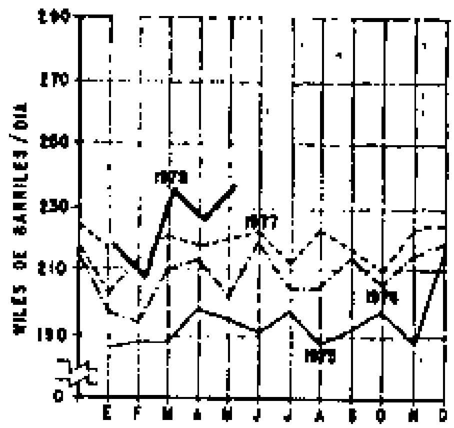
**Crudo y condensado más gas natural húmedo equivalente a crudo.*
Se considera un equivalente de 5 000 pies cúbicos de gas natural húmedo por barril de petróleo crudo.

VENTAS DE PRODUCTOS

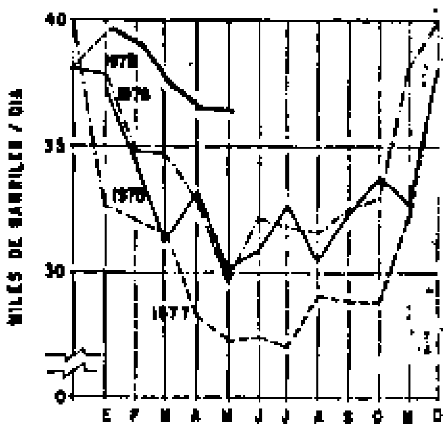
Gas Licuado



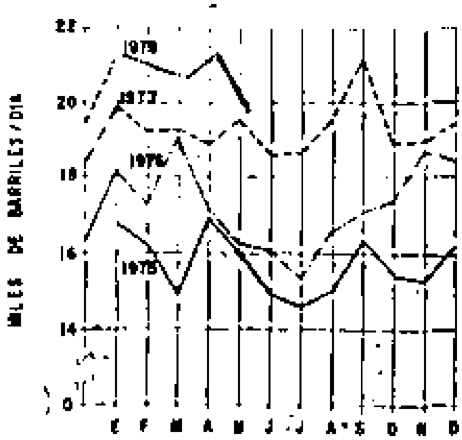
Gasolinas



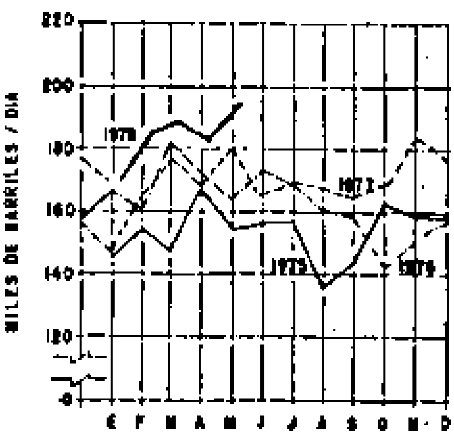
Kerosinas



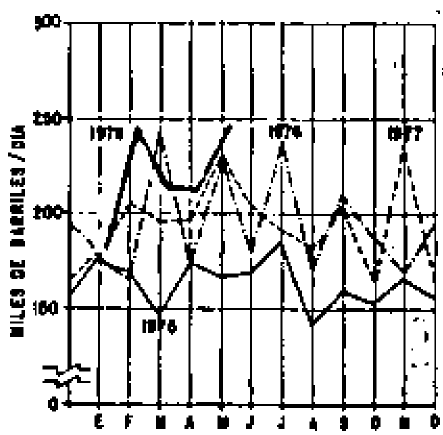
Turbosinas



Diesel

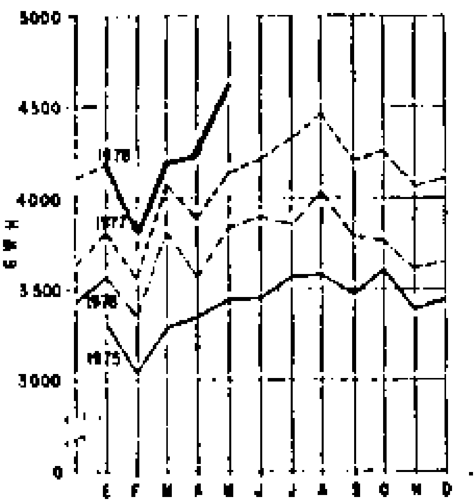


Combustóleo



Fuente: *Petróleos Mexicanos, oficina de Coordinación y Estudios Técnicos.*

Generación Bruta

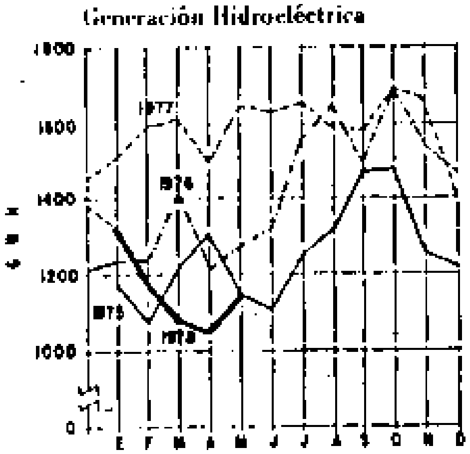


GENERACION BRUTA POR TIPO DE PLANTA (GWH)

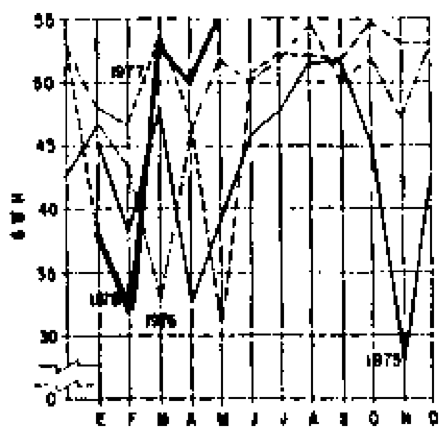
CONCEPTO	1977 ENE-MAYO	%	1978 ENE-MAYO	%	78/77
Generación Bruta	19 399.5	100	21 151. 8	100	9.03
Hidroeléctrica	7 845.2	40.5	6 091.0	28.8	-22.36
Termoeléctrica	11 554.3	59.5	15 060.8	71.2	30.35
a) Vapor*	10 581.0	54.5	13 398. 4	63.3	26.63
b) Geotérmica	225.1	1.2	228.7	1.1	1.60
c) Combustión Inter.	188.3	1.0	185.8	0.9	-1.33
d) Turbo - Gas	559.9	2.8	1 247.9	5.9	122.88

* Incluye ciclo combinado

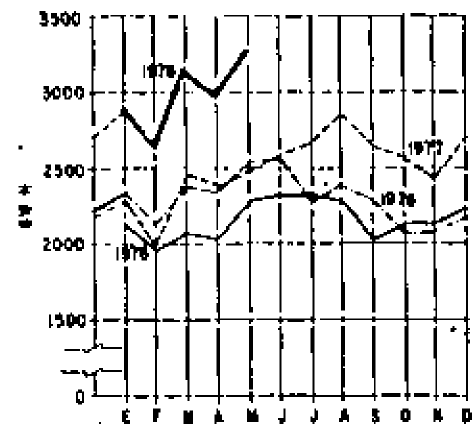
Generación Hidroeléctrica



Generación Geotérmica



Generación Termoeléctrica



Fuente: *Comisión Federal de Electricidad*

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PROCESS HOT WATER FOR TEXTILES

J. B. Trice and A. D. Cohen

A significant market is predicted from this solar process hot water demonstration.

An economic analysis has been made of the first demonstration of solar process hot water in the textile industry. This solar system for heating dye water, designed here at General Electric and funded by the US Department of Energy, was put into operation last June at a textile plant in South Carolina (USA). It is now undergoing evaluation.

Using cost and performance data from the demonstration project, we have determined the factors required to meet acceptable industry standards for payback periods, which are typically 5 years or less in the textile industry. With favorable government incentives, solar process hot water systems could begin to be competitive with conventional systems in certain parts of the country.

The particular textile mill selected for this demonstration project is part of the Riegel Textile Corporation, La-France, South Carolina. In the US, nearly 75% of all textile dyeing and finishing mills are located in the southeast part of the country, about half of them in the states of North and South Carolina. Thus, the results of this demonstration will be applicable to a broad segment of the industry. And although the solar system is installed in a textile plant, it could be adapted to a wide range of applications for chemical plants, metal finishing, and food processing.

The specific process that was solarized is atmospheric, batch fabric-dyeing, which requires a maximum temperature of 88°C (190°F). The equipment is standard (see Fig. 1) and is used for about 75% of the batch dyeing and finishing in the industry. In batch dyeing, about 100 yards of fabric are processed per load. The fabric forms a continuous loop around a tumbler which passes the cloth through the dye liquor contained in large vats (800 to 2400 gal) commonly called *dye becks*. The dyeing rate is a function of the liquor temperature and of dye concentration variables, which are adjusted by the dyemaster to achieve the desired color.

A schematic of the solar hot-water system is shown in Fig. 2. The configuration evolved from a number of other solar heating and cooling projects undertaken by General Electric. The solar system and its corresponding control logic are designed to collect energy at the lowest usable temperature since this results in the highest collection efficiency.

The solar system is comprised of three independent circulating loops that are connected thermally by means of heat exchangers:

- The solar collector loop (Fig. 2A) transfers the energy collected by the solar array to the collector-loop heat exchanger (HX-1). An ethylene-glycol/water heat transfer fluid provides freeze protection.
- The thermal-energy storage loop (Fig. 2B), containing an 8000-gal storage tank (TES), transfers the energy either to storage or to the plant-process heat exchanger (HX-2). Energy is apportioned between the two as appropriate, by automatically switching the flow.
- The stainless-steel dye-systems loop (Fig. 2C) thermally couples the solar system to the dye-beck water.

An outstanding feature of the collector design is the General Electric Co. high-temperature evacuated-tube solar collector. The high-performance collector was selected because studies had indicated that a significant part of the energy needs could not be provided by flat-plate collectors. A comparison of the predicted performance for the evacuated-tube and for flat-plate collectors is shown in Fig. 3.

Each Solartron tube consists of two concentric glass cylinders. The space between them is sealed and air is removed. The outer cylinder acts as the collector window while the inner cylinder is specially coated and serves as the radiation absorber. A U-shaped copper tube enters and leaves the end of each vacuum tube. The individual tubes are connected in series. Once heat is

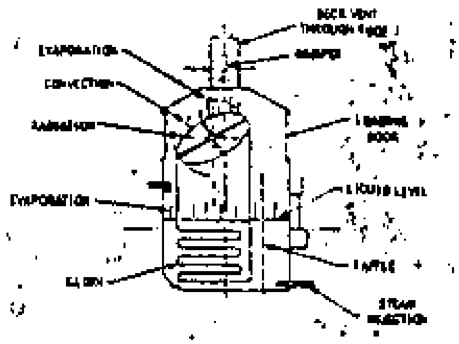

Fig. 1. Schematic of the open atmosphere dye beck, which contains a solution of dyes in water at about 190°F.

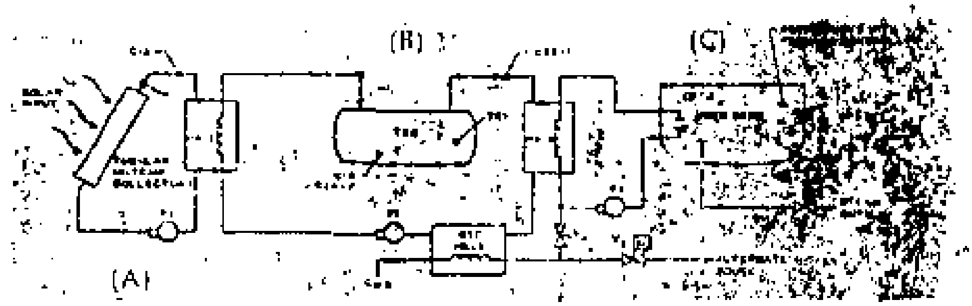

Fig. 2. Schematic of the solar energy system for the LaFrance textile mill: (A), the collector loop; (B), the storage loop; (C), the dye-systems loop.

The authors are with General Electric Company in King of Prussia, Pennsylvania (USA).

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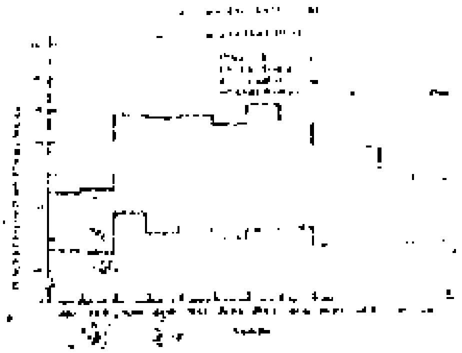

Fig. 3 Predicted performance for evacuated-tube and flat-plate solar collector systems for assumed dye beck load.

Fig. 4 Overall view of the LaFrance plant, with the collector array (left center).

trapped inside the collector tube, it is conducted by the inner glass cylinder to the metal fin and is removed by fluid flowing through the U-tube.

The solar collector array, which totals some 6800 ft², is located on a hillside facing south (Figs. 4 & 5). The 390 collector panels have been installed at an angle of 30 degrees on a 12-degree hill. Five hundred feet of piping takes the heated fluid (up to 132°C) from the collector array to the storage tank or dye becks.

About 90% of the energy required by the dye beck can be provided by the evacuated-tube system during the spring and summer months; in midwinter, it supplies about 50% of the energy.

Fig. 5 The LaFrance solar collector array.

Economic Analysis

In order to determine the potential for using solar energy to reduce the use of fossil fuels for heating water in the textile industry, analyses have been made of the energy savings at the unit process level, the plant level, and the industry level. The annual energy requirements and savings that have been estimated from hourly simulation runs for the LaFrance systems are presented in Table 1. The load-demand profile used as a composite for the

Table 1. Projected Solar Process Hot Water Requirements and Energy Savings for LaFrance

	Total annual process hot water energy demand Units: 10[illegible] Btu	Annual energy savings estimated via solar process heat Units: 10[illegible] Btu
Single 1100-gallon dye beck*	2.1	1.1
Total LaFrance plant (based on 53-beck requirement)**	8.5	4.4

*Results based on optimization parametric analysis described in Conceptual Design Report CDRL PA6, General Electric Doc. 78SDS4219.

**Values based on averaging data from the following sources:
- U.S. Dept. of Commerce, Doc. MC[illegible] (SR-6S), Fuels of Manufacturing: Fuels & Electric Energy
- Dr. C. A. Brandon, Clemson University, private communication
- U.S. Textile Equipment Manufacturers, private communication

three basic dyeing cycles utilized at LaFrance.

The total energy savings attainable through using solar heating in the entire textile industry is only a small fraction (about 1%) of the energy used for process hot water in the US industrial sector as a whole; however, the basic solar system developed here is applicable to most industrial hot water processes. Since process hot water accounts for 3 quads (3×10^{15} Btu) of energy per year, or about 8% of the total US industrial demand, there is indeed a significant potential for widespread fuel savings.

Capital investments for solar process hot water systems are not now competitive with conventional energy systems. However, technological advances, continued shortages of and escalating fossil fuel prices, and government incentives are expected to dramatically affect the future market for the solar systems.

One possible future scenario for a solar process hot water system is shown in Fig. 6. Assumptions used in developing the data are as follows:

- Collector array is 100,000 ft²
- Collectors deliver 250,000 Btu/year
- Cost for operation, maintenance, replacement, and insurance is $15,000/year
- Depreciation is [illegible] over 20 years
- Tax on profits is 50
- Boiler efficiency of an oil fired conventional steam system is 70%

In Fig. 6, the payback period is given as a function of initial investment, expressed as installed costs in dollars/ft² of collector. Results are in terms of three parameters: fuel costs, tax credit on initial investment, and equivalent fossil fuel tax credit (see Table 2). Two rates for fossil fuels are shown (all in 1978 dollars):

Table 2. Economic Scenario Parameters*

Curve	Fuel cost $/MM Btu	Investment tax credit (%)	Equivalent fuel tax credit (%)
1	4	0	0
2	4	25	0
3	6	0	0
4	8	0	0
	6	25	0
	4	0	50
5	8	25	0
	4	25	50
6	6	0	50
7	8	0	50
	6	25	50
8	8	25	50

*Assumptions
- System includes 100,000 ft² solar collector field.
- Annual thermal energy delivered is 350,000 Btu/ft² for total annual contribution of 3.5×10^{10} Btu

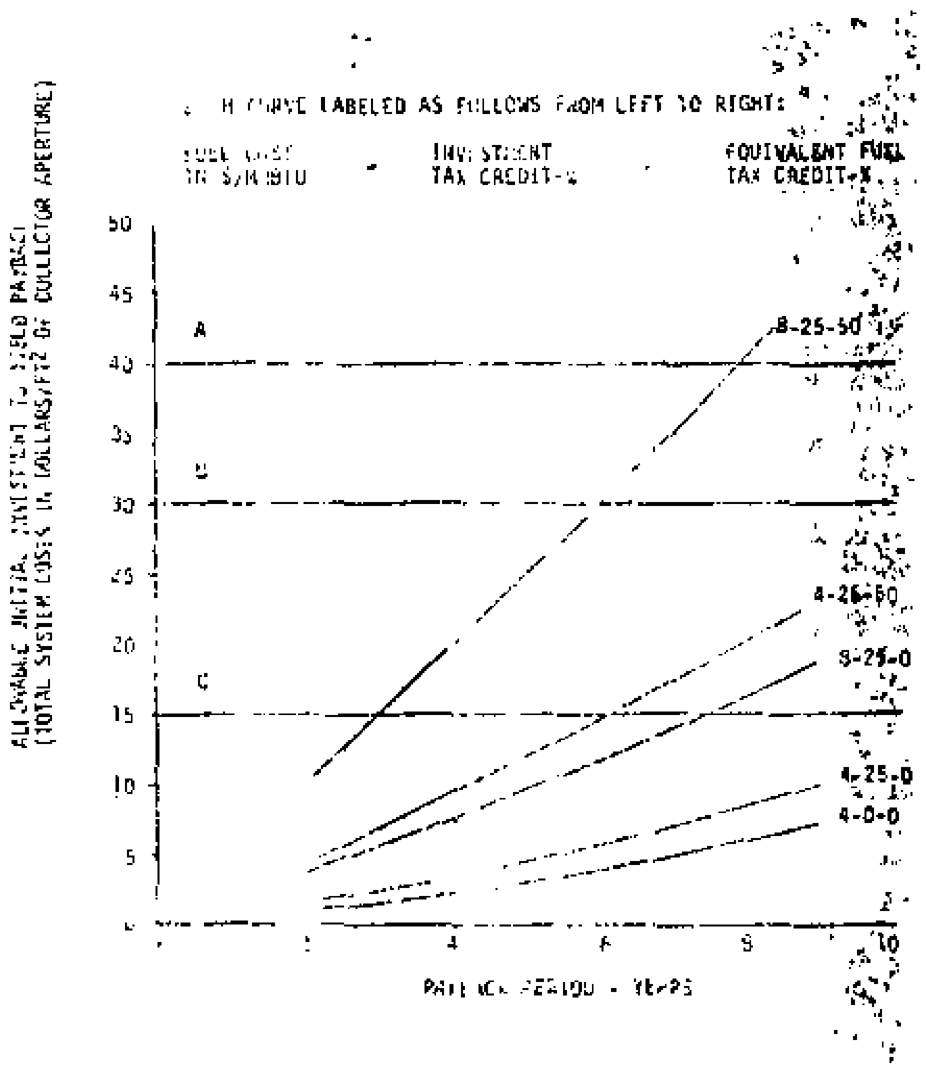

Fig. 6. Economic scenarios for solar process hot water systems similar to the LaFrance system. Note that [illegible]

three basic dyeing cycles utilized at LaFrance.

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- Tax on profits is 50%
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2	[illegible]	25	0
3	[illegible]	0	[illegible]
4	[illegible]	0	0
	[illegible]	25	0
	4	0	50
5	8	25	0
	4	25	50
6	6	0	50
7	8	0	50
	6	25	50
8	8	25	50

*Assumptions:
- System includes 100,000 ft² solar collector field.
- Annual thermal energy delivered is 350,000 Btu/ft² for total annual contribution of 3.5×10^{10} Btu.

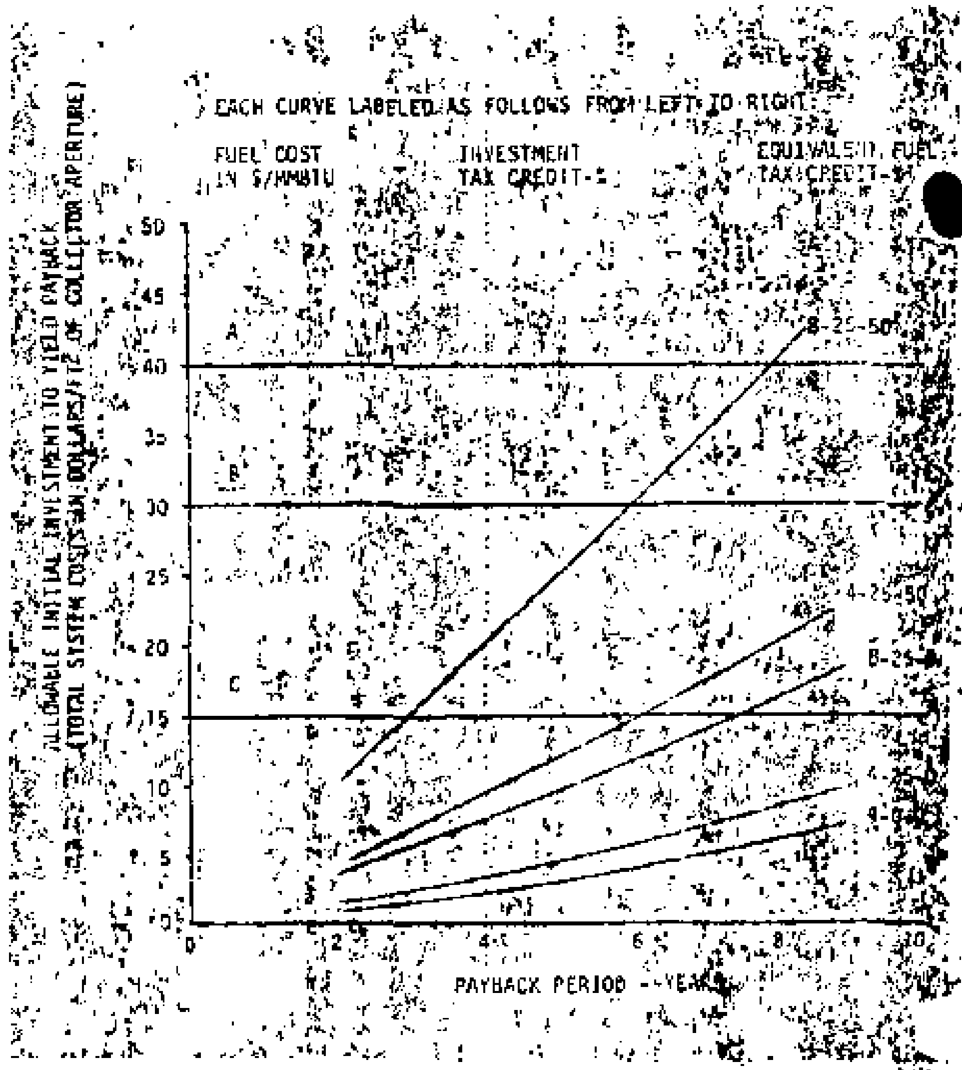


Fig. 6. Economic scenarios for solar process hot water systems similar to the LaFrance system. Note that: $4/MMBtu = $4/1000 ft³ gas = $0.55/gal oil.

• $4/million Btu, which represents an average industrial fuel cost in the 1980's
• $8/million Btu, which is a rate likely to occur throughout the United States before the year 2000

The curves in Fig. 6 also show results for the cases of no investment tax credit, 25% tax credit on initial investment, and an equivalent-fuel tax credit of 50%. This last item assumes that the government provides incentives by allowing as a business expense the cost of fossil fuel saved by the solar system, a practice in accordance with present tax structures for fossil fuel users.

The horizontal lines in the figure (A,B,C) represent initial cost/ft² for a 100,000 ft² collector system, as follows:

(A) Initial investment = $40/ft², based on system cost for the LaFrance project

(B) Initial investment = $30/ft², predicated on the introduction of automated mass-production of components

(C) Initial investment = $15/ft², based on mass-production improvements, product improvements, and increased proficiency in installation.

For (A), the minimum payback period is more than 6 years, even with the maximum likely fuel prices and tax incentives. However, for investment costs between (B) and (C), and with reasonable values for fuel prices and tax incentives, payback periods become attractive; we feel that this cost level is a realistic state for future economic conditions, providing an attractive incentive within the textile industry for the acceptance of solar process hot water systems. It can be seen that an investment tax credit greatly decreases the initial investment required to yield a given payback period.

For energy conservation improvements today the textile industry typically demands a payback period of years or less. Many companies set the expected rate of return from energy savings at a level about twice that for their mainstream business investments. As a consequence, capital spending is allocated to the mainstream investments while higher energy costs are passed on to consumers. If a more balanced allocation of capital by a company were to result in lower costs to consumers, there might be increased business for that company.

The results of our analyses indicate that projections of future fuel prices and solar system costs, combined with appropriate tax incentives, predict a significant market for solar process hot water systems. The timing is a function of several complex factors; but it is not unreasonable to expect that the necessary conditions will exist sometime during the late 1980's.

Improved Economic and Technical Performance

The timing suggested above assumes there will be reductions in solar system capital costs and increases in technical performance. Several areas have already been identified for improving the economics for future applications of solar systems, and additional changes and simplifications can be expected as operational experience is gained from the demonstration projects.

• Overall installation costs for new plants may be substantially reduced by integrating the solar equipment, especially the collector mounting system, into the building design. Where ground mounting is required, careful consideration should be given to the collector support system. Where feasible, costs can be reduced by maximizing the use of construction materials such as concrete and minimizing the need for structural steel.
• For any given solar industrial system, the larger the installation the lower will be the minimum cost per unit of energy delivered. Solar systems presently being constructed as experimental demonstrations have collector fields of about 5000 to 10,000 ft²; these cost more per unit of energy delivered than do larger systems of 100,000 to 500,000 ft². Thus economies of scale are possible.

Commercialization

To achieve wide usage of solar systems for industrial process hot water by the late 1980's there must be positive stimulation of commercial applications. The solar project at the LaFrance mill is highly visible and accessible to a broad segment of the textile industry. As such, it is a key step to future commercialization. Besides sponsoring further demonstration projects, the government also should initiate research and development programs to improve system performance and reduce the cost of future systems. Commercialization also could be helped by a government program along the following lines:

• Government subsidy to users, based on fuel and hardware cost.
• Direct government subsidy to manufacturers and installers.
• Guaranteed recovery of investment cost.
• No-interest and low-interest loans.
• Favorable taxation policies for users.
• Favorable tax policies on profit and equipment writeoff for manufacturers.
• Mandated use on some government buildings, such as military laundries and dining halls.

Hopefully, such government actions would stimulate industrial firms to participate in solar market development—through independent research and development; through corporate investment in plant and equipment; through establishment of distribution, sales, and service networks; and through the training of installers. Thus the transition to a conventional commercial market could take place as rapidly as the economic factors would allow. *

Getting Along Together

When solar meets utility, a little understanding helps.

By Paul Sullivan

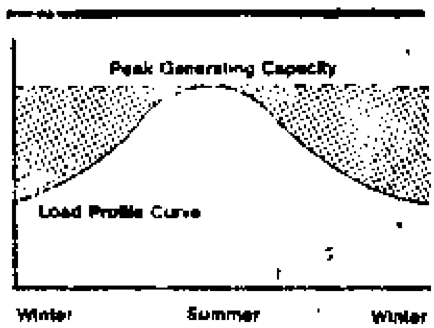
Electric utilities are under pressure to structure rates to reflect the real cost of producing (and continuing to produce) electric power. The solar industry, with buildings that so obviously differ in energy consumption patterns from conventional buildings, is understandably apprehensive about those utility rate structures. But each group—utilities and solar industry—can, with some forethought, help to solve some of the other's difficulties.

In calculating the cost of service to its customers, in order to establish electric rates, a utility considers three components. First are customer costs—meter reading, bill preparation, month-by-month record keeping. Energy costs are the second component, comprised of fuel costs and operating and maintenance budgets. Demand costs, the third component, are associated with the costs of financing the buildings; and owning or building the equipment—power plants, transmission, and distribution facilities—necessary to supply consumer demand for energy. Customer costs are charged first, for the first kilowatthours of electricity that one uses at the beginning of the month, and therefore can be attributed to lighting loads rather than to electric backup loads. For most utilities the larger portion of what is left represents demand costs. Energy costs usually are significantly less.

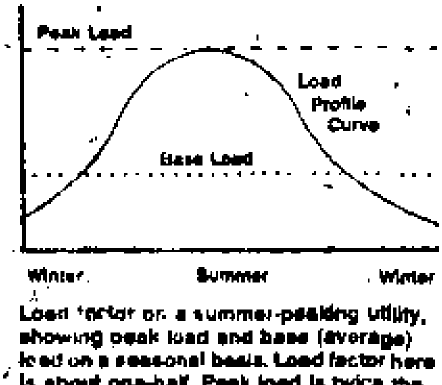
The present low cost of electric resistance heating equipment is quite attractive to first-cost-conscious builders, and the unavailability of alternative fuels such as gas, in some areas, has resulted in a growing use of electricity as a backup for solar systems. A typical solar building can be expected to supply 50 to 70 percent of its space conditioning energy from the sun. This solar fraction directly displaces sales of kilowatthours by the utility, and causes a 40 to 60 percent reduction (due to declining block rates) in the consumer's electric bill. Therefore, from the utility's point of view, the big question is "if revenues from this solar building are only 60 to 40 percent of those a conventional building can supply, is each element of the cost of service reduced by the same amount?" Does solar use, in other words, decrease the utility's need to build or maintain expensive generation, transmission, and distribution facilities as it reduces need for fuel?

If solar buildings go merrily along, consuming very little electrical energy (and paying very little), then suddenly switching to electricity on that cold cloudy day when the utility experiences its peak demand, the answer quite obviously is "no." The cost, to the utility, is roughly the same for service to both solar and non-solar buildings. The utility's worst fears will have been realized and, because utilities are required by law to supply electricity on a cost recovery basis, high "solar building rates" will be forthcoming.

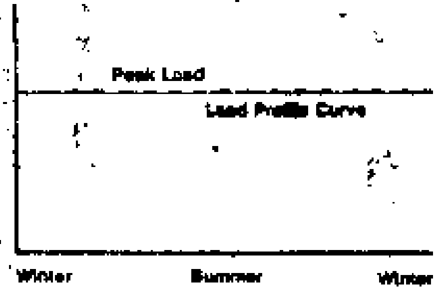
Some utilities in the recent past have assumed that this line of reasoning was fact, and set up rate structures accordingly. The Public Service Company of Colorado, with the concurrence of the Colorado Public Utilities Commission, assuming that electric backup heat for solar buildings had a load pattern similar to that of conventional buildings, instituted an "energy demand" rate for all new residential electric heating customers in 1976 (see *Solar Age*, August 1976). This rate would have penalized solar buildings with electric backup units severely. Under strong



Seasonal load profile for a summer-peaking utility.



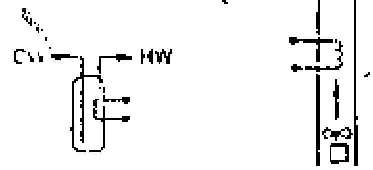
Load factor on a summer-peaking utility, showing peak load and base (average) load on a seasonal basis. Load factor here is about one-half. Peak load is twice the magnitude of the base load.



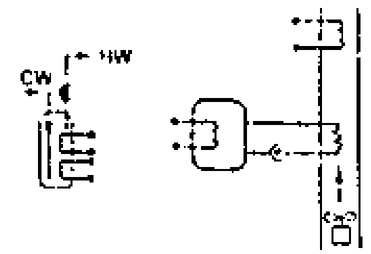
If the utility's seasonal load profile was flat, the load factor would be 1.0, and all generating capacity would be used 100 percent of the time.

Paul Sullivan is vice president in charge of research for Total Environmental Action, Inc., Harrisville, New Hampshire.

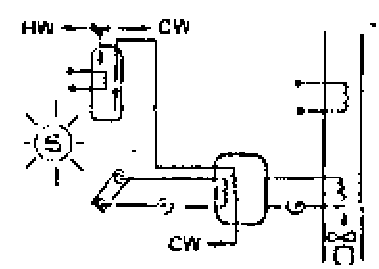
Conventional hot water heating and space heating systems without storage.



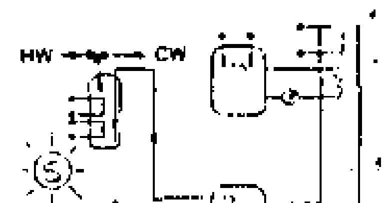
Load Management integrated into conventional hot water and space heating systems. Thermal storage is again an important part of the system.



Solar Energy integrated into conventional hot water and space heating systems. Thermal storage is again an important part of the system.



Both solar energy and load management integrated into conventional hot water and space heating systems. Separate thermal storage units serve the solar and load management.



Key to Symbols:
CW - Cold Water
HW - Hot Water

These four system diagrams represent typical designs for conventional, solar, and load management hot water and space heating systems. "System Definition Study — Phase 1: Individual Load Center, Solar Heating and Cooling Residential Project", by Arthur D. Little, Inc., published by Electric Power Research Institute, December 1977.

pressure from consumers and builders, the Colorado PUC reversed its ruling, disallowing the rate. The Public Service Company has continued to appeal. A similar assumption by the municipal electric company serving Columbus, Mo., resulted in a "non-refundable deposit" requirement for solar buildings with electric auxiliary heat, to pay for the anticipated increase in unrecovered costs. Meetings with local solar people convinced the municipality to withdraw the requirement because of lack of definitive evidence that it was necessary.

Neither utilities nor consumers win in such cases. The rates are withdrawn, but fewer solar buildings are built because uncertainty surrounds use of auxiliary heat. Consumers and utilities ought to be able to provide one another with the proper signals and responses to achieve socially optimum solutions—but proper signals rarely are supplied, nor do responses necessarily move us toward optimal goals. Because utilities do not price electricity to reflect replacement costs, consumers are unaware of true costs. Even with the proper signals, consumers might prefer the low first cost of electric backup equipment. If societal costs, in terms of capital and human and natural resources, are to be minimized, other forms of backup may be more appropriate—but very little is presently known about the long-range effects of choices between electric backup and such other forms.

Solar buildings do not necessarily have negative impacts on the utility cost/revenue balance. Studies by Clark University/Total Environmental Action, Inc., Franklin Institute, Arthur D. Little, Inc., and the Colorado Springs Department of Public Utilities (to name only a few) have found a number of design configurations for solar buildings that may actually improve that balance over one for conventional buildings. In areas of the country with reasonably high heating loads, it is not unusual to find adjoining electric utilities with differing peak seasons. One utility may peak in the summer because of urban needs for air conditioning, for example, while its neighbor, with more rural customers, peaks in the winter. A conventionally designed active solar building might hurt the winter-peaking utility's load curve. A few miles away, the same building design would help to eliminate a domestic water heating load from the utility's summer peak. A relatively simple change in design, to replenish storage with off-peak or intermittently interrupted electric use, could solve the problem for the first utility.

Climate, building use patterns, utility load and generation mix, as well as peaking season also have significant impact on the cost/revenue balance. Building or system designs can be made to mitigate unfavorable impacts. A conventional heat pump system in a moderately cold climate, for example, may exhibit a Coefficient of Performance (COP) of 1, because of resistance heating, low ambient temperatures, or defrost cycles. A properly designed series solar-assisted heat pump can have a COP much greater than might be expected—and can improve economics significantly for both customer and utility. A passive building with shuttering devices can reduce peak demand to a point at which the cost/revenue balance is significantly better than that for a similar non-solar building faced away from the south, without shutters.

Those on both sides of the solar building/electric utility interface need to show more concern for one another's problems. Solar designers can recognize the realities of utility costs and use their skills to improve the pattern of use and therefore, of financial return to the utilities. Utilities must show more recognition of the opportunities for load management inherent in solar buildings—and in so doing, can help to assure the life-cycle cost assumptions that solar users necessarily make, by providing sound and stable electric rates. If we do not begin to make use of the opportunities, both in education and in solar building design decisions, solar users at some future date may be required to pay significantly for their electrical backup energy.

An Example in Cooperation

By Sherry Robinson

Electric utilities engaged in solar research and development have occasionally been accused of attempting to "own the sun," to sandbag the solar industry by proving solar energy is economically unfeasible or by threatening to raise rates to solar homeowners. But utilities have some very practical reasons for their interest in solar power that have nothing to do with the reasons projected by some solar advocates. Within utilities, the knowledge and expertise are already in place to extend what we know about power generation and space conditioning. Why not use it? Here in New Mexico, solar is already a household word. Depending upon individual expectations, solar systems are economically competitive with traditional all-electric resistance heating right now. By 1985, solar energy could be competitive in many parts of the country.

Utilities should want to know what impact the use of solar energy will have on their systems. Hence, the involvement by Public Service Co. of New Mexico (PNM) and Long Island Lighting Co. (LILCO) in a project designed by Arthur D. Little, Inc., and funded by the Electric Power Research Institute, an industry-supported organization, to construct ten solar heated houses, five in each state. The goal is to evaluate the effect of solar houses on the utility grid, to assess various solar systems for each of the two climates, and to identify control strategy so that those systems do not adversely affect utility peak demands. It is the most definitive study of its kind so far.

Peak demand and load management represent the crux of the issue of alternative energy sources for utilities. An electric utility is legally bound to maintain a reserve generating capacity above peak use demand. We believe it is possible to develop and demonstrate solar systems with controls that would insure back-up use only during off-peak hours. In this way solar systems could help utilities by shaving demand peaks through load management, and in turn could become eligible for the lower off-peak rates presently under study by many utilities.

> Solar systems can be designed to use back-up electricity only during off-peak hours.

The prime contractor for the Residential Solar Heating and Cooling Project, Arthur D. Little, Inc. (ADL), has developed a computer model capable of predicting the interaction between solar systems and utilities [see box]. The project is expected to validate and refine that model.

The first of four phases was completed in August 1977. This entailed a system study by ADL to determine preferred concepts, develop building designs, and select builders. The study considered monthly electric usage patterns for nonheating and air conditioning rate schedules for both utilities, exact demand cost of supplying electricity, load profiles for typical weekdays and weekends in each month, and weather influence on those load profiles.

In the next phase, working drawings of the residences were completed and mechanical systems integrated with the architectural and building forms of solar houses. Completion of the houses and installation of systems is the third phase. The final phase will consist of two years of monitoring, to end in 1980. Upon completion of the program, EPRI will make house and system designs available to the nation's electric utilities and builders. Operating data will be reported as they are collected and analyzed. EPRI has just announced the availability of the computer model, for use by utilities in designing rate structures, and in advising on solar house design.

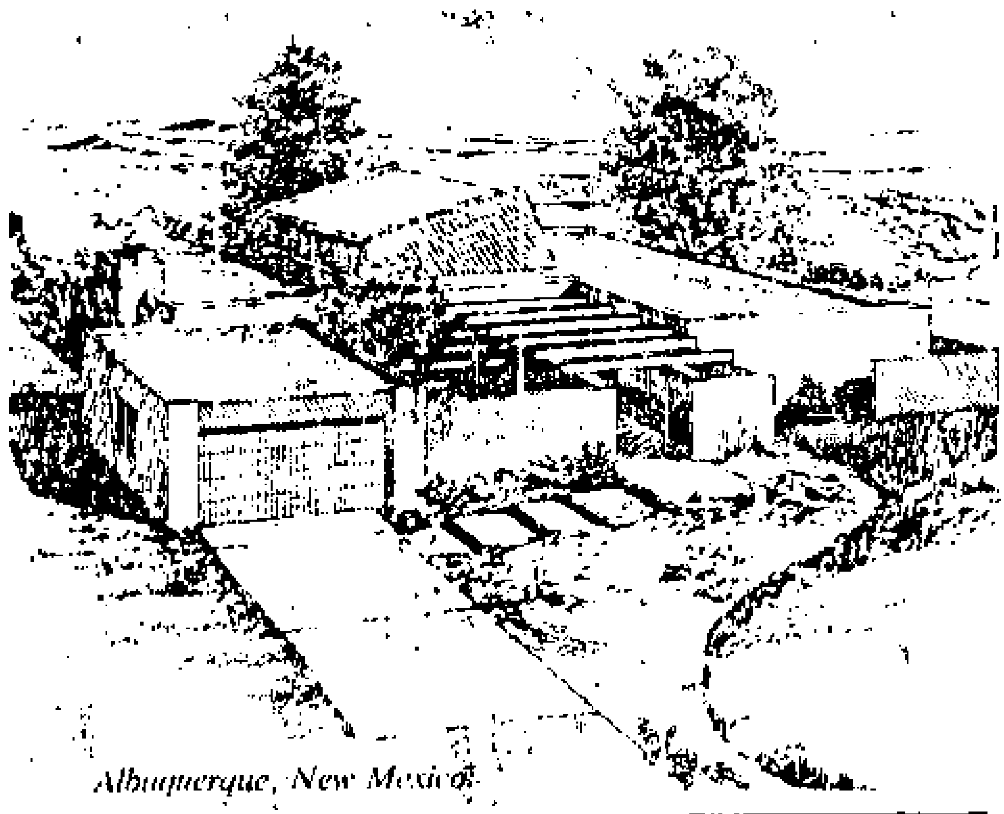
The residential units of the project are located in two geographic regions characterized by minimums of 5,000 and 3,000 degree day heating and maximums of 1,000 and 2,000 degree days cooling for the northeastern and southwestern regions, respectively. Each house has 1,500 to 2,000 square feet of floor area and is consistent with the bulk of the new construction in each area. Back-up systems are electric.

Five different system designs will be tested and evaluated in a variety of configurations of use. HVAC subsystem components used are commercially available. Insulation and other materials considered essential to a viable solar system are included in the first costs associated with the solar systems. Life cycle costs for the collector will be based on a twenty-year collector system lifetime with nominal maintenance.

Besides its development of the computer model used to complete the experiment design, ADL has analyzed equipment types, sizes, and configurations to determine baseline systems, and provided the architectural designs for the ten houses.

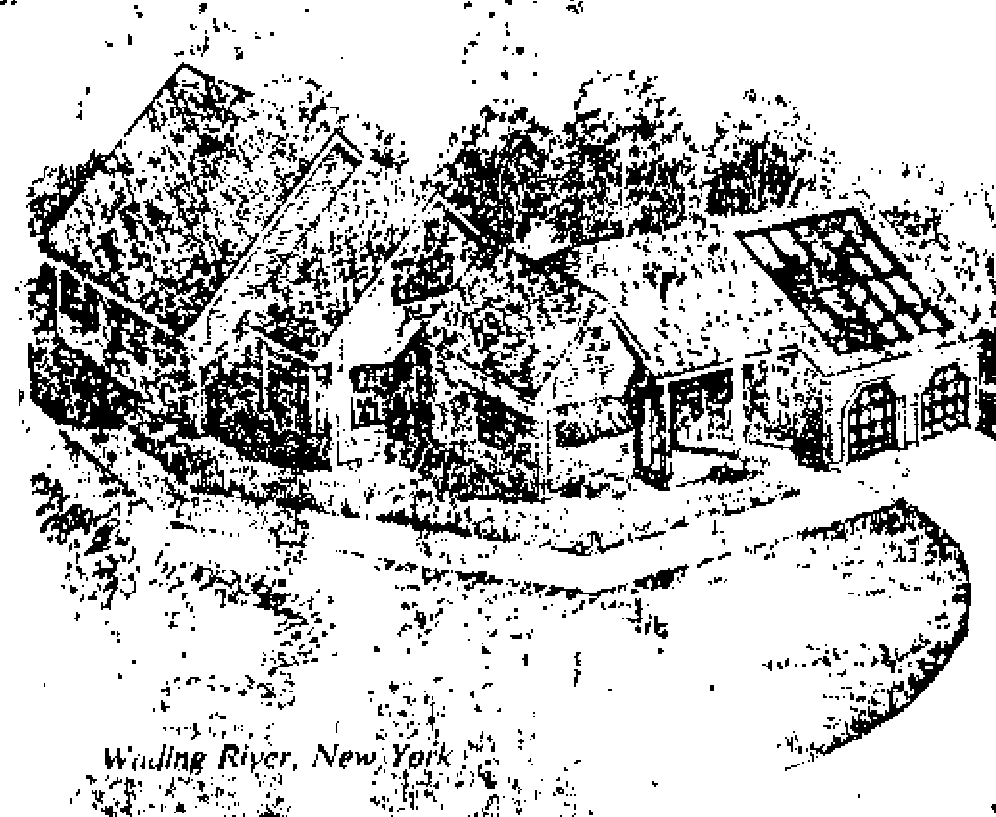
All five of the designs planned for the Albuquerque area call for flat-roofed, single-story, frame-stucco construction, with concrete slab foundations—the most popular style of house in the area. The local building contractor is Moss-

Sherry Robinson is information coordinator for the Public Service Company of New Mexico



Albuquerque, New Mexico

The Public Service Company of New Mexico and the Long Island Lighting Company cooperate with Arthur D. Little, Inc., and the Electric Power Research Institute to look at solar's relationship to utilities.



Wading River, New York

man-Gladden, Inc. Collector panels are integrated into the roof in some cases by means of a modified clerestory (a partially raised roof that contains windows). Skylights are built into the north wall of the clerestory with the collector panels in the south wall. A false ceiling hides the solar plumbing and back side of the collector panels. A small equipment room contains most of the heating, cooling, and hot water equipment, plus the instrumentation system. Large thermal storage tanks for load-managed heating and cooling are located in the equipment rooms or buried at the rear of the homes.

The Long Island houses are also typical of the area, with pitched roofs, wood-frame construction built on a combination concrete foundation and basement. Three of the houses have two stories; the others are single-story. Collector panels here are also integrated into the roof. In four houses, they are mounted over a connected garage; in the remaining house, panels are in the main roof. (An attached garage offers flexibility in solar collector orientation without requiring modifications to the lines of the main house.) The local contractor is Clarendon Construction Corp.

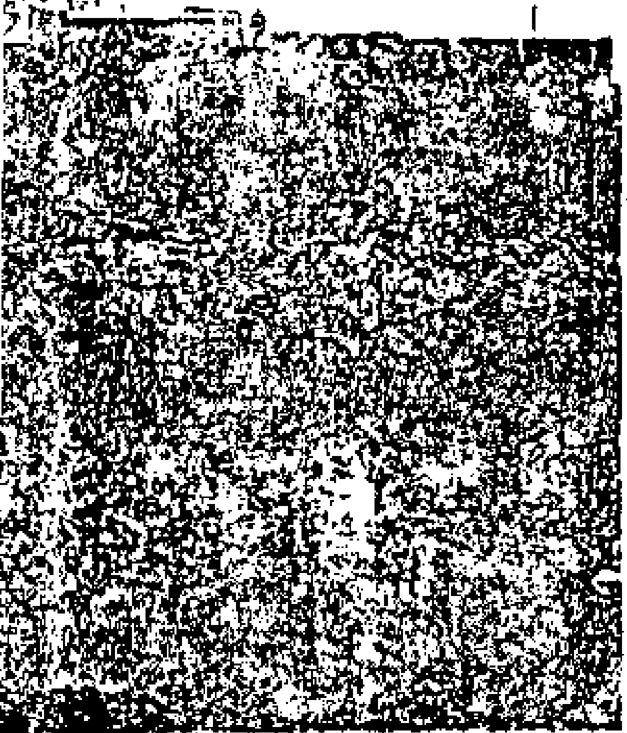
Spacious basements and garages allow the storage of load management equipment, storage tanks, and instrumentation. The systems themselves are variations on the solar-assisted heat pump. The houses are in the $85,000 to $100,000 range, but the data collected during the project will be applicable to houses in all price ranges.

Albuquerque Installation No. 1 is a combined cooling, heating, and hot water solar/load management system with heat pump auxiliary. This system is capable of simulating a wide range of system types.

Albuquerque Installation No. 2 is a combined cooling, heating, and hot water system—similar to Installation No. 1, except that a single integrated tank, possibly combined with a high-performance solar collector, replaces the two tanks. This installation could also be used for the demonstration of heat-generated air conditioning.

Albuquerque Installation No. 3 uses load-management-only for space heating and solar/load management for hot water. In this installation an evaporative swamp cooler, the conventional air conditioner for Albuquerque, cools the house.

Installation No. 4 is similar to Installation No. 3 except that load management is provided for both space heating and cooling. This system can use either a conventional tank or a swimming pool for load management. (The swimming pool might have unique advantages as a heat sink or cooling pool.) The presence of a second system for nonsolar load manage-



These two adobe houses are representative of the five experimental houses in New Mexico.

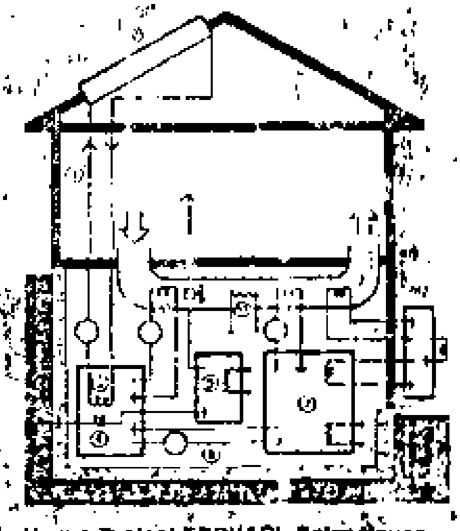
New England wood-framed construction typifies the five experimental houses on Long Island, a sharp contrast to New Mexico adobe.

ment for space heating and/or cooling is justified because load management with solar, in regions like Albuquerque where average electric costs are low, but demand charges are high, is particularly effective.

Albuquerque Installation No. 5 is a combined cooling, heating, and hot water system using an air collector with rock storage for heating and/or cooling, and conventional liquid storage, with an air-to-liquid heat exchanger, for the hot water solar storage. This system may provide opportunities for nocturnal cooling in Albuquerque.

Long Island Installations 1, 2 and 5 are the same in basic concept and schematic. Long Island Installation 3 uses load management for heating and cooling in conjunction with solar/load management for hot water. This system is similar to Albuquerque Installations 3 and 4. The reduced emphasis on load-management-only for heating and cooling in Long Island (one system in Long Island versus two in Albuquerque) results from the fact that with Long Island's higher average rate for electricity, energy conserving features such as solar and heat pumps are likely to compete better with load management.

Long Island Installation No. 4 is identical to the combined system of Albuquerque and Long Island Installation No. 1. The justification for duplicating this system in the Long Island area is because solar and heat pump arrangements are in a better position in Long Island than in Albuquerque.



How a Typical EPRI/ADL Solar House Works With Peak Load Management
Eight of the EPRI solar houses have water systems such as the one shown here, while two have air systems. In an air system, air is circulated through the solar panels and over a large bin of rocks to store heat.

1. Water (or an antifreeze solution) is pumped to solar collector panels.
2. Liquid flows from bottom to top in the solar collectors, which are heated by the sun. Each collector has a black surface that absorbs the sun's heat.
3. Heated liquid from the solar collectors flows through a heat exchanger and heats water in a solar storage tank.
4. Cold water is heated as it flows through a heat exchanger in the solar storage tank on its way to the hot water tank.
5. Hot water is stored in a tank until it is needed. If the water is not hot enough as it comes from the solar storage tank, an electric heating system is used to raise the temperature.
6. Water from the solar storage tank is pumped through a heat exchanger in the main air duct to heat air for the house.
7. The load-management storage tank "smooths out" the differences between the energy available from the sun or from a utility and the energy demands of the residents.
8. The solar storage tank and the load-management storage tank are interconnected. When the solar system is producing energy, heated water can be pumped to the load-management tank to be stored for later use. At other times, water can be pumped in the other direction to heat incoming cold water for the domestic hot water system.
9. When the solar system cannot heat air for the house, water from the load-management storage tank can be pumped through a heat exchanger in the main air duct to warm the house.
10. The heat pump can be used alone to heat or cool the air in the house or the water in the load-management storage tank.
11. When other sources of energy cannot meet the demand, a conventional heating system can be turned on to heat air for the house.

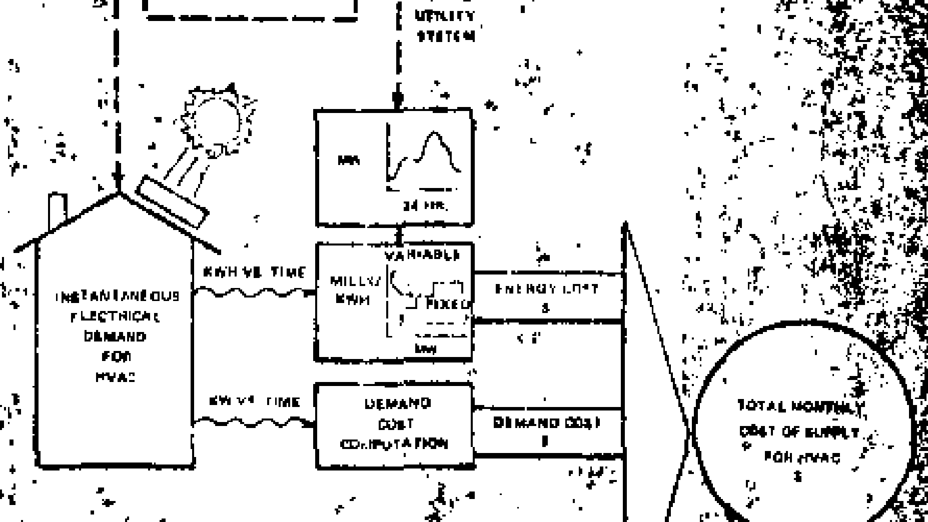
Computation of Energy Costs
The procedure for computing the cost-of-supply incorporates hourly energy demand at the residence and at the utility. The calculated electric energy demand at the residence depends on the thermal characteristics of the house, the HVAC system and climatic data on weather tapes. The utility system-wide load is determined from hourly load profiles which are related to weather

A Computer Model to Analyze the Solar/Utility Interface

The solar heating and cooling project designed by Arthur D. Little, Inc. (ADL) and funded by the Electric Power Research Institute (EPRI), is basically an attempt to validate a computer model. A preferred solar heating and cooling system, according to ADL's analysis, is one that minimizes the total life-cycle costs for both customer and utility.

The ADL computer model developed for EPRI helps achieve this result. It answers questions such as, what particular designs of solar and load management are appropriate? What functions (hot water, space heat, cooling, or combinations) are feasible? What is the appropriate preferred system for a utility with its particular configuration of load profile, generation mix, fuel, [illegible] demand cost? How might rate structures be designed to foster solar/utility cooperation?

What is the best method of incorporating a heat pump in a solar system? How sensitive are the preferred systems to uncertainties of weather, load patterns, peaking characteristics, economics? How will solar/load management affect generation capacity needs, fuel, and transmission and distribution requirements? What is the payback for given options, separately and in aggregate?



The ten houses just completed in New Mexico and Long Island are being carefully monitored. Some eighty variations of solar systems could be extrapolated and analyzed from the results of the monitoring.

THE PRESENT STATUS AND THE FUTURE POTENTIAL OF SOLAR INDUSTRIAL PROCESS HEAT

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ABSTRACT

The potential for the use of solar process heat in industry appears to be significant. Industrial process heat accounts for a significant fraction of the amount of energy consumed in the U.S., and surveys have indicated that a certain portion of this process heat technologically could be provided by solar. However, in spite of this potential, the use of solar energy in industry faces a number of obstacles. Solar systems, particularly for moderate- rather than low-temperature heat, are not fully proven. The economics of solar systems need to be demonstrated, particularly vis-a-vis competing fossil fuels. Little operating experience has been obtained with industrial solar systems, and no firm guidelines exist as to their design and operation. Much of the applicable technology is borrowed from the solar heating and cooling industry. Work needs to be done to develop solar system designs especially for industrial applications. Finally, a number of nontechnical issues have been identified which must be resolved. The purpose of this paper is to review the present status of industrial solar process heat systems, to indicate their potential, to discuss current efforts to demonstrate such systems, and finally to point out some problem areas which need further attention.

1. INDUSTRIAL USE OF ENERGY

It is widely recognized that among the various sectors of the U.S. economy, the largest energy user is the industrial sector. In 1974 it accounted for about 41 percent of the total national energy use. Of all of the various ways that energy is used in the industrial sector, the most significant use is for thermal energy--process steam and direct process heat together account for about two-thirds of the total industrial consumption of energy. It is thus clear that the greater portion of the energy used in the industrial sector is used in the form of thermal energy rather than in the form of electrical energy for power, and this indicates the significant potential for the use of solar thermal energy in industry.

However, one of the most important variables to consider in the application of solar process heat is the temperature that is required for the process. The temperature requirements for industrial process heat in the U.S. have been surveyed by two studies. In one study [1], the survey was performed from the point of view of process requirements rather than the point of view of current methods of using heat. Thus, the temperature of major interest was the required temperature of the process material rather than the temperature at which the heat is currently provided.

The data from this study were presented in the form of a cumulative process heat spectrum, which showed the percent of industrial process heat used as a function of terminal process temperature required. This cumulative process heat spectrum is shown in Figure 1. The data base for this curve consisted of process heat data from 78 different industries in both mining and manufacturing and included process heat applications consuming 1.03 x 10^{19} J (9.[illegible] x 10^{15} Btu) per year, about 59 percent of the estimated total use of process heat by U.S. industry, of 1.75 x 10^{19} J (1.66 x 10^{16} Btu), based on 1974 data.

Of particular interest in this spectrum of temperature requirements are the percent of process heat needed at terminal process temperatures below a temperature of 100°C--about 7-1/2 percent--which could perhaps be provided by low-temperature solar thermal energy systems, and the percent of process heat needed below a temperature of 288°C--about 28 percent--which could perhaps be provided by concentrating solar collectors. Additional information about this cumulative process heat spectrum is shown in another paper [2].

Two observations should be noted about the terminal-temperature spectrum in Figure 1. First, the temperature indicated is from the point of view of the process requirement, as opposed to the temperature of the present heat-delivering medium, which may be much higher. Second, in getting the temperature of the heat-delivering medium or the process material itself up to the terminal temperature, part of the heat could possibly be supplied by solar at a lower temperature as preheat. To illustrate the potential of using solar as preheat, the terminal-temperature curve was recalculated with the assumption that the amount of heat for each application could be supplied over a temperature range from a base of 16°C up to the terminal temperature required.

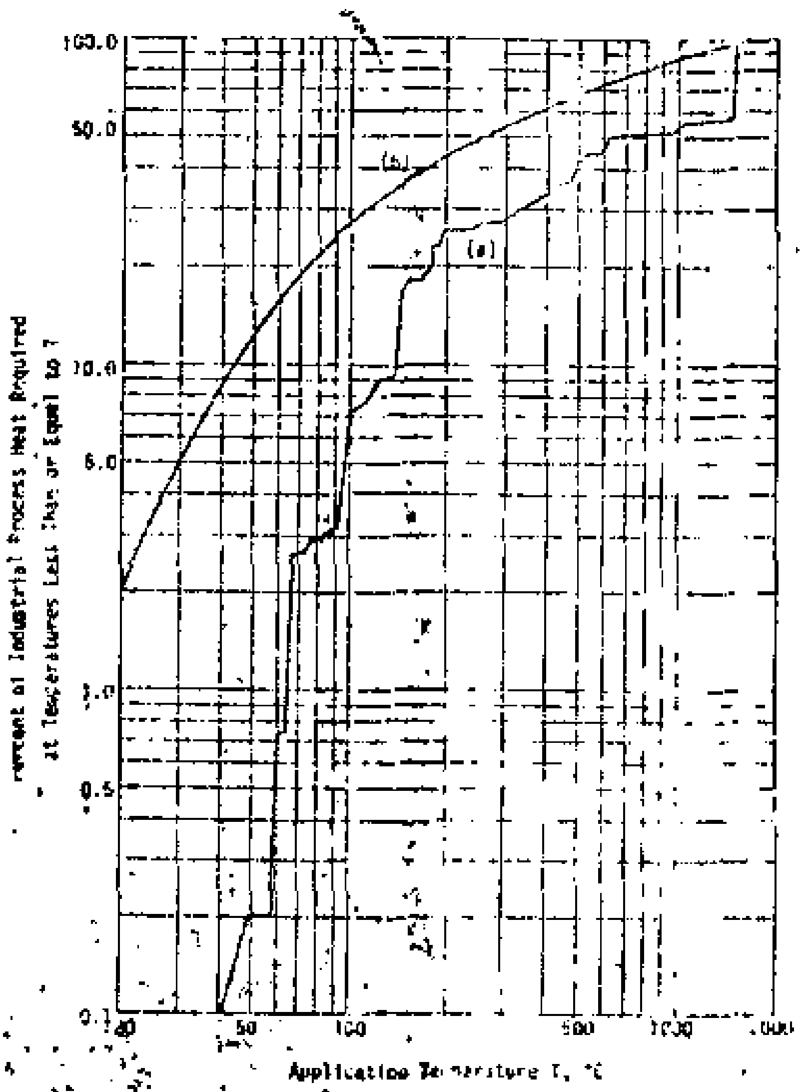

Fig. 1. Cumulative process heat requirements as function of process temperature: (a) all heat supplied at required process temperature; (b) heat supplied as preheat from 15°C up to T°C. Ref. 1.

Another study [2] surveyed the process heat requirements of 20 particular industries. From this study, Table 1 shows estimates of the future process heat requirements of these 20 industries by energy form and temperature. These requirements illustrate the relative potentials for solar process heat systems supplying either hot water, hot air, or steam, based solely upon technological requirements. This table shows a distribution of temperatures actually used for delivering the heat rather than process-required temperatures.

Other surveys have been made to assess the future potential of solar process heat, both for a specific industry, the textile industry [?], and for a specific state, California [5].

Energy form, temperature	Process-Specific Base Data	20-Industry Extrapolated Data: Present	Projected to 1985	Projected to 2000
Hot Water <212°F	73	120	148	205
Steam 212-350°F	1,212	2,600	3,211	4,2[illegible]
Steam > 350°F	496	563	695	842
Direct Heat/Hot Air < 212°F	98	140	173	234
Direct Heat/Hot Air 212-350°F	140	657	805	1,091
Direct Heat/Hot Air > 350°F	5,851	5,965	7,367	9,901
TOTALS	7,870	10,040	12,500	16,800
TOTALS BELOW 350°F	1,523	3,512	4,527	5,5[illegible]

Table 1. Summary of industrial process heat requirements for 20 selected industries. Figures in 10^{12} Btu/year. Ref. 3.

2. FUTURE POTENTIAL OF SOLAR PROCESS HEAT

The future potential of solar process heat is influenced by a number of variables, including the types of fossil fuels with which solar will be competing. The types of fuels used in industry are shown in Table 2, which shows that for fuel use, natural gas is the predominant energy form. According to these estimates, more natural gas than any other fuel will continue to be consumed by industry as fuel, synthetic gas being manufactured and used to augment natural supplies.

Fuel	1974	1980	1985	2000
Coal	7831	9456	11735	19907
Fuel use	(4093)	(4590)	(4630)	(5460)
Other uses	(3738)	(4866)	(7050)	(14447)
Petroleum	7455	9112	11124	12795
Fuel use	(3730)	(4290)	(4920)	(6,[illegible])
Other uses	(3725)	(5862)	(6204)	(7736)
Natural gas	12520	10762	10174	9497[2]
Fuel use	(9495)	(9240)	(8722)	(10360)
Other uses	(3026)	(1522)	(1444)	(1397)
Oil shale				
Synthetic liquids	--	--	156	1281
Other electric power (nuclear, hydro)	1786	3180	5527	25919
Total energy consumption	29600	32900	39700	69300
Electric power as % of industrial total	27.8	32.1	41.0	58.4
Total industrial energy consumption as % of total U.S. energy consumption	40.8	37.8	38.2	42.4

[1] Includes synthetic liquids--1830 x 10^{12} Btu.

[2] Includes synthetic gas--2260 x 10^{12} Btu.

Table 2. Industrial consumption of energy in U.S., 1974-2000. Figures in 10^{12} Btu/year. Ref. 3.

With respect to regional variations in fuel availability, data indicate that industrial fuel mixes for contiguous states tend to be similar. Fuel use in any given industry tends to reflect a region's fuel distribution rather than an industry's national fuel mix and fuel distribution, although some processes may require a specific type of fuel for process reasons. Analysis of regional use of fuels shows that gas is predominantly used for [illegible] in those parts of the country--the [illegible], Mountain states, Gulf Coast, and Southwest--where insolation is the highest and cost of solar is the lowest, improving the cost-competitiveness of solar in these particular regions.

The economic viability of solar thermal systems is in large part controlled by the cost of available competing fuels and their expected future costs. Future fuel costs [illegible] consideration to the solar [illegible] as an integral part of the life-cycle cost analysis. Many different estimates of future fuel costs have been derived, although few are published in readily available literature. As a basis for estimating future costs, various scenarios may be developed, resulting in widely varying estimates. It is beyond the scope of this review to discuss details of these estimates. Examples of estimates of future fuel costs and discussions of their influence on the future potential of solar process heat can be found in the original reports [1,3].

It should suffice here to say that analysis of the cost-competitiveness of solar with these estimated future fuel costs indicates that solar process heat will be most cost-effective in competition with petroleum and natural gas, because they are, and will continue to be, the most expensive fossil fuels. Indeed, a number of studies have concluded that it will be very difficult for solar to compete against coal strictly on the basis of fuel cost [4]. The advantages of solar as a clean fuel and a more detailed accounting of all of coal's costs such as for pollution control and materials handling may permit solar to compete with coal in specific situations.

The future potential of solar process heat is also influenced by the performance and cost characteristics of solar thermal energy systems. One recent study done for the Department of Energy [1] did a thorough comparative analysis of

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Energy form, Temperature	Process-Specific Base Data	20-Industry Extrapolated Data: Present	Projected to 1985	Projected to 2000
Hot Water 212 °F	73	120	146	201
Steam 212-350 °F	1,512	2,600	3,211	4,251
Steam > 350 °F	456	563	695	942
Direct Heat/Hot Air ≤212 °F	[illegible]	140	173	[illegible]
Direct Heat/Hot Air 212-350 °F	340	652	805	1,021
Direct Heat/Hot Air > 350 °F	[illegible]	[illegible]	7,365	9,561
TOTALS	7,870	[illegible]	12,620	16,800
TOTAL [illegible]	1,524	[illegible]	4,2[illegible]	5,677

Table 1. Summary of industrial process heat requirements for 20 selected industries. Figures in 10^{12} Btu per year. Ref. [illegible]

2. FUTURE POTENTIAL OF SOLAR PROCESS HEAT

The future potential of solar process heat is influenced by a number of variables, including the types of fossil fuels with which solar will be competing. The types of fuels used by industry are shown in Table 2, which shows that for fuel use, natural gas is the predominant energy form. According to these estimates more natural gas than any other fuel will continue to be consumed by industry, until synthetic gas is manufactured and used to augment natural supplies.

Fuel	1974	1985	1985	2000
Coal	7831	9508	11738	[illegible]
Fuel use	(4093)	(4010)	(1680)	[illegible]
Other uses	(3775)	(5666)	(2058)	(14307)
Petroleum	7425	9442	12124	[illegible]
Fuel use	[illegible]	(3370)	[illegible]	(6380)
Other uses	(3725)	(6062)	[illegible]	[illegible]
Natural gas	12520	12762	10124	[illegible]
Fuel use	(9495)	(9410)	(5320)	(10360)
Other uses	(3025)	(1952)	(1444)	(1397)
Oil shale Synthetic liquids			1065	3251
Other electric power (nuclear, hydro)	1785	2350	6527	25919
Total energy consumption	29800	32700	38700	69300
Electric power as % of industrial total	27.5	34.1	41.0	56.4
Total industrial energy consumption as % of total U.S. energy consumption	40.5	42.6	38.2	42.8

[1] Includes synthetic liquids—1200 × 10^{12} Btu.

[2] Includes synthetic gas—2200 × 10^{12} Btu.

Table 2. Industrial consumption of energy in U.S., 1974-2000. Figures in 10^{12} Btu/year. Ref. 2.

With respect to regional variations in fuel availability, data indicate that industrial fuel mixes for contiguous states tend to be similar. Fuel use in any given industry tends to reflect a region's fuel distribution rather than an industry's national fuel use and distribution, although some processes may require a specific type of fuel for process reasons. Analysis of regional use of fuels indicates that gas is predominantly used for thermal needs in those parts of the country—the Southwest, Rocky Mountain states, Gulf Coast, and Southeast—where insolation is the highest and cost of solar is the lowest, increasing the cost-competitiveness of solar in these parts of the nation.

The economic viability of solar thermal systems is in large part controlled by the cost of available competing fuels and their expected future costs. Future fuel costs are an important consideration to the solar designer because they are an integral part of the life-cycle cost analysis. Many different estimates of future fuel costs have been derived. Since few are publicly and readily available information, and tools for estimating future costs, various scenarios may be developed, resulting in widely varying estimates. It is beyond the scope of this review to discuss details of these estimates; examples of estimates of future fuel costs and discussions of their influence on the future potential of solar process heat can be found in the original reports [1,4].

It should suffice here to say that analysis of the cost-competitiveness of solar with these estimated future fuel costs indicates that solar process heat will be most cost-effective in competition with petroleum and natural gas, especially the latter, and will continue to be the most attractive [illegible] fuel. However, a number of studies have indicated that it will be very difficult for solar to compete against coal, strictly on the basis of fuel cost. However, advantages of solar as a clean fuel and a more detailed accounting of all of coal's costs such as for pollution control and waste handling may permit solar to compete with coal in specific situations.

The future potential of solar process heat is also influenced by the performance and cost characteristics of solar thermal energy systems. One recent study done for the Department of Energy [7] made a thorough comparative analysis of

Year	Total Process Heat		Applications > 550°F (288°C) Total		Solar		Preheat < 550°F (288°C) Total		Solar	
1976	16.6	(17.5)	4.6	(4.8)	0.002	(0.002)	4.0	(4.2)	0.002	(0.002)
1985	23.0	(24.2)	6.4	(6.7)	0.6	[illegible]	5.5	(5.8)	0.5	(0.5)
2000	36.6	(39.0)	10.2	(10.8)	7.3	[illegible]	8.8	(9.3)	6.0	(6.3)

Table 3. Assessment of potential use of solar process heat. Figures in 10^{15} Btu (10^{15} kJ). Ref. 1.

various types of solar systems. The results of this analysis were used to develop information on optimum percent load to be carried by solar in a typical process heat system as a function of geographical location, application temperature, competing fossil fuel, and point in time.

The influence of geographical location was determined in this study by defining constant-performance solar regions in the U.S. on the basis of performance calculations with a simple baseline solar hot water system for about 100 cities. Within each region, the performance of a solar system is approximately constant, and performance of different systems can be compared by comparing the results for representative cities, one city for each region. These constant-performance solar regions are shown in Figure 2.

This information on solar thermal energy systems was combined with the process heat data base, which showed how much thermal energy was needed for specific applications as a function of geographical location and time, and estimated fuel mixes (the proportions of coal, oil, and gas used) as a function of these same variables. The result was a quantitative assessment of the potential of solar process heat with respect to technological and economic variables. This assessment is shown in Table 3. The potential application of solar process heat increases significantly by the year 2000, primarily as the result of the estimated increased future costs of fossil fuels. Some applications are seen to be viable by 1985. Further information on this assessment is shown in [1,2].

3. PRESENT TECHNOLOGY

The basic building block in any solar system is the collector, and therefore the most significant part of the design of a solar process heat system is concerned with collector selection and sizing. Among the major variables affecting the choice of collector are: required amount of process energy, process energy demand pattern, required process temperatures, available solar energy, collector performance, and installed collector costs. There are a variety of collectors available for use in solar process heat systems. By and large, much of the technology available for solar process heat systems is borrowed from the solar heating and cooling industry--with the notable exception of the shallow solar pond. Some guidelines for collector selection for any particular application are given here.

For very low temperature applications (< 50°C) and in areas where the ambient temperatures and insolation are high, the loss-coefficient term in the collector efficiency equation becomes less important than the collection term. To maximize the collection, it is important to choose a collector with good heat-transfer characteristics (usually a liquid collector), high cover-plate transmission (usually a single glazing of low-iron glass [τ = 0.88 - 0.92] or clear plastic) and high absorber-plate absorptivity (a good flat-black paint is best with α = .95 - .98).

For high-temperature applications (> 100°C), the loss-coefficient term becomes important. To minimize the effect of losses, a concentrator system with a small-surface-area absorber is usually required. To be effective, such systems normally require a sun-tracking capability.

For applications requiring intermediate temperatures (55-100°C), a careful analysis needs to be done to determine the most economical system. In this temperature range, a higher performance by a concentrator system may or may not offset its higher cost when compared with a flat-plate collector system.

For certain applications, specialized collectors may prove to be most effective. For example, a solar pond may be best where low-tilt angles and temperatures are required and high insolation and ambient temperatures are experienced. An air collector may be best for an application which requires low-temperature air drying during daylight hours.

Although a flat-plate collector is a simple device, its performance is affected by many variables, including collection fluid, number of cover plates, cover-plate transmissivity, and absorber-plate absorptivity and emissivity. In addition, there are other items which affect collector performance. Among these are materials of construction, sensitivity to wind, size and location of manifolds and tubes, heat-transfer efficiency, and method of manifold interconnection. An additional factor of great significance is a collector's ability to withstand maximum dry-plate conditions. This occurs under no-flow conditions, at the highest ambient temperatures and incident insolation. Although such conditions may not occur often in the lifetime of a system, one such occurrence (with temperatures as high as 225°C) can be catastrophic and as such cannot be tolerated.

A collector which seems to be emerging as a top contender for a large variety of applications is

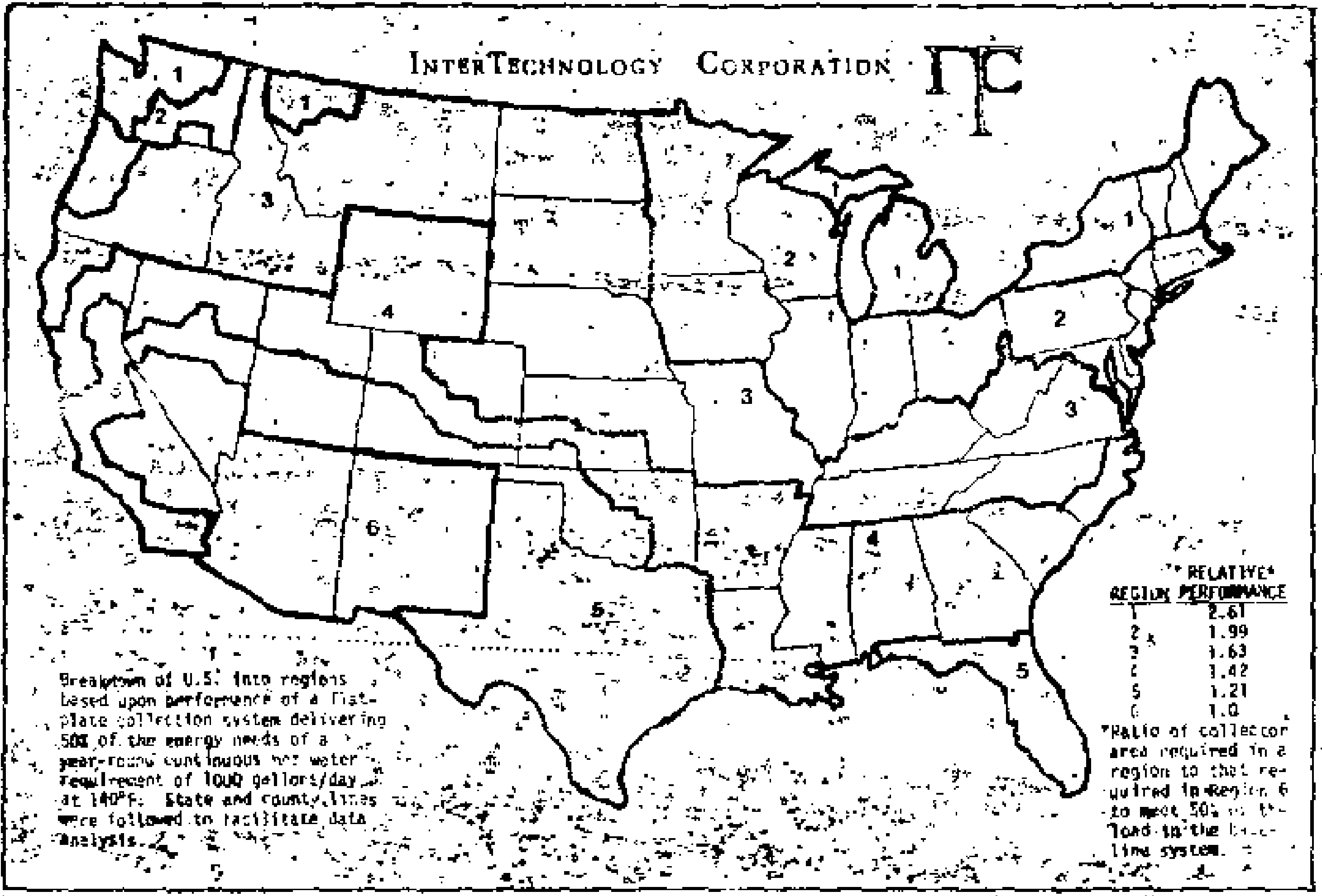

Fig. 2. Map of U.S. showing six "constant-performance" solar regions. Ref. 1.

a single-glazed (high-transmissivity glass) collector with a black chromium absorption surface. Such a collector combines good performance over a wide range of temperatures with good high-temperature stability. Table 4 gives typical cost ranges (1977 dollars) for flat-plate collectors of various types.

# Cover Plates	Collector Costs, $/m^2 Nonselective Surface	Selective Surface
0	15 - 40	-
1	75 - 120	85 - 135
2	95 - 130	105 - 145

Table 4. Costs for several types of flat-plate collectors. 1977 dollars. Ref. 1.

Air flat-plate collectors have several advantages and disadvantages compared with liquid flat-plate collectors. The advantages of air collectors are:

1. freedom from corrosion due to the coolant
2. freedom from freezing and boiling
3. the minor nature of leaks.

Disadvantages of air collectors are:

1. lower thermal performance
2. higher installation costs for ductwork
3. higher operating costs for energy transport
4. larger thermal storage size.

The costs of air flat-plate collectors are essentially the same as those shown in Table 4 for liquid flat-plate collectors.

Tubular collectors are cylindrical in shape and normally have a relatively high vacuum (10^{-4} torr) between an inner and an outer glass surface. The high vacuum eliminates a large fraction of the convective/conductive losses usually associated with flat-plate collectors. In addition, the absorbing surface can be coated with a selective absorber, thereby reducing the radiative loss considerably. Generally these collectors consist of a series of tubes mounted in a frame with a spacing of about one tube diameter between adjacent tubes. Either a white diffuse scattering surface or a curved reflective surface is placed behind the tubes to enhance the performance. Collectors such as these which incorporate insulated manifold piping have been selling at a cost of about $215/square meter of collector aperture area (1977 dollars).

A shallow solar pond, which is basically a shallow body of water, is insulated on the bottom to prevent heat losses, blackened on the bottom to absorb sunlight, and covered by one or two plastic covers on top to prevent evaporative and convective/conductive losses. The primary advantages of such a solar collector are its simplicity and a low installed system cost of about $60/m^2 (1977 dollars). The main disadvantages are its tilt angle limitations and relatively large loss coefficient. For these reasons, the shallow solar pond performs best in low latitudes where high ambient temperatures are experienced.

A concentrating collector is required to produce temperatures in the range of 150-300°C. In most cases where the direct component of solar radiation is being concentrated, a sun-tracking capability is required, which increases the incidence of radiation striking the collector surface as compared to a flat-plate collector. However, a sun-tracking system has greater mechanical complexity which will lead to greater maintenance costs than in the case of a flat-plate collector.

Various types of concentrating collectors include:

1. Linear Fresnel Lens Collector. A linear Fresnel lens collector consists of a rectangular-shaped Fresnel lens, an absorber tube situated along the lens' focal line, an assembly which serves as both a structure for the lens and absorber tube and a means for insulating the absorber from the environment, and a structure for supporting the collector assembly. In addition, a tracking mechanism is needed since this device collects principally beam radiation. Normally this type of collector is mounted with its long axis in a north-south direction but tilted at some angle with respect to the horizontal.

The cost of this type of collector including the supporting structure and tracking mechanism is approximately $270/m^2 (1977 dollars).

2. Compound Parabolic Collector. The compound parabolic solar collector is currently the only concentrating collector being developed which does not produce an image. Instead, the collector focuses the sunlight in a diffuse manner upon the absorber. To date, there have been no installations of working, nonexperimental systems employing compound parabolic collectors. It is anticipated that production-model collectors will cost in the range of $200-300/m^2 (1977 dollars).

3. Tracking Parabolic Cylinder Collector. A parabolic cylinder collector consists of a specularly reflecting trough whose cross-section is parabolic in shape. In this arrangement, the focus of the parabola forms a line which runs the length of the trough. The absorber is placed along this line and is usually a copper or stainless steel pipe. To reduce the radiative and convective/conductive losses, the absorber is sometimes enclosed in a glass tube, the annulus being either evacuated or nonevacuated.

Tracking is accomplished by rotating the reflective cylinder about the absorber axis. Three different absorber axis directions have been considered: east-west, north-south, and north-south but tilted at an angle with respect to the earth. Collectors mounted on the horizontal are simpler to install, requiring fewer support structures and less piping; however, the north-south but tilted arrangement eliminates "cosine losses" and therefore can collect significantly more energy. Insufficient data are currently available from actual installations to determine which of these arrangements gives the greatest cost benefit. The costs for these types of collectors have been in the range of $150-300/m² (1977 dollars), including supports (for horizontal mount) and tracking mechanism.

Further information on the state-of-the-art and a comparative analysis of these collector types may be found in [1]. A most significant result of this study was that for all delivery temperatures above 50°C, the polar-axis-mounted, single-axis-tracking concentrating collector gives a superior performance to all other collectors evaluated. In particular, the parabolic cylinder collector with its low loss coefficient looks especially promising at the higher temperatures studied.

Below delivery temperatures of about 80°C, the best performing flat-plate collector deserves serious consideration. From these calculations, a single-glazed collector with a black chrome selective surface appears to be the best performing and most cost-effective flat-plate collector. Although the polar-axis-mounted, single-axis-tracking concentrating collector gives a superior performance at these lower temperatures and collects more energy than a flat-plate collector, the lower cost of the flat-plate collector may offset the performance difference and give delivered energy at a lower cost.

At temperatures of less than approximately 60°C, a shallow solar pond appears to be the most economical solar system in the regions of the country with relatively high insolation. In these regions, the higher ambient temperature and the lower latitude angle help increase the net amount of collected energy. In addition, the shallow solar pond has a much lower installed cost than any other solar system (by nearly a factor of 2).

In addition to the collectors, several other subsystems in a solar system must be given careful consideration. Among these are storage, control, energy transport, and structural support subsystems. Several types of storage media can be used in conjunction with solar systems, including water, special high-temperature fluids, rock beds, and heat-of-fusion materials. It is also possible that for certain applications, no storage may represent an optimal condition. Some of the important factors which influence the choice of storage system type are daily demand pattern of energy usage, the desired solar fraction, the temperature required for the process, and the form in which energy is carried to the process (e.g., air, water, or steam).

In all cases where storage is selected, it is necessary to insulate the storage container. Selection of the proper amount of insulation is made on the basis of a life-cycle cost-benefit analysis.

The choice of storage size should also be made on the basis of a life-cycle cost-benefit analysis. Experience has shown that too little storage for a given collector area forces the system to operate at high temperatures. In such a case, collector efficiency is always reduced, and heat is often rejected when maximum acceptable temperatures are exceeded. Too much storage for a given collector area causes the storage temperature to remain low and usually involves a large heat-loss surface which allows more heat to be conducted or radiated away.

A rule of thumb which may be followed is that for water storage, about 60 l/m² should be used. Similar rules for other storage media may be deduced. However, such rules of thumb should not be followed blindly since analysis of a specific application may indicate a different amount of storage (for example, if a larger amount of storage is already in place).

The control subsystem may be divided into two parts, that concerned with the collection of solar energy and that concerned with energy delivery. The controls concerned with energy delivery are normally application specific, and therefore it is not possible to make general definitive statements. However, as guiding principles, the lowest acceptable delivery temperature should be used and the simplest functional control system should be selected.

Flow rates in a system may be fixed, or varied by a variable-speed or multispeed pumping arrangement. Variable- or multispeed pumping allows the system to collect 2-3 percent more energy per year. Control systems for accomplishing this should not cost more than the value of the additional energy collected over the lifetime of the system.

Additional controls which must be considered are those which protect the system from excessively high and low temperatures.

Experience with solar systems has indicated that energy transport and structural support subsystems can be major cost items. Structural support requirements are normally dominated by wind loading considerations. Major considerations in energy transport subsystems are the pipe size required to meet flow-rate and pressure-loss requirements, amount of insulation required to reduce energy losses, and piping configuration required to keep a balanced flow.

Expected cost ranges for various subsystems in a solar industrial process heat system are shown in Table 5.

4.2 DESIGNS AND DEMONSTRATIONS

Little experience has been obtained with the design and operation of solar systems in industrial plants. It is thus not possible to present specific guidelines for the design of solar systems for specific applications. However, for solar process heat systems designed as a utility system, basic generalized designs have been conceived and are available in the literature [1]. For example, designs are available to provide process hot water, to heat process fluids indirectly, and to

Item	Materials Cost Range	Installation Cost Range	Range as Percent of Total System Cost
Collectors	$75-$300/m²	$20-$50/m²	40-60%
Support Structures	$10-$30/m²	$10-$30/m²	10-[illegible]
Storage	$0.13-$0.40/l	$0.13-$0.40/l	5-10%
Energy Transport			15-20%
Controls			2-5%

Table 5. Summary of costs for solar process heat systems. 1977 dollars. Ref. 1.

provide steam.

In an effort to help commercialize solar process heat systems, the Department of Energy (DOE) is sponsoring a series of demonstration projects. Some of these projects have already been designed and built, although little operating data have been obtained yet. These demonstration projects are grouped in the categories of hot water systems, hot air, commercial agriculture, low-temperature steam, and high-temperature steam. Demonstration projects in the first three of these categories which are already underway are listed in Table 6 [6].

As part of the program, DOE has funded five projects in hot water generation which are representative of the variety of potential solar applications. These five hot-water projects are:

1. Can Washing: In this project, a solar system is being designed to supply heated water to be used to wash empty and full soup cans on one of 20 parallel can washing lines at a Campbell Soup plant in Sacramento, California. The collector field is made up of a mixture of flat-plate and trough-shaped parabolic concentrating collectors producing water at 88°C (190°F);

2. Curing of Concrete: In this project, hot water from a solar system will be used to cure concrete blocks. The collector system consists of a fixed collector bar mounted over a bank of movable blade reflectors which focus radiation on the collector bar. It is designed to give a 24-to-1 concentration effect, operate at 50 percent efficiency, and produce water at over [illegible]°C ([illegible]);

3. Textile Processing: In this project, a mixture of water and ethylene glycol will be heated to 121°C ([illegible]°F) using a high-performance collector. The working-fluid heat will be transferred to a secondary water stream supplying a dye tank;

4. Laundry: In this project, both hot water and steam are to be generated with a solar system for use in [illegible] cleaning. The collectors use mirror concentrators with individual tracking drives and a stationary receiver tube. The [illegible] water [illegible] is proposed to generate 92°C (200°F) water with over 60 percent efficiency; and

5. Uranium Mill: In a demonstration project now under way in New Mexico, a shallow solar pond built in the ground is used for hot water generation. Water heated to 46°C (114°F) is produced and pumped to a nearby uranium mill.

DOE has recently funded six design projects to use solar hot air to meet industrial processing needs in the drying and/or dehydration of a range of commodities. The projects include:

LOCATION	CONTRACTOR	APPLICATION
Hot Water		
Pasadena, CA	Jacobs Engineering	Commercial Laundry
Sacramento, CA	Acurex Corporation	Can Washing
Grants, NM	Lawrence Livermore Lab.	Shallow Solar Ponds
Harrisburg, PA	AAI Corporation	Concrete Block Curing
LaFrance, SC	General Electric Company	Textile Dye Vat Heating
Hot Air		
[illegible]Fur, AL	Teledyne-Brown Engineering	Soybean Drying
Lavelax, AL	Honeywell	Textile Drying
Fresno, CA	California Poly. State U.	Raisin and Prune Drying
Gilroy, CA	Trident Engineering	Onion Drying
Lawrence, KS	Midwest Research Institute	Alfalfa Drying
Canton, MS	Lockheed-Huntsville	Lumber Drying
Commercial Greenhouses		
Brentwood, CA	Sunlok Research	Vegetables
Spartanburg, MS	Daystar Corporation	Ornamentals
Springfield, OH	Lockheed-Huntsville	Ornamentals
Allentown, PA	Rutgers University	Tomatoes
El Paso, TX	Solargenics Inc.	House Plants

Table 6. ERDA industrial process heat demonstration projects as of 1977. Ref. 6.

1. Lumber Drying: In this project, solar-generated hot air will be used to dry hardwood lumber in a conventional lumber kiln. A flat-plate collector will be used to produce drying air at 43°C to 82°C (110°F to 180°F);

2. Food Drying: In this project, a set of flat-plate collectors will be used in various modes (air-once-through, recirculate to drier, and with an auxiliary heater) to dry a variety of food goods;

3. Soybean Drying: A conventional grain dryer in Decatur, Alabama, will be used to dry soybeans using drying air from a solar collector and storage system. A 1,375-m² (14,800-ft²) collector mounted at an angle next to the concrete drying silo can dry up to 127 m³/day (3,600 bu/day);

4. Onion Dehydration: This project will demonstrate the use of solar hot air on a continuous conveyor dehydrator which processes over 2,724 kg/hr (6,000 lb/hr) of onions using variable temperatures in a 4-stage drying sequence;

5. Textiles: A solar concentrating half-axis parabolic collector will be used to produce steam which will heat a cylindrical dryer. This will then support the open-air drying of textiles at an Alabama plant; and

6. Dehydration of Alfalfa: Solar-based hot air will be used to preheat combustion air for a gas-fired rotary dehydrator that produces 2,724 kg/hr (3 tons/hr) of dried alfalfa.

Five projects are being sponsored by DOE to demonstrate the use of solar energy in commercial greenhouses:

1. Vegetables: In this project, the solar collector is the top of the greenhouse. Three layers of highly transmitting membranes are suspended at the header height inside the greenhouse, which forms the base of the solar collector. The air in the triangular roof section heats to temperatures of 49°C to 66°C (120°F to 150°F) and is blown through an insulated rock bin adjacent to or under the greenhouse and stored for future use. This project will be typical of a tomato growing operation in central California.

2. Ornamental Plants: The collectors will be mounted on triangular structures adjacent to the greenhouse, trapping hot air which is blown over an air/water heat exchanger. The warm water is pumped to the greenhouse, and the heat is transferred through a water/air heat exchanger, conditioning the growing space. This project should be a good example of a southern New England greenhouse operation for ornamental plants.

3. Ornamental Plants: The collector field is erected on triangular supports adjacent to the greenhouse, and the hot water produced is stored in a 113 m³ (4,000 ft³) insulated concrete tank. The heat is delivered upon demand to the greenhouse through hot-water finned radiators on the growing benches. This operation is typical of an ornamental crop greenhouse in northeastern Ohio.

4. Tomatoes: This project uses a unique plastic film solar collector, porous floor storage, and a vertical curtain heat exchanger, which can be raised or lowered as needed and also act as insulation. The solar collector is an inflated, [illegible] trickle system to produce warm water which is returned to the floor of the greenhouse. The thick rock subfloor acts as the storage chamber for the hot water. This installation will be typical of a Pennsylvania greenhouse operation producing tomatoes.

5. Ornamental Houseplants: This system uses a water collector erected adjacent to the greenhouse. The hot water is transferred to the greenhouse upon demand and passed through a water/air heat exchanger. The surplus heat produced in the greenhouse by insolation is blown through a rock storage, thus using the excess energy produced in the greenhouse. During the summer the rock storage may be cooled at night by circulating air over the rock bed. This project will be typical of a houseplant greenhouse installation on the dry high plains of the Southwest U.S.

DOE is in the process of evaluating additional sets of experiments aimed at the use of solar-produced steam.

The current federal program has focused on demonstrating systems that are more or less commercially available in an effort to promote more widespread use in the near future. Further information may be found in the literature on project descriptions [6,7] and on the up-to-date results of these projects [8].

In addition to the designs for these demonstration projects, detailed system designs have been done by the Jet Propulsion Laboratory for four possible industrial retrofit applications [9]. If solar energy is to have a near-term impact on industrial energy consumption, retrofit of existing plants will be required. Retrofitting a solar energy system is more difficult and costly than integration of solar systems into a new plant design. This study focused on retrofitting to quantify just how costly retrofitting might be and to explore the level of difficulty to be encountered. These four retrofit/cost cases involved solar water heating at: 1) brewery (beer pasteurizing process), 2) paper manufacturer (water for paper pulping), 3) milk company (milk truck tank washing), and 4) vegetable oil processing plant (oil tank heating).

Selected design and estimated performance data from these four JPL design studies and, for comparison, from four of the DOE demonstration projects are presented in Table 2. The DOE programs include three retrofit solar installations and one new installation. The average cost of the DOE retrofit systems is 463 $/m² (43 $/ft²). Coincidentally, the average cost of the JPL systems is also 463 $/m² (43 $/ft²). The only new installation in this data set is significantly

Application	Beer Pasteurizing	Paper Pulping	Milk Truck Washing	Vegetable Oil Heating	Concrete Block Curing	Kiln Drying of Lumber	Textile Drying	Can Washing
	[illegible] DESIGN STUDIES				ERDA [illegible] PROJECTS			
Owning Company	Joseph Schlitz	Crown Zellerbach	Carnation [illegible]	Pacific Vegetable Oil	York Building Products	La Cour Kiln Services	West Point Pepperell	Campbell Soup
Location	Van Nuys California	Los Angeles California	Los Angeles California	Richmond California	Harrisburg Pennsylvania	Canton Mississippi	Fairfax Alabama	Sacramento California
Collector Type	Flat	Flat	Flat	Flat	Concent.	Flat & Refl. [illegible]	Concent.	Flat & Concent.
Installation	Retro.	Retrofit	Retrofit	Retrofit	New	Retrofit	Retrofit	Retrofit
Collector Area-ft^2	24,100	65,100	3,700	14,700	9,216	2,520	6,31[illegible]	4,134 - 2,[illegible]
Storage-Gal.	24,000	74,000	[illegible],000	-0-	-0-	4,000	-0-	14,200
Nominal Temp. of Collector Fluid °F.	[illegible]	100-170	[illegible]10	[illegible]-140	140-180	1[illegible]-200	[illegible]	[illegible]-195
Daily Collection-Annual Average [illegible]/ft^2-day	660	[illegible]60	700	400 (Note 1)	[illegible]50	537	[illegible]	819
[illegible] Btu/yr.	[illegible],300	61,30[illegible]	70[illegible]	[illegible],750	[illegible]	[illegible]	[illegible]	2,809
Percent Energy Supplied by Solar System	32	21	66	34	[illegible]	44	4[illegible]	77
Total System Installed Cost-$	975,00[illegible]	2,[illegible]92,[illegible]	[illegible]2,[illegible]	63[illegible],0[illegible]	250,560	103,[illegible]7	4[illegible]6,000	29[illegible],733
Normalized Cost-$/collector ft^2	40.4[illegible]	32.14	[illegible].63	42.8[illegible]	27.19	37.07	51.1[illegible]	39.55
Levelized Solar Cost-$/10^6 Btu	14.2[illegible]	12.38	25.90	19.27	12.50	9.10	22.0[illegible]	10.00
Payback-Yr.	30	25	35	31	34	25	36	>20

1 This number reflects the energy collected from 24[illegible] days (assumed duty cycle) divided by 365 days. A larger duty cycle would reflect in a higher daily average.

TABLE [illegible]. Comparison of solar designs for industrial process heat applications. Ref 9.

[illegible]	NORMALIZED COST — $/collector ft²			
	[illegible]	[illegible]	[illegible]	PACIFIC VEGETABLE OIL
Solar collectors	11.27	11.90	[illegible]	11.90
[illegible]	2.66	[illegible]	3.10	4.42
[illegible]	1.04	[illegible]	1.61	0.54
Pumps	0.83	[illegible]	1.61	[illegible]
Controls	0.41	0.95	[illegible]	[illegible]
Piping & insulation	[illegible]	0.72	[illegible]	1.26
Storage tank & insulation	2.07	-0-	[illegible]	-0-
Heat exchanger	0.41	[illegible]	0.64	4.76
Expansion tank	-0-	[illegible]	0.02	0.39
Mechanical Subtotal	20.73	16.51	25.42	23.57
Panel support structure	5.60	5.68	12.25	5.58
Electric	1.45	1.47	0.15	1.50
Miscellaneous	2.74	2.38	3.79	2.59
Change order allowances	1.53	1.30	2.09	1.70
Contractor overhead & profit	4.77	4.10	6.61	5.10
Permits & fees	0.20	0.14	0.32	0.41
Architects & engineers fee	[illegible]	[illegible]	4.77	2.04
TOTAL	40.43	32.12	56.41	42.69

Table 8. Comparison of solar system cost elements for JPL designs--normalized cost. Ref. 9.

lowest in cost at 291 $/m² (27 $/ft²).

For the studies shown in Table 7, the cost of solar energy has been estimated to be between [illegible] and 24.70 $/10⁶ kJ (9 to [illegible] $/10⁶ Btu). This estimate reflects today's technology and is not necessarily reflective of future systems. For example, manufacturers of solar panels are [illegible] the residential space and water heating market and generally offer a 2 to 3 m² (20-30 ft²) panel. If panels of 10 or more square meters were mass produced, savings could be expected in the costs of the collector, installation, mounting and plumbing [9]. These items now account for substantial portions of the total costs. By using larger panels, savings would result in all of these cost areas. In addition, contractors have no experience with large solar installations and are therefore estimating high until some background is developed.

To provide some details with regard to a breakdown of total system costs with respect to components, Table 8 shows the cost breakdown for JPL's design/cost studies in terms of a normalized cost per unit area of collector. Similar detailed information is available for DOE's demonstration projects.

In addition to these publicly funded projects, a number of private pilot projects are being designed and operated [e.g., [illegible]], but little detailed information is available.

Although each application of solar energy for industrial process heat appears at first unique, common design procedures, requirements, problems can be observed. In each application the combination of operating temperature, array size, process duty cycle, interface requirements, and availability of roof area do combine to make a unique system.

However, in the DOE solar projects and the JPL case studies, a very similar evaluation and design procedure was used. A generalized design procedure [9] will involve the following:

1. Preliminary evaluation
   a) Plant location
   b) Process temperature needs
   c) Heat recovery potential
   d) Annual duty cycle
   e) Roof/land area available
   f) Thermal storage requirements
2. Conceptual design
   a) Determine process energy requirements
   b) Establish component requirements
   c) Generate performance estimates
3. Detailed design
   a) Evaluate structural adequacy of buildings (retrofit application)
   b) Establish solar system/conventional system interface
   c) Produce specifications, layouts, and collector support structure
4. Cost estimate/contractor bid
5. Refine performance estimates
6. Economic analysis

In the preliminary evaluation, designers should look at the possibilities for energy conserva-

[illegible] and [illegible] potential. [illegible] amount [illegible] is [illegible] [illegible] The [illegible] of a plant is extremely impor[illegible] the applicati[illegible] of solar. As [illegible] applications [illegible] may at the [illegible]

[illegible] ISSUES

[illegible] from [illegible] a number of sources [illegible] industrial process heat market [illegible] compared to the solar heating [illegible] market. [illegible] residential uses, [illegible] and famil[illegible] for example. However, there are a number of unfavorable issues [illegible] impact on the potential use of solar process heat in industry.

One of the most important issues is that of land use. The pro[illegible] heat requirements of an industrial plant may require a solar system which is too large to be placed on the plant [illegible]. For retrofit applications, the [illegible] may not be structurally adequate [illegible] a solar system. A significant [illegible] lead to [illegible] [illegible] available in urban [illegible] industr[illegible] markets [illegible] solar [illegible] heat sys[illegible] [illegible] much.

[illegible] issues [illegible] concerns [illegible] [illegible] of solar [illegible] and [illegible] goals and alternative [illegible] issues.

Glare and [illegible] solar radiation from solar collectors can be [illegible] significant safety hazard.

The use of solar heat in industrial applications should yield some desirable environmental benefits. By displacing fossil fuels, solar will directly reduce [illegible] and other air pollutants.

One very serious financial barrier to the use of solar process heat [illegible] policy, which permits fuel costs to be [illegible] expense in the current year, whereas a solar system is a capital investment which is depreciated over a number of years. This difference in tax treatment has a [illegible] increasing the cost of solar relative to fossil fuels. This [illegible] could be [illegible] [illegible] accelerated depreciation [illegible] [illegible] for example.

In addition, the cost of capital [illegible] [illegible] for [illegible] potential solar markets be [illegible] and the resulting demand for a high return on investment [illegible] the use of solar process heat [illegible].

Finally, other institutional issues which may influence the use of solar in industry include the establishment of solar rights, standardization and certification of solar components and systems, and resolution of certain [illegible] issues [1].

[illegible] CONCLUSIONS

The technical potential of solar industrial process heat is [illegible]ficant, based on temperature requirements for [illegible] processes and performance of solar systems available today. Potential applications of solar process heat systems have been identified [illegible], and [illegible] potential applications can be found throughout industry as a whole. A great deal of technology applicable to solar process heat exists, which is essentially [illegible] from solar heating and [illegible] development needs to be [illegible], particularly with moderate-temperature systems.

Solar process heat systems will not be economically competitive until solar costs are lowered or, more likely, [illegible] fossil fuel [illegible] increase to a sufficient extent. Solar cannot compete with coal except perhaps in specific situations, although oil and gas will continue to be used predominantly by industry for [illegible]. Standardized designs of solar industrial process heat systems need to be developed to lower costs.

Design and operating experience needs to be obtained with solar process heat systems to demonstrate [illegible] reliability and [illegible] [illegible] of the federally [illegible] demonstration [illegible]. These demonstration projects and other [illegible] studies have [illegible] solar energy systems can be designed [illegible] grated into some existing industrial [illegible] to supply a portion of the process heat requirements. In general this can be accomplished without affecting the process and with a relatively simple interface. Full-capacity conventional-fuel backup systems have been found to be a basic design requirement for industrial applications.

In the industrial market, process heat requirements, temperature requirements, plant [illegible], plant operating modes, and phys[illegible] layout all significantly affect solar system [illegible]. As a result, solar energy costs will vary considerably [illegible] one application to another. The [illegible] cost of solar energy for process heat is currently high in retrofit applications. The range of estimates is between [illegible] and 24.70 $/10 [illegible] ([illegible] [illegible]). These [illegible] reflect 1977 technology and a conservative design approach. As experience is gained, costs can be expected to decrease.

Finally, there are significant obstacles to the widespread implementation of solar process heat, including financial barriers, which [illegible] be [illegible] with appropriate incentive [illegible] question [illegible]. Solutions to these potential [illegible] will have to be found before the[illegible] impede the widespread implementation [illegible] process heat.

[illegible] Analysis [illegible]
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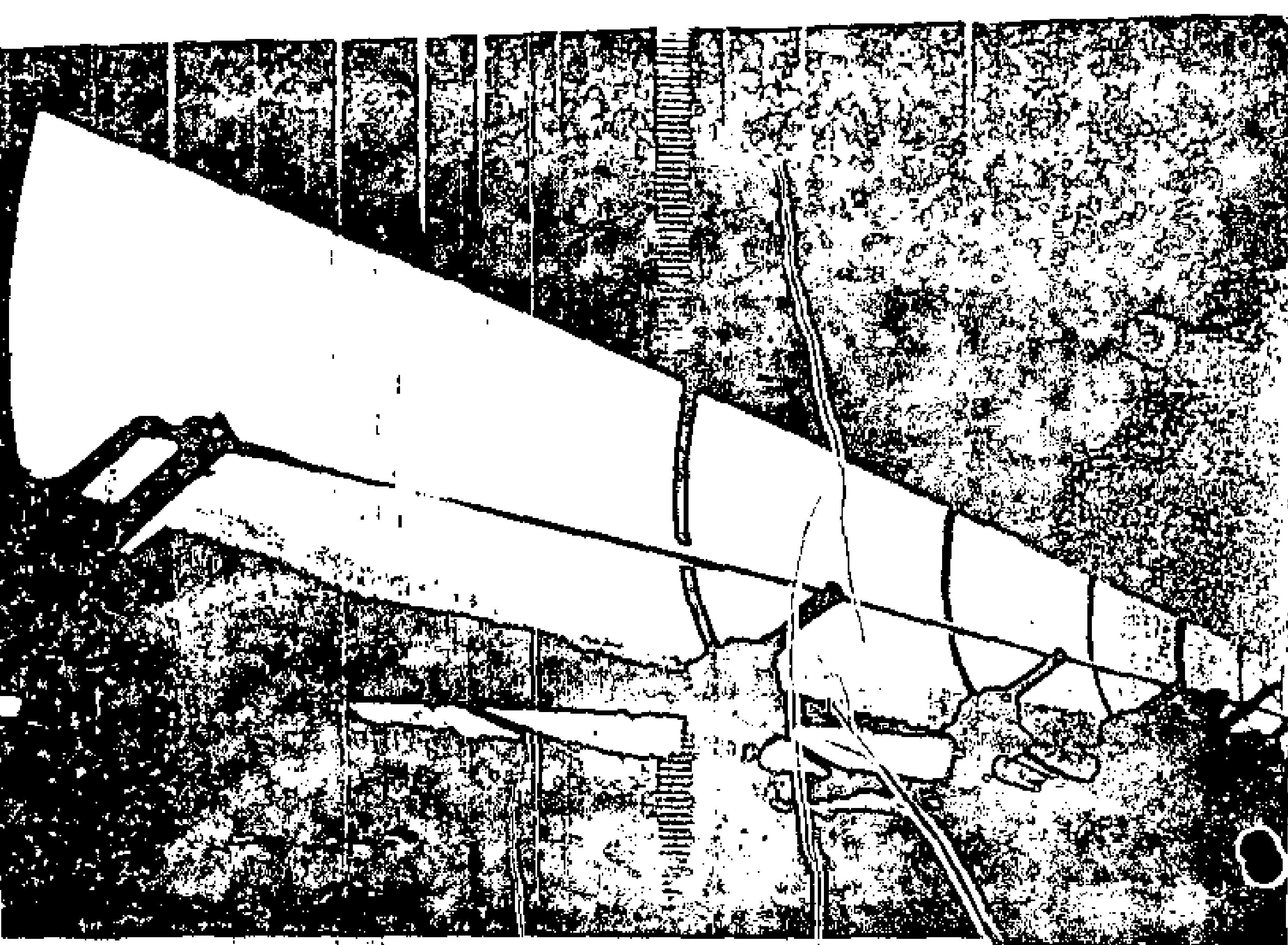


Industrial Process Heat

Creative Opportunities in Solar Design

Industry uses 40 percent of our nation's purchased energy. About 28 percent of this is used by manufacturers, and the remaining 12 percent by agriculture, mining, and service industries. Of the energy purchased by industry, about three quarters is used to supply thermal energy—for producing process steam or for direct process heating. Use of over 80 percent of the thermal energy is concentrated in six major industrial categories.

A significant portion of industrial process heat is used within temperature ranges available from today's solar collectors. For example, 40 percent of the process heat used for direct applications and preheating occurs below 600°F (315°C).

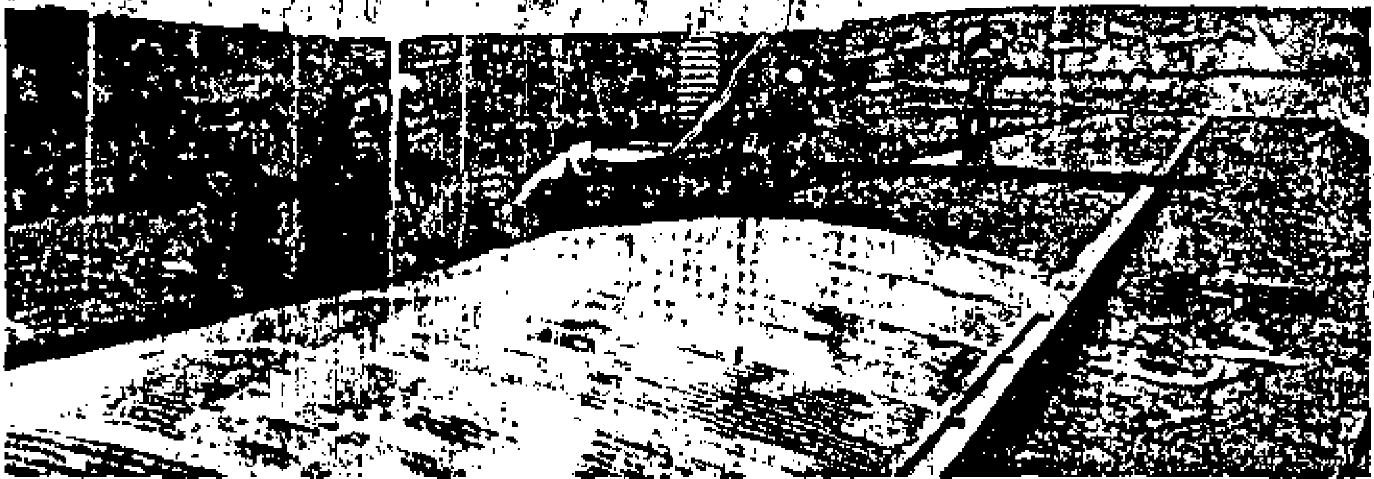
Interest in using solar for industrial process heat is growing quickly within both industry and government. Conventional flat-plate collectors are adequate for many low-temperature applications—up to 150° (65°C) above ambient. Large shallow solar ponds are also providing low-temperature hot water. Evacuated tubular collectors and concentrating collectors are available for producing higher temperatures.

Industry usually uses process heat continuously rather than intermittently. Heat storage can help bridge periods of intermittent sunlight (and store weekend solar heat), but process heat requirements are usually so great that the collector array must cover a large area if solar is to significantly reduce purchased energy consumption. Most industrial solar systems will be sized then, to supply less than the process load during even the sunniest conditions. This results in a high utilization rate of the heat collected by the solar system.

This higher energy output, coupled with the elimination of heat storage, gives solar an economic edge not normally found in building applications. Collectors, too, can be less expensive than those on buildings, since they rarely stand idle and are not subject to the debilitating effects of no-flow (stagnation) conditions. This allows the collectors to be made of less costly materials.

Industry, of course, requires a very short payback period. Also, fuel costs are written off immediately as a tax deduction. Industry is reluctant to accept "new venture" technology. Energy conservation is, and will be for some time, preferred by industry over solar.

However, large amounts of capital are available in industry, and significant tax breaks will often give solar an economic edge. Public relations benefits and fast-rising energy prices add to solar's attractiveness. Finally, interruption in the supply of other energy sources will make the adoption of solar inevitable for many industries.



Shallow solar ponds, designed by Lawrence Livermore Laboratory, are installed at the Sohio Petroleum Co. in New Mexico. They consist of long plastic bags filled with 2 to 4 inches of water that rest on uninsulated beds and are glazed with low fiberglass roofs.

Applications: Ponds

Perhaps one of the simplest solar energy systems for IPH applications is shallow ponds. Although construction of a complete pond system at the Sohio Petroleum Company in Grants, New Mexico, has not begun, three prototypes have been operating there for the past two years. Designed by Lawrence Livermore Laboratory, the ponds consist of a long plastic bag filled with two to four inches of water. It rests on an insulated bed and is glazed with a low fiberglass sheet roof. The total area is 80,000 square feet.

The bags are filled at sunrise, absorb heat during the day, and are drained into an insulated tank in the late afternoon when water temperatures reach their peak. The hot water is used to accelerate the chemical leaching process that concentrates uranium ore. The system has yielded an average annual collection efficiency of about 45 percent. Lawrence Livermore Laboratory has prepared a design manual, *Design Guide for Shallow Solar Ponds*. ($5.25 from NTIS, 5285 Port Royal Rd., Springfield, VA 22161. Ask for Report no. UCRL-52385.)

Applications: Hot water

Many industrial processes use low temperatures (below 212°F, 100°C).

At the Campbell Soup Company plant in Sacramento, California, for example, a solar energy system designed by Acurex Corporation (Mt. View, CA) heats water for washing cans. Single-glazed, flat-plate collectors (4,698 square feet) heat water to about 140°F (60°C), and 2,880 square feet of parabolic-trough concentrators raise the temperature to 195°F (88°C). The heated water is stored in a simple 20,000-gallon accumulator tank, insuring a continuous supply of water. During peak season, the system supplies 12,000 gallons of hot water per day.

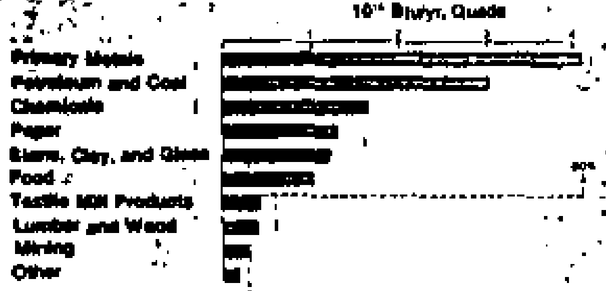
Another low-temperature application in Auburn, Indiana, heats water used to soap, rinse, and coat automotive parts with rust inhibitor. The Spicer Clutch Division of Dana Corporation processes 137,000 pounds of steel parts, requiring a constant water temperature of 130°F (54°C), each week. The system uses 52 flat-plate collectors and a 3,000-gallon storage tank. During five months of last year, the system provided 100 percent of the needed hot water for one of the plant's five washers.

Many IPH processes require large amounts of water. It has been estimated, for example, that 1.3 million barrels of fuel oil are used each year for curing concrete blocks. The York Building Products Company plant in Harrisburg, Pennsylvania, can produce 15,000 concrete blocks in a normal day. Since each block absorbs nearly 3/4 pounds of water during curing, a continuous supply of hot water is needed. Solar energy has provided 35 percent of this need since 1977.

AAI Corporation's (Baltimore, MD) model 24/1 concentrating collectors span the roof of the plant. Each of the 70 modules is 17 feet long by 9 feet wide and contains eight 1-foot-wide, slightly curved mirror strips. The mirrors are connected by a mechanism that automatically adjusts their angle to track the sun's movement and keep the reflection concentrated on the receiver. The receiver is a steel tube with a special coating to enhance the absorption of solar energy. The tubing is supported by structural arms so that it is about 8 feet above, and parallel to, the mirrors. Water circulating through

Industry's Energy Requirements

Process Heat Requirements in Major Industrial Groups

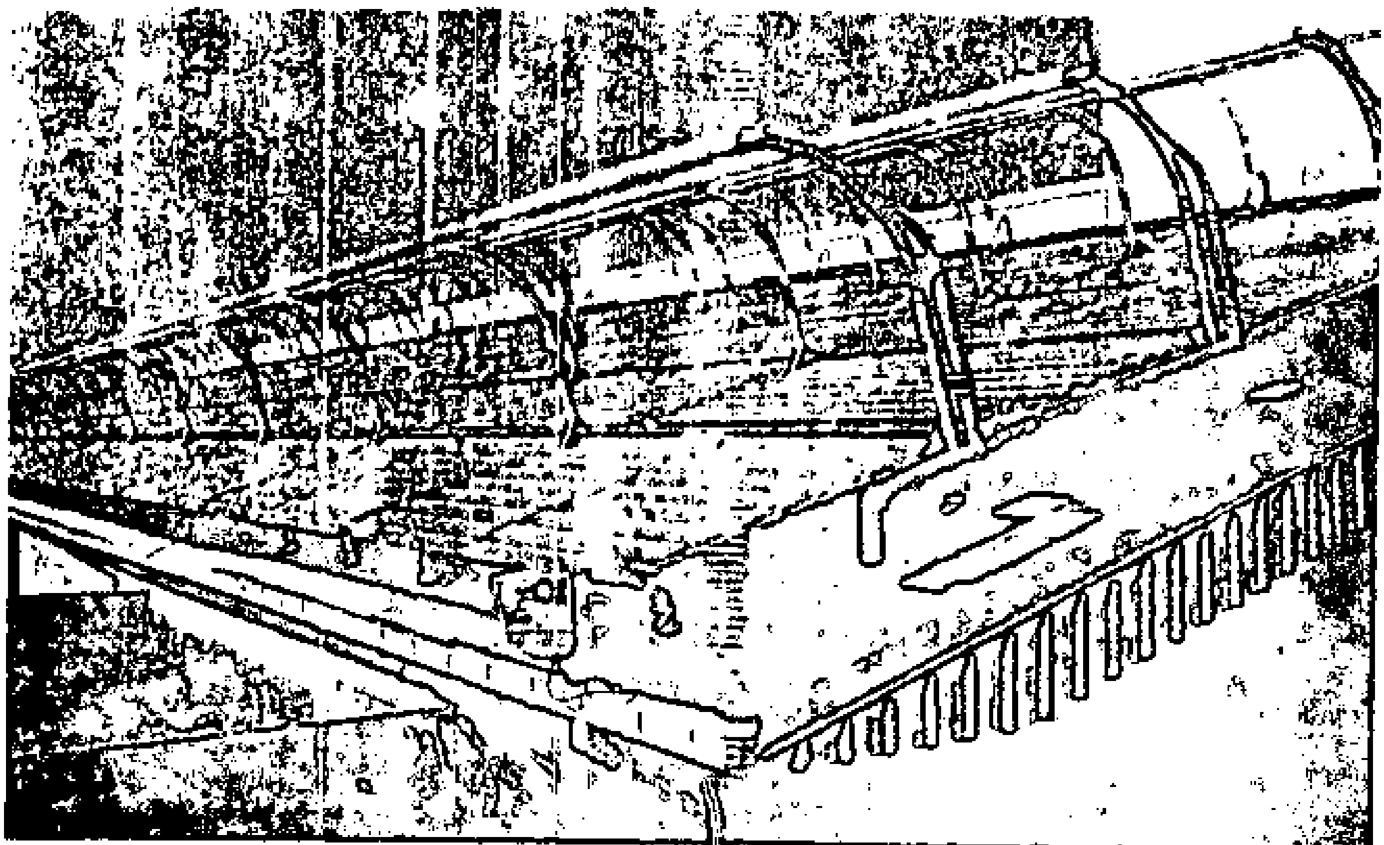


Prepared by Solar Energy Research Institute

Summary of Industrial Process Heat Requirements, 10^{12} Btu/year

Energy Form	Present	1985	2000
Hot Water (212°F)	120	120	201
Steam (212°-350°F)	2,600	3,211	4,361
Steam (over 350°F)	563	[illegible]	942
Direct Heat/Hot Air (212°F)	140	173	234
Direct Heat/Hot Air (212°-350°F)	652	805	1,091
Direct Heat/Hot Air (over 350°F)	5,965	7,367	9,981
Totals	10,040	12,400	16,800

Prepared by Battelle Laboratories

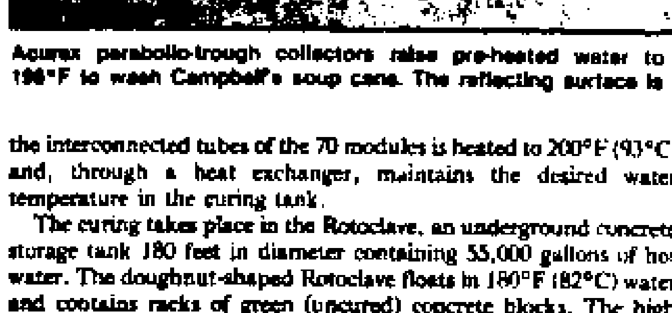


Acurex parabolic-trough collectors raise pre-heated water to 196°F to wash Campbell's soup cans. The reflecting surface is aluminum lighting sheet, and each collector is equipped with a steel receiver tube.

the interconnected tubes of the 70 modules is heated to 200°F (93°C) and, through a heat exchanger, maintains the desired water temperature in the curing tank.

The curing takes place in the Rotoclave, an underground concrete storage tank 180 feet in diameter containing 55,000 gallons of hot water. The doughnut-shaped Rotoclave floats in 180°F (82°C) water and contains racks of green (uncured) concrete blocks. The high temperature and humidity cures the green blocks as the tank slowly rotates. With 2,500 concrete block plants in the U.S. producing 3.5 billion blocks annually, this solar energy process has tremendous potential.

Solar energy can be used for a wide variety of IPH applications. Tanks at the ERGON terminal store heavy crude oils and refined petroleum products like No. 6 fuel oil. These materials are so thick that at normal temperatures they are more like solids than liquids. To pump these heavy oils, they must first be heated to over 125°F (52°C). Last year this job took over 1,500 barrels of oil, but this year an Acurex solar system will supply nearly half of the process heat for a storage tank at ERGON.



Since 1977, solar energy has provided 35 percent of the hot water needed to cure concrete blocks in Harrisburg, PA. The solar array consists of seventy modular collectors from AAI Corporation that are 17 by 8 feet.

Applications: Process drying

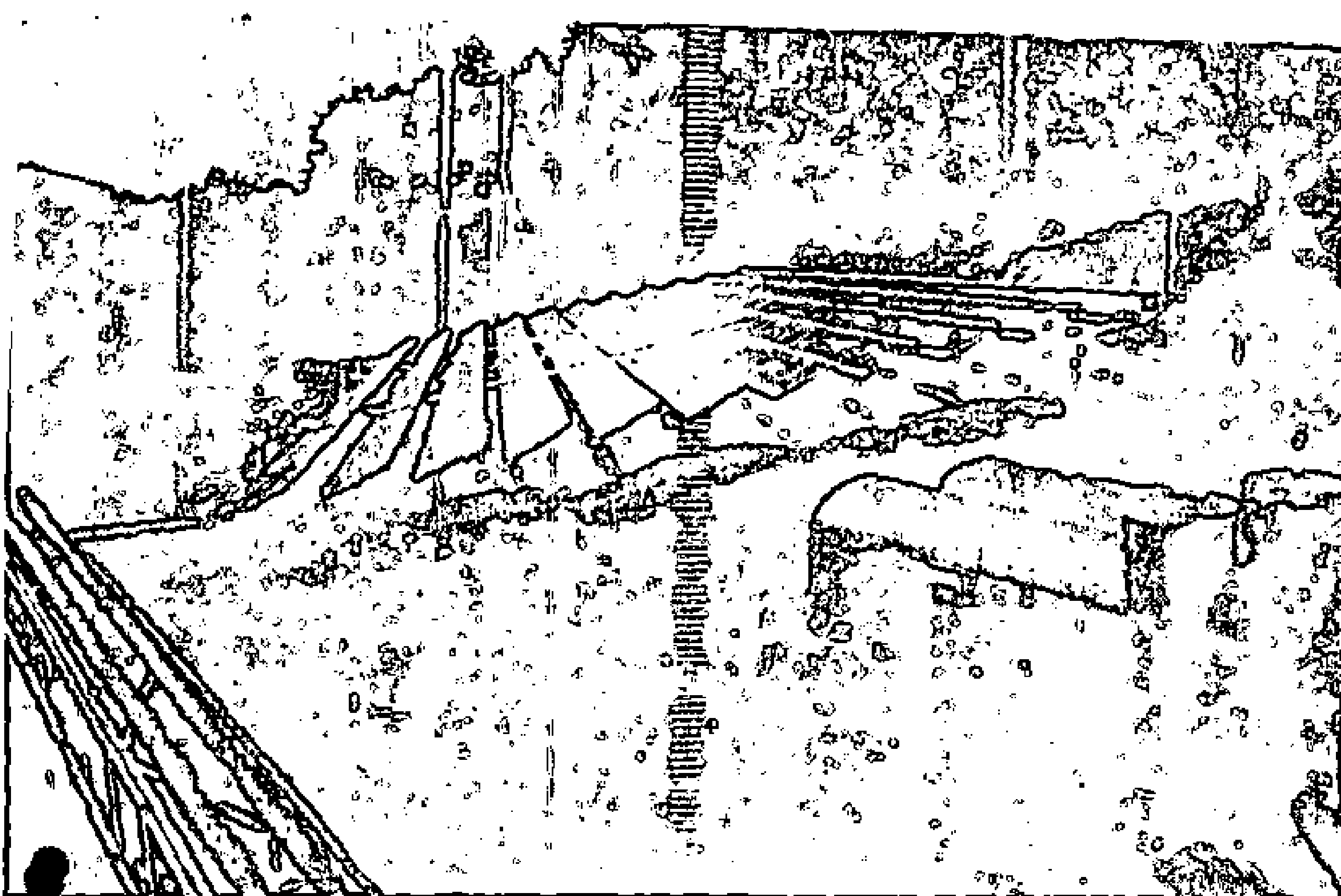
Drying processes, too, often require low temperatures, and can use simple solar energy designs. In fact, 80 percent of the hot air needed to operate one dehydration tunnel at the Lamanuzzi and Pantaleo (L&P) plant near Fresno, California, will be provided by the sun. The system, designed and built by California Polytechnic State (San Luis Obispo, CA) consists of 21,000 square feet of single-glazed, flat-plate collectors. The 14,000 square feet of rock storage delivers heated air to a tunnel dehydrator 54 feet long, requiring approximately 1.5 million Btu per hour to dry raisins and prunes at 160°F (71°C).

Single-glazed, flat-plate collectors are also drying soybeans at Gold Kist, Inc., in Decatur, Alabama. Designed and built by Teledyne Brown Engineering, the 13,000 square feet of collectors are mounted on racks and supply heated air to the combustors of conventional oil-fired equipment. The system is expected to save 28,000 gallons of fuel oil annually.

Lockheed Missiles & Space Company, Inc. (Huntsville, AL), designed and installed a solar heated kiln for drying lumber at I.A. LaCour Kiln Service, Inc., Canton, Mississippi. Double-glazed, flat-plate collectors with reflectors generate hot water and provide hot air for drying. The heat is stored in a 5,000-gallon water tank. The performance will be monitored through June, and the system is expected to provide 44 percent of the process.

Applications: Steam

A higher-temperature (400°F, 204°C) solar energy system is providing process steam to dry fabric (slashing) at West Point Pepperell Martex, Fairfax, Alabama. This system, designed by Honeywell, Inc. (Minneapolis, MN), uses twenty-four single-axis, tracking, concentrating collectors to generate 1,000 pounds per hour of process steam to the existing process. The system includes a closed high-temperature water loop (HTW), a steam generator, and a steam loop, and will provide 46 percent of three slashers' demand. Another textile process in LaFrance, South Carolina, is described below. ○



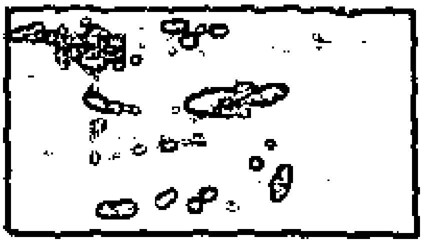
Industrial Process Heat

GE's system at Riegel Textile Corp: Another first.

By James B. Trice

Industrial process hot water uses approximately four percent of the nation's total energy, and textile processes alone require hot water equalling about 17 *million* barrels of oil per year. Riegel Textile Corporation's solar collecting field in *LaFrance*, South Carolina, is an attempt to reduce those figures.

Riegel's systems, designed and equipped by the General Electric Company, began operating last October. The $300,000 DOE-funded project is in its third and final

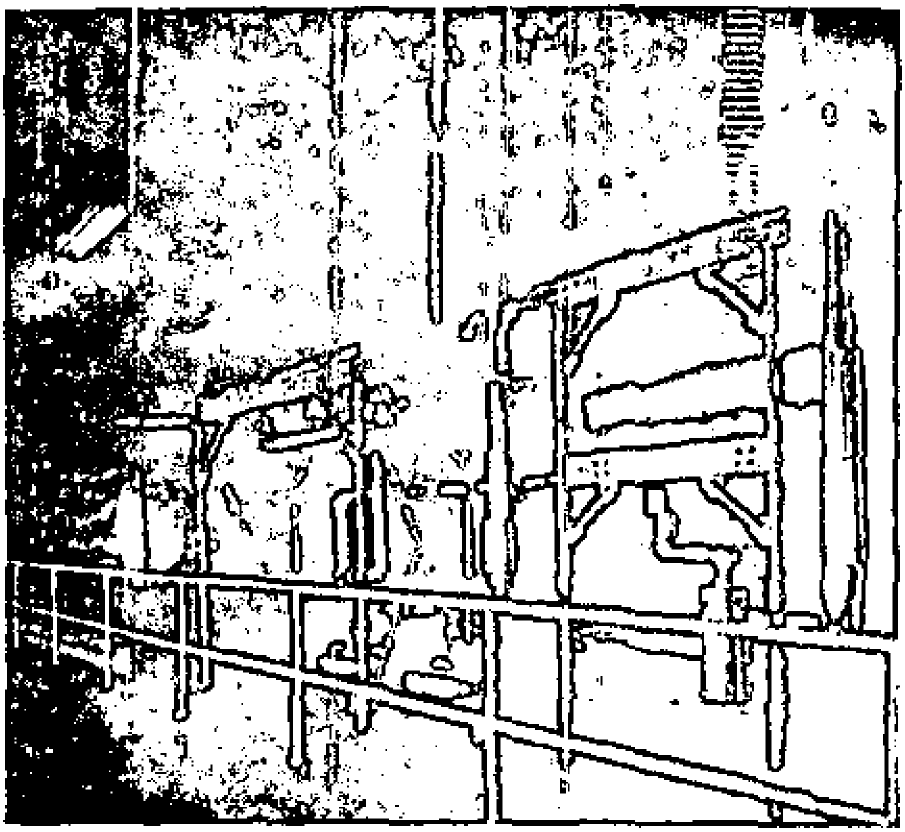


phase: evaluating the system's operation, efficiency, maintenance, cost-effectiveness, and potential energy savings. Anticipated energy savings projected throughout the textile industry as a result of such applications equal approximately 8 million barrels of oil per year. The GE system heats water in an open fabric-dyeing vat, and has been designed to provide from 50 to 70 percent of the process heat required for a single unit.

A typical mill uses two million gallons of water a day. Twenty-five percent of this is process hot water with an average temperature of 160°F. The amount of energy used for hot water processes in the typical plant is 10^{11}Btu/year, corresponding to approximately 5×10^{14}Btu/year for dyeing and finishing in the entire textile industry.

The particular process selected, an atmospheric batch dyeing process that uses a maximum temperature of 190°F, is typical of the industry. If Riegel's plant demonstrates that solar energy for process hot water is practical and economical, it will undoubtedly be accepted widely throughout the industry.

James B. Trice is Program Manager, Solar Industrial Process Heat, at General Electric Company, Space Division, Advanced Energy Programs, Philadelphia, PA.



General Electric's solar process hot water system at the La France plant cost approximately $300,000. The project, funded by the U.S. Department of Energy, was dedicated in October 1978. The collector array (left) totals 6,600 square feet, with 500 feet of pipe to convey heated water from the field to the 8,000 gallon thermal energy storage tank (above). The outstanding feature of the system is the General Electric TC-100 Solartron™ thermal absorbing vacuum tube that consists of two glass cylinders. The system is used to heat water to 190°F in an open fabric-dyeing vat and is designed to provide from 50 to 70 percent of the process heat required for one dye unit.

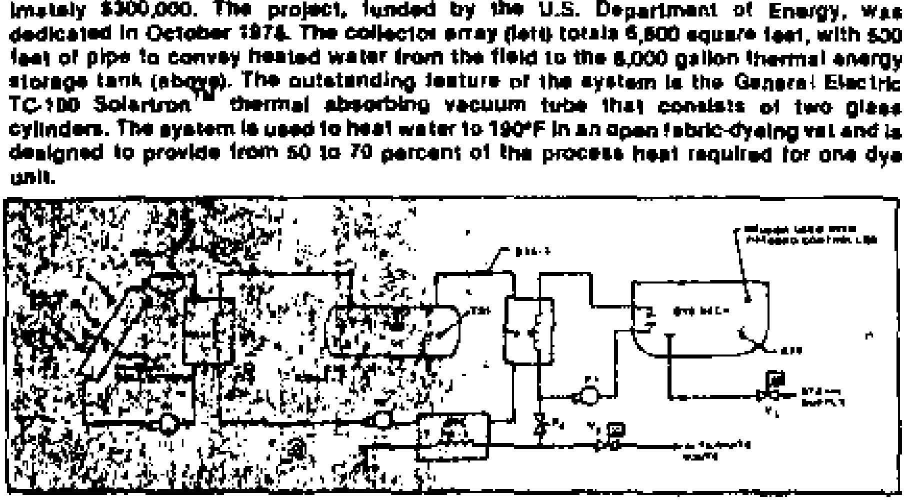


Figure 1. A Schematic of the Solar Energy System for the LaFrance Textile Mill

System Description

Three independent circulating loops are connected thermally with heat exchangers. The first loop, shown on the left side of Figure 1, transfers solar energy absorbed in the collector array to the collector loop heat exchanger. An ethylene glycol solution prevents freezing during cold weather.

The second loop contains water circulated by Pump No. 2. It transfers the collected solar energy to either the 8,000-gallon thermal energy storage (TES) tank or the plant process heat exchanger—or it apportions the collected energy between the two components as appropriate. On cloudy days, stored energy in the TES tank can be transferred to the second loop to the process. This flexibility for energy transfer is accomplished with dual modulating control valves.

The third loop, shown on the right side of the diagram, is the integration scheme, described later.

Figure 1 also shows the temperature locations and equipment used in the control of the system. The collector loop pump, P1, is turned on whenever solar radiation heats the collector absorber plate above the thermal storage temperature or the industrial process temperature. This allows preheating of the collector loop with solar radiation prior to solar heat collection for either storage or use in the industrial process.

The energy storage loop, pump P2, is activated when:

1. The collector loop is running and its temperature is higher than the storage temperature. This indicates that storable solar energy is available.

2. There is need for process heat and the collector loop is running at a temperature higher than the process requirement. This indicates that collected energy can be used directly for process heat.

3. There is a demand for process heat, and the energy storage tank is above the process temperature. This indicates that stored energy is available for process heat.

For those cases where more than one of the above operating procedures is possible, a control logic selects the proper mode by operation of the modulating valves. If the process heat can be supplied by the collector loop or the storage tank, comparison of temperatures T2 and T3 is used to select the setting on valve V2. Valve V2 apportions the flow through and around the TES tank to maintain a particular temperature at T4 or the highest possible temperature at T4.

An interlock turns off pump P3 when the process temperature exceeds the highest possible temperature at T4. The actual T4 set point temperature will vary and depend on the time-related process temperature requirement discussed in the next section. If the collector loop is below a temperature level adequate to meet the specific process heat requirement, thermal energy is transferred directly from the TES tank to the process heat exchanger.

Valve V1 modulates the hot fluid flow through the process heat exchanger device to maintain either a set point temperature or a rate of temperature rise in the dye process at T1. If the solar system cannot satisfy the process load, modulating valve V4 associated with the auxiliary (existing) steam input line is opened to meet the requirement. Automatic reset controls are available so that the T1 temperature can be varied at any time in the process cycle.

Solar System Integration

There are two interfaces between the solar energy system and the dye beck (dyeing vat): a heat transfer interface and an operational control interface. The heat transfer interface, in turn, can be either internal or external to the dye beck. An external arrangement (shown on Figure 1) imposes minimum modification to the existing dye beck and no interference with its operation.

The required control interface between the solar energy system and the process restricts the operation of the normal heating process (*i.e.*, the steam) unless the solar energy system cannot provide the required thermal energy. The process solar heating and the conventional (auxiliary) heating systems operate from an internal control network. This network uses the existing process temperature controller for sequencing the solar and the conventional thermal energy inputs, as necessary, to the dye beck.

As long as the solar energy system provides the required heat at the necessary rate, the process controller does not call for auxiliary heat. But if the solar energy system is deficient in available energy, then the controller calls on the conventional system to add heat in the normal manner to maintain the desired conditions.

System Performance and Energy Savings

The solar energy system performance is calculated with a GE-developed Solar Energy System Simulation (SESS) computer program. This program uses data on weather conditions, the process heat thermal load demand, the operating characteristics of the components in the solar energy system, and the system control procedure to predict, on an hourly basis, the solar energy used and the auxiliary energy required (if any) to satisfy the load demand. Predicted system performance for a set of system size and operating parameters, thermal load requirements and Charleston, SC, weather data is shown on a month-by-month basis in Figure 2. Approximately 80 percent of the energy required in the summer and spring months for the heat to load operation and the dye period can be supplied with a system using evacuated tube collectors. Even in midwinter, about half of the energy load can be supplied by the solar system.

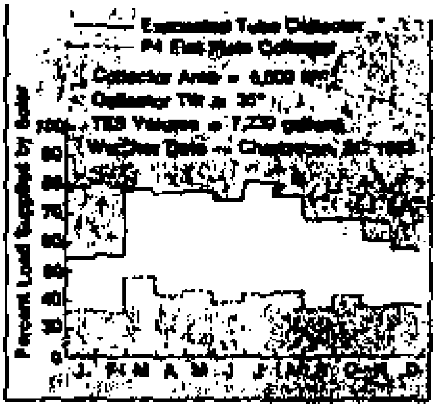


Figure 2. Month-by-Month Performance of Two Solar Energy Systems for Assumed Dye Beck Load

At the current regional oil price of about \$2/10⁶Btu, annual energy savings from solar heated process water would amount to about \$72,000 for a typical South Atlantic Region textile plant. Assuming 6 percent annual oil price escalation over a fifteen-year system lifetime, the \$72,000 initial savings will grow to over \$172,000 at the fifteenth year. A levelized savings value computer program accounts for both fuel price escalation and a 9 percent discount rate and gives a levelized value of \$107,565 annually.

For example, if the levelized operating and maintenance expenses on the solar process heat system are \$20,000 annually, a firm with a 22 percent fixed charge rate would have a break-even price of about \$400,000 for the system. The cost of the system was approximately \$300,000. This comparison of levelized costs to levelized benefits enables optimization of solar panel area for maximum payoff.

Extrapolation of the LaFrance plant savings to other textile plants yields preliminary savings of 170,000 gallons of oil per day for each 100 plants supplied with solar process heat. Demonstrated economic and technical feasibility at Riegel will provide strong impetus for solar process heat throughout the heavily gas- and oil-dependent textile industry.

Conclusions

- Preliminary calculations show that solar energy used in a single textile plant could result in annual energy savings equivalent to 7.2 x 10^{11} Btu of purchased fuel. For the entire textile industry, annual savings could equal six million barrels of oil.
- Because of the similarities in temperatures and usage of process hot water, the solar process used in the textile industry would be transferrable to other industries such as food (can washing, for example).
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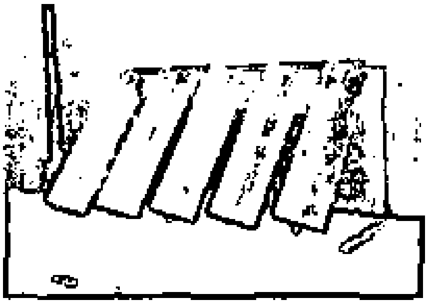
Concentrating Collectors

Editor's Note: Industrial process heat applications are opening up new opportunities for using concentrating collectors. The variety of possible designs is limited only by people's imaginations. In addition to the collectors used in the projects described in previous pages, the six shown here are but a sample of the dozens now appearing "on-the-shelf." The text is representative of the technical specs in the *Solar Product Specifications Guide* (see page 2a for more information).



Sol-R-Beam SB-205. Package includes preassembled array of five SB-201 concentrating collectors, complete with insulated header piping, solar tracking linkage, and prefabricated support hardware for mounting at 45° elevation angle on a level surface. Each collector is a clad-finished aluminum parabolic cylinder with copper focus tube and polyvinyl fluoride cover.

Options: mounting hardware for other elevation angles or surface contours
Installation requirements/considerations: components can be handled by two persons
Collector dimensions and net aperture area: 9 by 15 by 1½ ft; aperture VAN, 68.5 sq ft (5 collectors)
Concentration ratio: about 5
Absorber material, surface a/e: flat black paint or black chrome; a/e approx. 1 or e/e approx. 9.0
Concentrating surface: reflectivity and longevity: specular reflectivity 83%, Min. 20 yr
Performance test data: collects 85,000 Btu/day at 200°F water; daylong efficiency, 47% at 200°F water temperature
Pressure and temperature limitations: Operating water system, 150 psi and 250°F, per Uniform Plumbing Code; dry collector temperature 350°F
Design flow rate and pressure drop: 10 in. water pressure drop between inlet and outlet at 5 gpm
Recommended heat transfer fluid(s): water or other heat transfer fluid compatible with copper
Limitations: freeze switch, over-temperature switch, circulator pump not included with the kit
Guarantee/warranty: 3-yr. warranty on repair or replacement of defective components
Maintenance requirements: none
Manufacturer's technical services: systems engineering and consultation, repair and replacement of materials
Availability: 6 wk
Suggested retail price: $1 400
Contact: Benjamin H. Beam, Beam Engineering, Inc., 732 N. Pastoria Ave., Sunnyvale, CA 94086 (408) 738-4573

Hot Line™ Collector PL 1. Tracking and focusing mechanisms are eliminated from this optical tracking concentrator, which operates from a stationary position. Receives direct and diffuse energy from entire winter sky.

Features: close orientation not necessary, due to patented optical tracking
Installation requirements/considerations: HVAC skills and methods
Collector dimensions and net aperture area: 26 by 98 by 10 in. (typical), 14.6 sq ft
Concentration ratio: 1.6 to 1
Absorber: material, surface: Aluminum with NOVAMET 150
Concentrating surface: reflectivity and longevity: Mirrol, Coilzak
Performance-test data: 10-min. intervals under clear sky from 0.41 to 0.76 Btu. average 0.67

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Pressure and temperature limitations: 1.5-ft water, temperature limit 400°F plus

Design flow rate and pressure drop: 5 cfm/sq ft of aperture, 0.2 in

Recommended heat transfer fluid(s): Air

Limitations: 55 degrees elevation, 150 degrees horizontal

Guarantee/warranty: 1 yr full, 5 yr limited

Maintenance requirements: lubricate motor, keep glazing clean

Availability: 4 to 6 wk

Suggested retail price: under $250

Contact: Dan Lightfoot, Hot Line Solar, Inc., 1811 Hillcrest Drive, Bellevue, NE 68005 (402) 291-3889

Sunpump SCM-20t. Non-tracking, focusing collector (patented); water vaporized within absorber tube and self-transported to storage tank/heat exchanger. Passive system, one square meter (10.8 sq. ft.) collection aperture, 1.3:1 concentration ratio, double glazing. No auxiliary electrical equipment needed for operation.

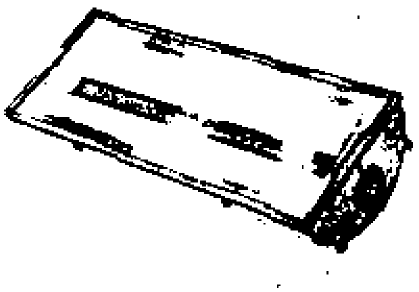
Features: system output always has temperature of 200°F minimum. System is self-pumping from collector to storage

Options: distilled water may be recirculated from storage to collectors

Installation requirements/considerations: collectors may be mounted on horizontal, vertical or sloping surfaces, on building or on ground-racks

Collector dimensions: 80.5 in by 29.62 in by 15.7 in

Absorber: Outer shell 0.040-in aluminum with baked enamel finish, insulation, 3-in high-temperature fiberglass batt, glazing: double-pane tempered glass with 0.375-in air



space, black chrome over extruded aluminum with 95% absorptivity and less than 10% emissivity. Internal surfaces treated with corrosion-resistant process

Concentrating surface: reflectivity and longevity: 87% specular, 20-yr minimum

Performance-test data: 44% (sun-on to sunset in July)

Pressure and temperature limitations: Less than 1 psi at 212°F at sea level

Guarantee/warranty: 5-yr limited warranty on materials and workmanship (Design life 20-yr with periodic maintenance)

Maintenance requirements: periodic inspection and cleaning of external glazing surfaces

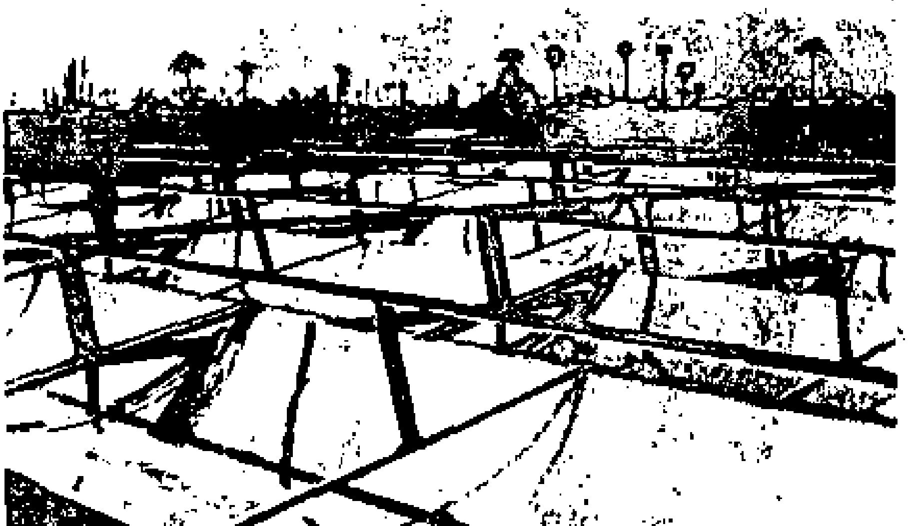
Manufacturer's technical services: total system design and sizing

Regional applicability: not practical for parts of Pacific Northwest and Alaska

Availability: 30 to 90 days, depending on quantity.

Suggested retail price: contact manufacturer

Contact: Hank Valentine, Entropy Limited, 5735 Arapahoe Ave., Boulder, CO 80303 (303) 443-5103



Sunpower Parabolic Concentrator, Series 400. Used on applications requiring temperatures to 400°F, the lightweight Series 400 collector has a polished aluminum surface, copper absorber tube, and dual axis tracking. The absorber housing insulation is a high-temperature silica fiber that will not outgas or physically decompose until 3200°F.

Features: flexibility in banking of collectors

Options: black chrome absorber and three different tracking options

Installation requirements/considerations: southern sloped roof (altitude or orbit tracking), flat roof (altitude or orbit), ground mount (orbit)

Concentration ratio: 40 to 1

Absorber material: copper absorber tube, black chrome absorber

Concentrating surface: reflectivity and longevity: polished aluminum, 80% new, 15 to 20 yr approximate

Performance-test data: Available from manufacturer

Pressure limitations: 150 psi

Operating temperature: 150 to 350°F

Design flow rate and pressure drop: variable depending on size of collector system and of performance characteristics

Recommended heat transfer fluid(s): ethylene glycol water, propylene glycol, or better

Tracking devices supplied: yes: sensor head model 3000P, completely digital logic analyzer model 3010

Guarantee/warranty: 5 yr limited warranty, 1 yr limited warranty on tracking device

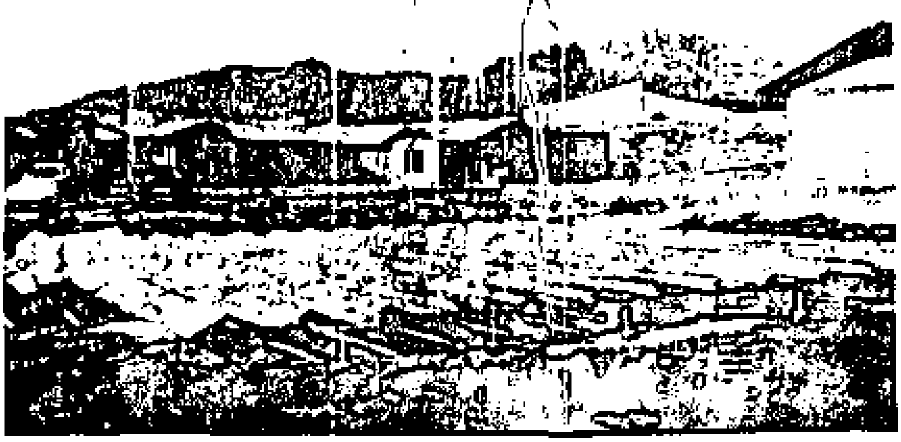
Maintenance requirements/considerations: none

Manufacturer's technical services: architectural, engineering, design consultation

Availability: 2 to 6 wk between order and delivery

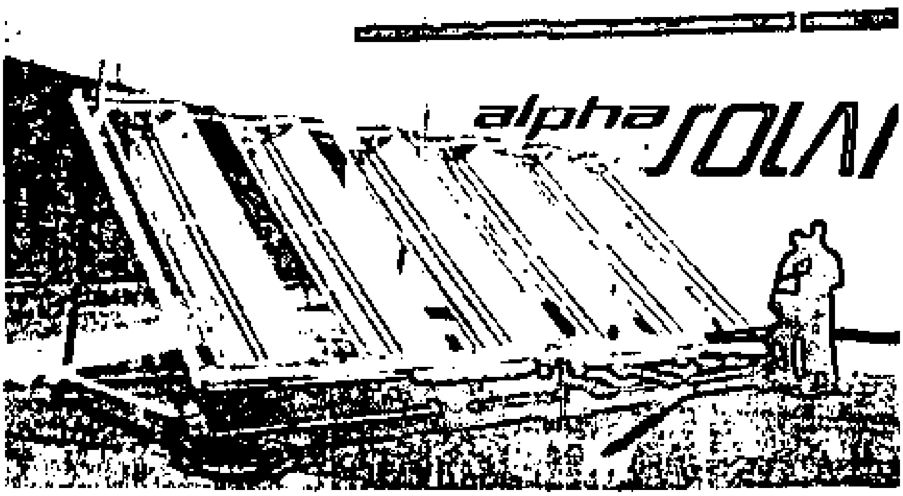
Suggested retail price: dependent on model number specifically requested

Contact: Dan Super, Sunpower Systems Corporation, 510 South 52nd St., Tempe, AZ 85281 (602) 894-2331.



Whiteline Concentrating Solar Collector. This parabolic trough has an anodized aluminum reflector, chemically-blackened copper pipe, and acrylic cover plate. Overall size is 16½ in. by 8¼ ft. Panels weigh approximately 22 lbs. each; frame(s) should be designed to support each panel.

Features: wash-out hole for cleaning in place
Options: glass cover plate
Installation requirements/considerations: panels to face south
Concentration ratio: not specified
Concentrating surface: reflectivity and longevity: 82% minimum, 20 to 30 yr. estimated
Performance test data: 1000 Btu/sq. ft. (clear day conditions); ASHRAE test has also been run
Pressure and temperature limitations: None within practical limit
Design flow rate and pressure drop: 0.24 ft. per panel at 10 gpm
Recommended heat transfer fluid(s): Water or water glycol
Tracking devices supplied: Tracking devices available at additional cost
Guarantee/warranty: 5-yr. limited warranty
Maintenance requirements: monthly focusing
Manufacturer's technical services: sizing and installation advice
Availability: 4 to 6 wk. between order and delivery
Suggested retail price: $14 sq. ft.
Contact: George T. Whee, Whiteline Inc., P.O. Box 4071, Asheville, NC 28802 (704) 258-8405



Solarco Sun Trek ATH. This concentrating collector has six parabolic-trough tracking mirrors in array and is designed for power, air conditioning, process heating, heat pumps, turbines, and high temperature applications. The mirrors are protected aluminum and plastics; the receiver is black chrome on steel. Overall mirror size is 10 square meters (107.6 sq. ft.), and each array is self-contained. The transfer fluid passes through the concentrators in a cascade manner. The array has automatic diurnal tracking and annual adjustment.

Features: automatic acquisition and tracking, specially shaped receiver, and high-temperature synthetic bearings
Options: receiver shapes, pumps, receiver materials, glazing, vacuum jackets, 2-axis tracking, photovoltaic-powered drive
Installation requirements/considerations: requires flat space, 21 by 10½ ft., to install each array. Welding or hard soldering might be required in installation
Concentration ratio: not specified
Absorber: material, surface, air area, mirror protected aluminum and plastics, receiver black chrome on steel, area ft. 14
Concentrating surface: reflectivity and longevity: reflectivity 87%, longevity, 5 to 10 yr. without maintenance
Performance test data: At 300 Btu/sq. ft./hr. = 192,000 Btu/day at 76% efficiency (56.3 kWh)
Pressure and temperature limitations: Pressure to 500 psi, temperature to +650°C (+1000°F)
Design pressure drop: 0.20 ft. of water at typical flow rates
Tracking devices supplied: Yes, including sensors and automatic return to east, acquisition and tracking
Guarantee/warranty: 90 days on parts, 5 yr. limited warranty
Maintenance requirements: periodic inspection of moving parts. In some climates, mirror material might have to be replaced after 5 to 10 years; consult manufacturer
Manufacturer's technical services: full installation instructions
Availability: 6 to 8 wk. between order and delivery
Suggested retail price: $4,995 for single unit, $3,950 for 2 to 10 units; $2,995 for more than 10 units
Contact: M. Uroshevich, Alpha Solarco, 1014 Vine St., Suite 2230, Cincinnati, OH 45202 (513) 621-1243

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energéticos
BOLETIN INFORMATIVO DEL SECTOR ENERGETICO
año 3 no. 2 febrero 1979

Panorama mundial de los hidrocarburos en 1978

1.— INTRODUCCION

Respecto de 1977, la situación mundial de los hidrocarburos manifestó, el año pasado, algunos cambios que resulta interesante destacar. Entre ellos, tal vez el más importante sea la revitalización de la demanda mundial, en virtud de la cual se produjo una notoria disminución de los excedentes de crudo que antes inundaban los mercados internacionales, aunque debe advertirse que el descenso de la producción en los países de la OPEP también contribuyó a disminuir los excedentes.

Los acontecimientos más relevantes que repercutieron en la industria y el comercio mundial de los hidrocarburos, fueron los siguientes:

En primer lugar, dentro de la OPEP, se llegó en el curso del año a conciliar las posiciones "duras" y "blandas" respecto del precio del crudo. El precio de US$12.70/barril, confirmado en la reunión de Caracas en diciembre de 1977, se mantuvo congelado durante todo el año 1978, a pesar de las polémicas internas suscitadas entre ambas posiciones, y de la inquietud por encontrar un mecanismo capaz de resguardar el precio frente a la devaluación del dólar. Finalmente en la 52 reunión de la OPEP, celebrada en diciembre último en Abu-Dhabi, se logró convenir en una solución intermedia, que descartando proposiciones como la "canasta de precios", sirviera empero para dar relativa protección a los intereses de los exportadores petroleros. El sistema adoptado consiste en aplicar durante 1979, alzas trimestrales sobre el precio anterior del crudo, hasta completar a fines de año un aumento total de 14.5%. De esta forma, se aplicó un alza de 5% sobre los US$12.70 el 1o. de enero último, resultando un precio de US$13.335/barril; el 1o. de abril próximo se aumentará un 3.809% sobre el precio del primer trimestre, quedando el barril de crudo en US$13.843; el 1o. de julio se elevará la cifra anterior en 2.294%, con lo que el precio del tercer trimestre será de US$14.161/barril; finalmente el 1o. de octubre, se subirá en 2.691%, resultando un precio de US$14.542 para el último trimestre del año.

El aumento de precios acordado en la Junta de Abu-Dhabi está íntimamente vinculado con la situación de Irán, cuya prolongación puede llegar a forzar los precios del crudo muy por arriba del alza decretada en diciembre. Por el contrario, la normalización de la producción iraní provocaría cambios inmediatos en el mercado internacional, que debilitarían drásticamente la facultad de la OPEP de aplicar los incrementos escalonados convenidos. Estas circunstancias permiten pensar en que será la evolución del problema iraní —y no los acuerdos de Abu-Dhabi— los que determinen en

INDICE

definitiva las condiciones del mercado mundial del crudo en 1979.

En caso de concretarse los cuatro aumentos trimestrales previstos por la OPEP, el promedio de estos cuatro precios sería de US$13.97/barril, lo que correspondería a un 10% de aumento por encima del precio de 1978. Para los países occidentales, este sería un precio mayor pero pagado en dólares de 1979. Esto significa, considerando un nivel constante de importaciones semejante al de 1978, que el costo del crudo será entre 0.2 y 0.5% del PNB de 1978 de los países occidentales. España e Italia serían los más vulnerables, en tanto que EU, la RFA y el Reino Unido, con niveles menores de dependencia, se verían menos afectados; Francia y Japón estarían en condiciones intermedias.

Los factores mencionados determinan que el impacto de los aumentos, a pesar de no ser iguales a los de 1973, no pueda ser menospreciado. Sin embargo, no debe sobrestimarse el efecto real de las alzas, puesto que tendrán que tomarse en cuenta las tasas de intercambio y las tendencias de los precios.

Tabla 1: EFECTOS DEL ALZA DEL CRUDO EN ALGUNOS PAISES

País	Monto pagado por importaciones de crudo en 1978 *	Costo adicional en 1979*	% de PNB en 1978
EU	38,50	3.85	0.2
Japón	28,10	2,81	0.3
RFA	13,60	1,36	0.2
Francia	11,80	1,48	0.3
Reino Unido	6,60	0,66	0.2
Italia	10,70	1,07	0.5
España	5,70	0,57	0.5

* US$miles de millones

Fuente: *Conjoncture* (Banco de París y de los Países Bajos), enero 1979.

En segundo término, hay que incluir los acontecimientos políticos de Irán, que han modificado, al parecer irreversiblemente, las circunstancias en que se inscribía la política petrolera iraní y la posición privilegiada que gozaba este país en el seno de la OPEP. A pesar de que aún no están cuantificadas las pérdidas reales experimentadas por la producción petrolera iraní, se han adelantado algunas cifras que pronostican que, desde fines de octubre hasta mediados de diciembre, la pérdida habría sido de 75%, y que el promedio de producción en ese período habría sido de 1.4 millones de b/d en circunstancias de que, entre enero y agosto de 1978, el promedio registrado fue de 5.6 millones de b/d /1. Por otra parte, se señala un promedio de 3.5 millones de b/d producido en noviembre, sin proporcionar el dato correspondiente a diciembre, pero anticipando una baja de 10% en todo 1978 respecto del año anterior /2. En el plano internacional, la fuerte reducción de las exportaciones iraníes no ha tenido, hasta ahora, un efecto dramático sobre los aprovisionamientos, gracias a los stocks constituidos en los países industrializados y a los aumentos de producción logrados por otros países del cartel. No obstante, la prolongación de la crisis política puede llegar a afectar peligrosamente los suministros mundiales y la propia economía de Irán, en donde los US$23,000 millones de ingresos petroleros representan más de 68% de los ingresos presupuestales del país y 90% del total de los ingresos en divisas.

El trastorno de la industria iraní ha podido neutralizarse hasta el momento, con los aportes de otros miembros de la OPEP, especialmente Arabia Saudita. Sin embargo, el potencial árabe que hasta hace poco se consideraba suficiente para duplicar la actual producción petrolera y superar los 20 millones de b/d después de 1980, ha planteado varias interrogantes en el curso de 1978. Múltiples declaraciones emanadas principalmente de organismos oficiales estadounidenses, cuestionan tanto el volumen exacto de las reservas probadas como las posibilidades técnicas reales de seguir aumentando la producción petrolera en Arabia. Así, mientras las reservas oficiales se estiman sobre los 165,700 millones de barriles, el Secretario de Energía de EU advierte que éstas no superarían los 100 mil millones. A su vez, la actual capacidad de producción oscila entre 8.8 millones de b/d y 11.5 millones /3. La incertidumbre respecto a las posibilidades de incrementar la capacidad de producción en el corto y mediano plazo queda en evidencia en un estudio del Departamento de Energía de EU, que alude a serios "problemas técnicos" y al error de considerar que la capacidad de producción petrolera de Arabia Saudita puede aumentar ilimitadamente. Estas dudas impiden pensar en Arabia Saudita como la panacea que aliviaría, en 1979, los efectos de una prolongación de la crisis iraní.

Recientemente, el Ministro de Comercio Internacional e Industria de Arabia Saudita ha declarado que elevará su límite de producción nor-

/1 *Afrique-Asie:* 11 al 24 de diciembre de 1978.

/2 *Petroleum Economist*, enero de 1979.

/3 *Afrique-Asie:* "Arabia Saudita: el potencial petrolero real"; 18 al 30 de septiembre de 1978, citando a *Washington Post*.

mal de 7 millones de b/d a 9.5 millones de b/d, para afrontar los efectos de la situación iraní. Estas declaraciones afirman, además, que el alza al precio del crudo de 14.5% acordado por la OPEP, se aplicará sobre los 2.5 millones de b/d que produzcan por encima del límite normal.

En todo caso, las consecuencias de la crisis iraní han comenzado a sentirse en el contexto internacional. Se estima que los problemas de aprovisionamiento suscitados son comparables a los de 1973-1974, y varias trasnacionales petroleras han optado por reducir sus entregas de crudo durante algún tiempo. Así, la Royal Dutch Shell disminuirá en 15% sus suministros a partir de fines de febrero, en tanto que la British Petroleum se propone restringirlas hasta en 45% en los tres primeros meses del presente año. A su vez, la empresa norteamericana Exxon decidió reducciones de 10%, al igual que la Texaco. La Standard Oil de California y la Gulf Oil Corporation anunciaron a sus clientes extranjeros, que tendrán dificultades para cumplir con el 20% de sus encargos de crudo del Medio Oriente en el primer trimestre del año 74.

Además de los incrementos logrados por algunos países de la OPEP, que parcial y temporalmente han podido compensar las críticas reducciones de Irán, debe tenerse en cuenta el aporte de las nuevas regiones petroleras incorporadas al mercado mundial: Alaska, México y el Mar del Norte, cuya oferta, en 1978, se estima, habría sido de 3 millones de b/d. Estos nuevos suministros habrían pesado significativamente sobre el incremento de 9.2% (1.38 millones de b/d) registrado por la producción del hemisferio occidental.

II.— PETROLEO

1.—*Reservas*

En el curso de 1978, las reservas mundiales de crudo descendieron a 641,600 millones de barriles, lo que implica un decremento de 0.5% respecto del año anterior, ocasionado básicamente por tres factores: la producción masiva de crudo, los escasos descubrimientos importantes y los débiles resultados obtenidos en el desarrollo de los campos petroleros de ciertos países.

En general, se observan decrementos en las reservas de hidrocarburos en todas las regiones, con excepción de Medio Oriente y de algunas áreas nuevas, entre las cuales destaca México 75.

74. *Excelsior*, México, D.F., 5 de febrero de 1979, citando a *Financial Times*.

75. Véase "Reservas mundiales de petróleo crudo y gas natural".
Boletín *Energéticos*, Año 3, No. 1, pag. 22-23, enero de 1979.

Las reservas totales en el continente americano, estimadas en 75,750 millones de barriles en 1978, se mantuvieron prácticamente iguales a las del año anterior, de 75,870 millones de barriles. Por su parte, las de Europa descendieron en casi 300 millones de barriles, quedando en 23,970 millones de barriles; marcaron la pauta de la declinación los países petroleros del Mar del Norte, con excepción de Dinamarca, que incrementó levemente sus reservas. Para EU, las estimaciones situaron las reservas de crudo en 28,500 millones de barriles, nivel que implica una reducción de 1,000 millones. En el resto de América destacaron Canadá, que gracias a sus descubrimientos de West Pembina, llegó a 6,000 millones de barriles; México, que al 31 de diciembre de 1978 anunció 40,194 millones de barriles de reservas probadas, esto es, cerca del doble de las estimadas a principios del mismo año, y Argentina y Brasil, que obtuvieron incrementos relativos.

La única región que obtuvo grandes aumentos fue Medio Oriente, cuyas reservas totales alcanzaron 369,900 millones de barriles, cifra que supera aproximadamente en 4,000 millones las estimaciones de 1977. El aumento provino fundamentalmente de Arabia Saudita, que reportó un incremento de 15,700 millones de barriles alcanzando así 165,700 millones. Este aumento fue contrarrestado por la declinación de las reservas de Irán, Irak y Omán.

En Asia-Pacífico, los logros de Australia y Malasia compensaron ligeramente las modestas declinaciones de otros países; las reservas ascendieron a 20,000 millones de barriles. A su vez, las reservas de Africa registraron una disminución de 1,300 millones de barriles, para situarse en 57,900 millones; siendo la excepción las reservas egipcias, las que el último año se incrementaron en cerca de 750 millones de barriles.

Tabla 2: RESERVAS DE CRUDO Y GAS NATURAL

Región	Variación porcentual 1978/1977
Asia Pacífico	— 0.7
Europa	— 3.4
Medio Oriente	1.2
Africa	— 5.5
América	— 0.02
Países socialistas	— 2.1
Total Mundial:	— 0.7

Fuente: *Oil and Gas Journal*, 25 de diciembre de 1978.

En síntesis, la declinación total de las reservas petroleras en el área no socialista alcanzó a 0,044%, quedando en 547,000 millones de barriles. Por su parte, en el área socialista, el descenso de las reservas de crudo fue de 5%: por sí sola, la URSS experimentó un decremento de 4,000 millones de barriles con lo que las reservas del área disminuyeron a 94,000 millones de barriles.

2. *Producción*

La producción mundial de aceite crudo y de líquidos del gas natural sumó aproximadamente 58.6 millones de barriles diarios en 1978, aumentando 0.2% respecto de la registrada el año anterior. La mayor participación de los nuevos productores recientemente incorporados al mercado internacional —EU (Alaska), México y el Mar del Norte— fue uno de los factores que indujo a disminuir la producción de casi todos los miembros de la OPEP, con excepción de Kuwait, Katar, Dubai y Argelia. Hay que recordar, en este punto, las interrupciones que en los dos últimos meses del año sufriera la industria petrolera iraní, cuyas consecuencias aún no han sido debidamente cuantificadas, como se mencionó con anterioridad. Por el contrario, en el área socialista la URSS y China incrementaron cerca de 4.5% su producción.

Sin duda, lo más sobresaliente en el panorama productivo mundial de 1978 fue el descenso cercano al 6% de la producción de la OPEP, que totalizó solamente 28 millones de b/d. Este volumen representa cerca del 48% de la producción mundial y el 62% de la correspondiente al área no socialista (cabe comparar dichos porcentajes con los registrados antes del embargo petrolero 1973-74, de 54 y 65%, respectivamente). La situación de la OPEP en el curso del año pasado, reflejó la fuerte competencia que debió enfrentar el cartel ante el ingreso de nuevos productores al mercado mundial, como Alaska, México, el Mar del Norte y otros. Por otra parte, las áreas no socialistas ajenas a la OPEP elevaron su producción total de crudo a 17 millones de b/d, completando 29% del total mundial, mientras China, la URSS y los países de Europa oriental, con 14.4 millones de b/d, produjeron el 23% del volumen global.

Regionalmente, la situación de la industria extractiva de crudo en 1978 fue la siguiente 76:

América del Norte y Sudamérica

En EU, la producción de aceite crudo y líquidos del gas natural se elevó en cerca de 6%, alcanzando un nivel estimado de 8.6 millones de b/d. Esta inversión de la tendencia declinante, ya histórica en el país, se debió exclusivamente a los campos de North Slope en Alaska, cuya producción llenó la capacidad total del oleoducto de 1.2 millones de b/d, desde fines del primer semestre. En el tercer trimestre del año pasado, el crudo extraído de Alaska promedió más de 1.3 millones de b/d, duplicando casi la producción de 1977.

Por su parte, la producción de Canadá decayó 3% en 1978, promediando 1.4 millones de b/d. No obstante, el leve crecimiento de la demanda doméstica de las refinerías pudo ser satisfecho gracias a los continuos recortes impuestos a las exportaciones hacia EU, que se redujeron en cerca de 70,000 b/d respecto del año anterior.

Respecto del panorama latinoamericano, lo más destacado fue la caída de la producción venezolana, que en la primera mitad de 1978 se contrajo en 9.5%, y mostró una ligera recuperación en el segundo semestre, con lo cual la disminución media en el año fue de 7%. Estimativamente, la producción promedió 2.1 millones de b/d y su bajo nivel habría obedecido a la debilidad de la demanda. Otro acontecimiento destacado en el área fue el incremento de 19.3% de la producción mexicana, cuyo promedio superó 1.2 millones de b/d, frente a 1.08 millones de b/d registrado en 1977. Por su lado, Perú logró duplicar la producción nacional, alcanzando cerca de 152,000 b/d, gracias a la iniciación de operaciones del nuevo eslabón del oleoducto central, que abrió las posibilidades de explotación en el interior del país.

Medio Oriente

Arabia Saudita, tercer productor mundial de crudo y primer exportador, redujo 15% sus niveles productivos en los 10 primeros meses de 1978. Sin embargo, en el último bimestre del mismo año y a raíz de la crisis iraní, la situación se revirtió, incrementándose la producción saudita en 2 millones de b/d, hasta promediar 10 millones de b/d. El promedio anual para 1978 fue de 8.3 millones de b/d, es decir, 10% menos que en 1977.

En Irán, debido a las circunstancias ya reseñadas, se estima tentativamente que, en 1978, la producción promedio habría sido de 5.2 millones de b/d, cifra 10% inferior a la de 1977. Como contrapartida a esta situación, se incrementaron las exportaciones del área, en Kuwait, Irak, los Emiratos Arabes Unidos (EAU) y principalmente en Arabia Saudita.

Africa

El principal productor africano de petróleo,

76 Petroleum Economist, enero 1979.

Tabla 3: PRINCIPALES PRODUCTORES DE CRUDO EN 1978
(miles de barriles por día)

Lugar	País	1977	1978	Cambio Porcentual 1978/1977	Por ciento del Total Mundial en 1978
1	URSS	11,070	11,518	4.00	18.21
2	EU 1/	8,240	8,660	5.10	13.69
3	Arabia Saudita	9,257	8,279	—10.56	13.09
4	Irán	5,699	5,149	—9.65	8.14
5	Irak	2,298	2,348	2.00	3.71
6	Kuwait	1,978	2,189	10.65	3.46
7	China	1,880	2,100	11.70	3.32
8	Venezuela	2,238	2,072	— 7.38	3.28
9	Libia	2,070	1,976	— 4.56	3.12
10	Nigeria	2,090	1,916	— 8.34	3.03
11	EAU	1,860	1,710	— 8.06	2.70
12	Indonesia	1,676	1,640	— 2.15	2.59
13	Abu Dhabi	1,638	1,437	—12.28	2.27
14	Canadá	1,450	1,404	— 3.20	2.22
15	Argelia	1,154	1,247	8.01	1.97
16	México	1,027	1,226	19.32	1.94
17	Reino Unido	758	1,070	41.25	1.69
18	Katar	444	496	11.80	0.78
19	Australia	436	473	8.48	0.70
20	Noruega	274	355	29.40	0.60
21	Dubai	319	360	12.76	0.57
22	Omán	338	320	— 5.20	0.51
23	Rumania	293	296	1.02	0.47
24	Trinidad	227	230	1.33	0.40
25	India	201	221	9.88	0.35
26	Malasia	183	217	18.60	0.34
27	Gabon	223	218	— 2.00	0.34
28	Siria	213	210	— 1.24	0.33
29	Brunei	206	210	1.88	0.33
30	Brasil	161	160	— 0.63	0.30
31	Ecuador	175	190	8.67	0.30
32	Angola	171	188	9.96	0.30
33	Colombia	138	130	— 5.45	0.20
34	Perú	79	152	92.89	0.20
35	Alemania Occidental	108	104	— 3.90	0.16
36	Túnez	85	93	9.10	0.15
37	Yugoslavia	79	82	3.80	0.13
38	Bahrain	56	54	— 3.12	0.09
39	Egipto	39	52	30.74	0.08
40	Turquía	54	50	— 6.85	0.08
41	Argentina	436	460	5.64	0.07
42	Hungría	438	43	— 1.83	0.07
43	Albania	38	40	5.26	0.06
44	Congo	36	38	4.45	0.06
45	Austria	36	35	— 1.62	0.06
46	Antillas Nerlandesas	32	29	— 9.10	0.05
47	Sharjah	27	24	—10.96	0.04
48	Italia	22	28	24.77	0.04
49	Zaire	23	25	11.01	0.04
50	Burma	26	28	7.70	0.04
51	Bolivia	32	28	—11.84	0.04
52	Francia	21	22	6.07	0.03
53	España	24	17	—30.56	0.03
54	Chile	19	18	— 7.40	0.03
55	Japón	12	11	— 5.40	0.02

Cabe señalar que estas cifras son preliminares.
Los datos para la mayor parte de los países incluyen crudo, condensado y líquidos del gas natural; y se expresan en toneladas, para convertirlos a barriles por día, se aplicaron los factores de conversión utilizados por la OECD.

1/ Dato tomado de *Oil and Gas Journal*, diciembre 25 de 1978. *Fuente:* Petroleum Economist; enero de 1979

Nigeria, se vió sometido a severas reducciones durante el primer semestre de 1978, debido a la creciente competencia de crudos con características similares al nigeriano: el del Mar del Norte, en los mercados europeos, y el de Alaska y México, en EU. En la primera mitad del año en cuestión se registró un decremento de 25% respecto del mismo periodo de 1977; durante los primeros nueve meses de 1978 se mantuvo un descenso de 17%, con un promedio de producción de 1.8 millones de b/d. Esta tendencia se modificó hacia fines de año, respondiendo a la restricción que experimentaron los suministros de crudo en Africa del Norte y Medio Oriente. En total, el promedio de producción durante 1978 se estima que habría sido de 1.9 millones de b/d.

Europa occidental

Reflejando los grandes logros obtenidos en el Mar del Norte, la producción de crudo de Europa occidental se elevó en un 29% estimativo, de acuerdo con lo cual habría alcanzado un promedio de 1.7 millones de b/d. A pesar de lo anterior, a principios de diciembre último, el Departamento de Energía del Reino Unido redujo su pronóstico inicial de producción de crudo, disminuyéndolo de 1.07 millones de b/d a 1.02 millones de b/d en promedio. Resulta de interés señalar que la meta de autosuficiencia se sitúa entre 1.5 y 1.7 millones de b/d para 1979 y entre 1.7 y 2.1 para 1980.

Otro de los países productores de crudo de la región, Noruega, obtuvo considerables incrementos, elevando su producción de 270,000 b/d en 1977, a 355,000 el año siguiente.

Europa oriental

Dentro del área socialista de Europa, la URSS es el único país con una industria petrolera relevante, encabezando la jerarquía mundial de los productores de crudo. En 1978 conservó el primer lugar, incrementando su producción en más de 4%, aproximándose a 11.5 millones de b/d.

Lejano Oriente

A partir de 1975 sobresale en la región la república Popular de China como el productor más importante. Aparentemente, en 1978 el país incrementó en cerca de 12% su producción, logrando 2.1 millones de b/d, nivel que le acerca a las proyecciones que señalan entre 3.8 y 5.7 millones de b/d en la próxima década.

Indonesia, segundo productor regional, disminuyó 2% sus niveles de 1977, descendiendo a 1.6 millones de b/d en 1978.

III.— GAS NATURAL

1.— Reservas

Por primera vez, desde 1975, se observó el año pasado una declinación de las reservas mundiales de gas natural. Este decremento se atribuye a los altos y acelerados niveles de producción, así como a la escasez de los nuevos descubrimientos en el mundo. La disminución de las reservas fue del orden de 17.6 billones de pies^3 (algo más del 0.7% del total mundial), con lo que el volumen global se situaría en 2,502 billones de pies^3.

Desde la perspectiva regional, la situación observada en 1978 fue desigual. Como en el caso del petróleo, también respecto del gas natural fue Medio Oriente el área que registró un mayor crecimiento de las reservas —aproximadamente 12 billones de pies^3— hasta totalizar 730.7 billones. Los países que lograron mayores aumentos fueron Arabia Saudita y Bahrain.

En Europa occidental se logró un incremento de 5 billones de pies^3, con lo cual alcanzó un total de 143.3 billones. Estos aumentos se debieron fundamentalmente a los descubrimientos de Noruega, los Países Bajos, Dinamarca y Francia. Para el continente americano, los incrementos representaron una ligera alza de sus reservas de gas natural, las que se acercan a los 380 billones de pies^3.

Otras regiones experimentaron, en cambio, ciertos decrementos. Así, Asia-Pacífico disminuyó en 5 billones de pies^3 sus reservas de gas natural, las que a fines de 1978 representaban 119.85 billones de pies^3. De manera similar, Africa experimentó decrementos que totalizan 21 billones de pies^3, quedando con un nivel de 186.3 billones de pies^3. A su vez, los países socialistas registraron una reducción de 10 billones de pies^3, con lo que su volumen de reservas quedó en 945 billones de pies^3.

En el contexto anterior y dentro de Asia-Pacífico, fueron Australia y Brunei los países más afectados por los decrementos, los que totalizaron 1 billón y 250,000 millones de pies^3, respectivamente. En el continente africano, la declinación recayó principalmente en Argelia que sometió sus anteriores estimaciones a una revisión profunda, mediante la cual se obtuvo la cifra de 105 billones de pies^3 como reservas totales de gas natural del país. Por último, en el sector socialista, la URSS sobrellevó las mayores pérdidas.

2.— Producción

Resulta difícil determinar las fluctuaciones experimentadas por la industria productora de gas

Tabla 4: PRINCIPALES PRODUCTORES COMERCIALES DE GAS NATURAL EN EL MUNDO*

(Miles de millones de pies^3 diarios)

Lugar	País	31 de diciembre de 1976	31 de diciembre de 1977	Variación porcentual entre 1976 y 1977
1	EU	54.65	54.85	0.36
2	URSS	31.05	33.47	7.8
3	Países Bajos	9.28	9.11	— 1.84
4	Canadá	8.40	8.67	2.5
5	Rumania	2.88	2.69	— .6
6	RFA	1.82	1.85	1.6
7	México	1.66	1.70	2.4
8	Irán	1.70	1.70	0.0
9	Italia	1.43	1.33	— 7.0
10	Venezuela	1.19	1.32	10.9
11	Argelia	0.82	0.90	9.75
12	Brunei	0.75	0.85	13.33
13	RDA	0.80	0.82	2.5
14	Francia	0.68	0.74	8.82
15	Argentina	0.72	0.73	1.38
16	Hungría	0.58	0.64	10.34
17	Polonia	0.57	0.58	1.75
18	Kowait	0.53	0.57	7.54
19	Pakistán	0.50	0.56	12.0
20	Australia	0.48	0.54	12.5

* No se incluye el gas natural inyectado ni el quemado en la atmósfera.

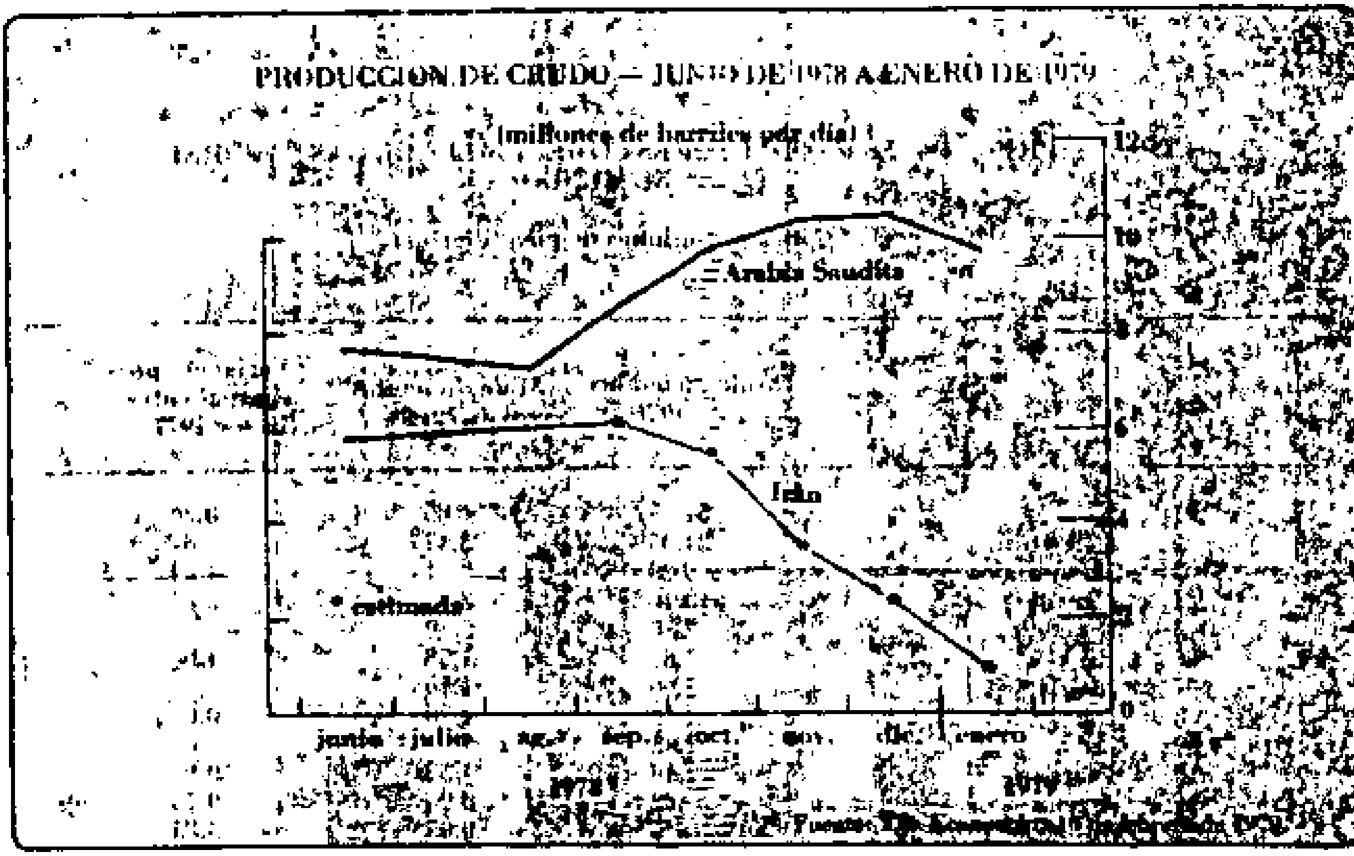
Fuente: *Petroleum Economist*, septiembre de 1978.

natural en 1978, debido a la falta de información o al bajo nivel de sistematización que caracteriza a la información del sector. Sin embargo, pueden señalarse algunos resultados y acontecimientos observados en el curso de 1978.

En Europa occidental se abrieron nuevas perspectivas para producir gas natural fuera del ámbito del Mar del Norte. Ejemplo de ello es el potencial del Mar Céltico, frente a las costas de Irlanda, en donde la Marathon Oil ha reportado el hallazgo de un campo que actualmente se encuentra en producción y del cual se espera obtener 125 millones de pies^3 diarios en 1979. Sin perjuicio de estos descubrimientos, los campos noruegos ya conocidos de Ekofisk y Tor, en el Mar del Norte, elevaron el año pasado su producción hasta llegar al tope máximo de 1,000 millones de pies^3 día.

También en el Mar del Norte, el área marítima perteneciente a los Países Bajos hizo aportes considerables, con el ingreso a la producción de 7 de los 22 campos últimamente descubiertos. Se supone que la producción costafuera compensará la rápida disminución de las reservas del gigantesco campo terrestre de Groningen. En la actualidad, la producción holandesa costafuera es de 500 millones de pies^3 diarios y se espera incrementarla a 950 millones en 1979, para alcanzar 1,400 millones de pies^3 diarios en 1982.

Respecto de otras regiones, destaca en Africa la producción argelina, de gran importancia comercial. En efecto, Argelia es el principal proveedor de gas natural licuado a EU y a varios países europeos, y está empeñada en desarrollar los suministros de gas para alimentar al máximo el



gran complejo de licuefacción de Arzew, destinado a producir GNL para la exportación. Por lo demás, durante 1978 se siguió avanzando en la construcción del ducto submarino transmediterráneo, destinado a transportar gas natural desde los campos argelinos hacia las costas de Italia.

Fuentes:

I.- Introducción: *Petroleum and Economic Digest*, 12 de septiembre de 1978; *Afrique-Asie*, 18 al 30 de septiembre y 21 al 24 de diciembre de 1978; *Petroleum Economist*, enero de 1979; *Conjoncture*, enero de 1979 y *Excelsior*, México, D.F., 5 de febrero de 1979.

II.- Petróleo: *Petroleum and Economic Digest*, 12 de septiembre y 1º. de octubre de 1978; *Oil and Gas Journal*, 25 de diciembre de 1978 y *Petroleum Economist*, enero de 1979.

III.- Gas Natural: *Oil and Gas Journal*, 25 de diciembre de 1978 y *Petroleum Economist*, septiembre de 1978.

NUEVA LEY NUCLEAR

El pasado 26 de enero apareció en el Diario Oficial de la Federación la nueva Ley Reglamentaria del Artículo 27 Constitucional en Materia Nuclear.

Como es del dominio público, esta ley es el resultado de una iniciativa presidencial enviada al Congreso de la Unión en diciembre de 1977, la cual fue ampliamente discutida en las dos Cámaras del Congreso así como en audiencias públicas realizadas, durante varios meses de 1978, por la Cámara de Diputados.

La ley da vida a la Comisión Nacional de Energía Atómica (CNEA), a dos organismos públicos descentralizados del Gobierno Federal: Uranio Mexicano (URAMEX) e Instituto Nacional de Investigaciones Nucleares (ININ), así como a un órgano desconcentrado de la Secretaría de Patrimonio y Fomento Industrial que se denomina Comisión Nacional de Seguridad Nuclear y Salvaguardias (CNSNS).

Esta Ley abroga la Ley Orgánica del Instituto Nacional de Energía Nuclear, del 30 de diciembre de 1971, por lo cual el INEN deja de existir, siendo la CNEA la encargada de distribuir el patrimonio, los derechos y obligaciones de aquél entre los organismos creados por la nueva Ley.

Fuente: ININ, febrero de 1979.

COMERCIO INTERNACIONAL DEL GAS NATURAL

En EU, la participación del gas natural en la satisfacción de sus necesidades energéticas se duplicó de 1946 a 1966; en Europa, después de los descubrimientos de gas en Groningen y en el Mar del Norte, el impacto ha sido más sensible. Al desarrollarse técnicas de licuefacción de gas, se facilitó el comercio internacional de éste y a partir de 1964, se inició un fuerte intercambio principalmente entre Alaska y Japón.

Como se puede observar en el cuadro anterior, hay una gran disparidad tanto en los niveles de penetración del gas en la economía como en las tasas de crecimiento, dentro de las principales áreas consumidoras. Así, en EU, los controles sobre el precio del gas, que lo mantuvieron bajo, provocaron una distorsión en el nivel de penetración, ya que elevados volúmenes de gas se queman en las calderas industriales. La reducción progresiva en las reservas internas revertirá posiblemente esta situación y agudizará el problema de suministro en las áreas prioritarias (doméstico y residencial) a partir de 1985.

Del consumo realizado en 1974 en las tres áreas consignadas, 700 MTCE, el 87% se produjo internamente, y sólo el 13%, o sea 93 MTCE se movieron en el comercio internacional. De estos 93 MTCE, unos 81 MTCE o sea 87% representan transferencias interregionales (por ejemplo de Holanda a Francia), y sólo 12 MTCE se movieron fuera de la región de consumo.

PARTICIPACION DE GAS NATURAL EN EL BALANCE ENERGETICO PRIMARIO REGIONAL

	1956 MTCE	%	1966 MTCE	%	1976 MTCE	%
EU	249.3	26.8	463.8	32.7	516.4	28.4
Europa Occidental	5.5	1.0	23.1	2.6	167.3	13.3
Japón	1.21	0.4	1.9	1.1	10.9	3.1

MTCE = millones de toneladas de crudo equivalente.

BALANCE OFERTA/DEMANDA, 1980-2000 PROYECCIONES REGIONALES (MTCE)

	1980	1985	1990	2000
EU				
Demanda	434	528	561	754
Oferta	391	444	465	562
Importaciones	43	84	96	192
Europa Occidental				
Demanda	225	272	310	417
Oferta	191	197	180	132
Importaciones	34	77	130	185
Japón				
Demanda	28	55	93	125
Oferta	—	—	—	—
Importaciones	28	55	93	125

En el cuadro anterior se observa que tanto Europa como EU se enfrentarán a una situación crítica si se mantiene la importancia que se ha dado hasta ahora al gas natural. Japón, en ausencia de reservas domésticas significativas, continuará dependiendo de las importaciones.

Para 1985 el volúmen de gas comercializado internacionalmente deberá elevarse a 262 MTCE y el comercio interregional entre 160 y 177 MTCE.

La posición de la OPEP dentro de las existencias mundiales de gas natural no es tan importante como en el caso del petróleo, sin embargo se estima que cuenta con reservas mayores, ya que la mayoría de este gas ha sido descubierto accidentalmente.

Si se quiere desarrollar el comercio internacional del gas natural satisfactoriamente, es importante destacar las diferencias entre la comercialización de crudo y la de gas como serían:

a) El grado de dependencia entre el vendedor y el comprador.
b) La competitividad técnica de los procesos especialmente en relación con el GNL (gas natural licuado). La infraestructura requerida, tanto económica como social es bastante mayor para el gas que para el crudo.
c) El elevado costo de estos proyectos, y la necesidad de pasar parte de éste al comprador o directamente al consumidor.
d) El tiempo requerido para la construcción de las instalaciones y la necesidad de planearlas con antelación.

Chemical Economy and Engineering Review, octubre, 1978, pp. 7-9.

RESERVAS PROBADAS Y POSIBLES DE GAS NATURAL

(10^9 BCE)

	OPEP	NO OPEP
Probadas	140 (36%)	249 (64%)
Posibles	270 (20%)	1,130 (80%)
TOTAL:	410 (23%)	1,379 (67%)

BCE = barriles de crudo equivalente.

ESTADO ACTUAL DE LOS COMBUSTIBLES IRRADIADOS

Según la información proporcionada por los países participantes en el INFCE (Evaluación Internacional del Ciclo de Combustible Nuclear), en el llamado "mundo occidental" había almacenadas a finales de 1977 unas 6,500 ton de metal pesado (U + Pu) en forma de elementos combustibles irradiados. Casi 4,000 ton provinieron de reactores de agua ligera, otras 2,480 ton de reactores de agua pesada (Canadá e India) y el resto de reactores enfriados por gas.

Los ritmos de "producción" de combustibles irradiados se estiman de la siguiente manera: 2,700 ton/año entre 1978 y 1980; 6,600 ton/año entre 1981 y 1985; 12,000 ton/año en el periodo 1986-90.

Por su parte, la OCED (Organización para la Cooperación Económica y el Desarrollo) es más conservadora en sus cálculos, estimando que en el periodo 1978-80 el ritmo de producción será de 2,700 ton/año, en el lapso 1981-85 será de 4,700 ton/año y en el de 1986-90 entre 8,500 y 10,700 ton/año.

La tabla adjunta resume la situación actual y futura, por países, que hasta ahora ha manejado el INFCE. Como medida de comparación se dan en la parte inferior las cifras estimadas por la OCED. Las diferencias entre las cantidades "producidas" y las "almacenadas" corresponden a las que habrán sido reprocesadas.

Se añade también la capacidad de diseño de las plantas de reprocesamiento de algunos países.

De las cifras contenidas en la tabla puede destacarse lo siguiente:

— De las 48,000 ton producidas hasta 1985, 10,950 provendrán de reactores de agua pesada (Canadá, India y Argentina) y de las 108,000 estimadas para 1990, 23,148 corresponderán a reactores HWR (Canadá, India, Argentina y Rumania). Aunque las cifras referentes a combustibles irradiados en reactores de uranio natural son muy altas, con relación a la capacidad total de los reactores que los producen, debe tomarse en cuenta que su almacenamiento y reprocesamiento presentan menores problemas que los combustibles irradiados en reactores de uranio enriquecido.

— Algunos países están interesados en el reprocesamiento comercial de combustible irradiado y la tabla muestra la capacidad de diseño proyectada para 1985 y 1990. Se estima que ésta sería, en total, superior a 2,200 ton en 1985 y a 7,800 en 1990, según el INFCE.

— De lo anterior se desprende que, los países productores de nucleoelectricidad habrán de hacer frente en los próximos años a una gran demanda de almacenamiento de combustible irradiado, pues sus planes de reprocesamiento son aún conservadores.

COMBUSTIBLE IRRADIADO EN EL MUNDO OCCIDENTAL

Ton de metal pesado (U + Pu)

Cantidad producida		Cantidad producida acumulada a fin de:		Cantidad almacenada a fin de:			Capacidad de reprocesamiento ton/año	
País	1980	1985	1990	1977	1985	1990	1985	1990
Alemania	n.d.	3,200	7,200	280	n.d.	n.d.	35	1,435
Bélgica	n.d.	700	1,566	64	510	849	300	100
España	n.d.	955	2,030	155	915	2,590	0	4
Francia	n.d.	2,900	8,100	?	500	1,000	1,600	2,400
Italia	n.d.	430	2,607	40	430	2,607	0	1,000
Reino Unido	n.d.	1,000	2,300	50	1,050	1,250	0	1,200
Suecia	n.d.	1,150	2,030	50	1,050	2,020	0	0
Suiza	n.d.	702	1,389	91	273	710	0	0
Otros Europeos	n.d.	548	1,320	55	357	507	0	0
Argentina	n.d.	600	1,200	n.d.	n.d.	n.d.	?	?
Canadá	n.d.	9,300	18,900	2,300	9,300	18,900	0	0
EU	n.d.	22,200	46,700	3,000	22,200	46,700	0	0
India	n.d.	1,050	2,400	120	150	1,300	100	200
Japón	n.d.	3,900	8,500	300	1,500	2,700	210	1,500
México	n.d.	100	300	0	100	300	0	0
Otros	n.d.	134	1,180	n.d.	47	955	0	0
Total INFCE	n.d.	48,869	108,322	6,571	38,388	82,388	2,045	7,839
Informe OCED	10,400	37,000	80,000	6,200	n.d.	n.d.	1,500	6,000

n.d. = no disponible

Fuente: ININ noviembre de 1978.

PERFIL ENERGETICO DE FRANCIA

Francia, al igual que sus vecinos europeos, sufre de un permanente déficit en su capacidad de generar, con sus propias fuentes, la energía necesaria para el consumo interno del país. La dependencia de las importaciones hacen al país sumamente vulnerable a cualquier interrupción o disminución de los suministros.

Para asegurar al máximo el abastecimiento continuo, la política exterior francesa ha adoptado una línea de apoyo a las posiciones de los países árabes proveedores de crudo, que se ha traducido en acuerdos de asistencia técnica, financiera y militar, así como en operaciones conjuntas. Esta actitud resulta muy comprensible, teniendo en cuenta que del total de las importaciones de crudo (aproximadamente 2.5 millones de b/d), el 80% proviene del Medio Oriente. Arabia Saudita sola abastece el 35%, es decir, alrededor de 870,000 b/d; otros 300,000 b/d provienen de Irak, 260,000 de Irán y volúmenes menores de Argelia, Nigeria, Gabón y Siria.

La actual política de Francia se propone disminuir su dependencia de petróleo árabe, diversificando los orígenes de sus abastecimientos (razón por la cual ve con particular interés el petróleo mexicano), promoviendo medidas para la conservación de la energía y aumentando la explotación de otras fuentes internas, como la nuclear, la hidráulica y nuevas formas de energía.

Reservas

Las reservas energéticas en territorio francés son sumamente reducidas; en consecuencia la producción nacional apenas excede el 20% de los requerimientos. Tomando en consideración datos de 1976, las reservas de recursos energéticos fósiles se constituyen como sigue:

FRANCIA: VIDA DE RECURSOS ENERGETICOS FOSILES

Mtpe	Reservas probadas (a)	Consumo (b)	Año a/b
Carbón	300	32	9
Gas natural	132	19	7
Petróleo	0	109	0
Total fósiles:	441	160	2.8

Fuente: CEA (Commissariat a l'energie atomique): *Notes d'information*: Programme nucléaire français et coopération internationale", por André Giraud; abril de 1978.

En 1976, el consumo total de energía en Francia fue de 175 Mtpe, en tanto que la producción nacional no superó los 40 Mtpe, de los cuales 18 correspondieron al carbón, 1.5 al petróleo, 6.5 a gas, 11 a energía hidráulica y 3 a energía nuclear. En consecuencia, Francia dependía ese año en 77% de los recursos energéticos importados (en 1955 sólo lo era en 36%). Debe señalarse que las posibilidades de aumentar la producción hidráulica no superan los 5 Mtpe, ya que los recursos que se explotan actualmente representan entre 80 y 85% de la disponibilidad total. Respecto del gas natural, las importaciones se elevaron aproximadamente en 14%, alcanzando un volumen de 1,700 millones de pies3 en 1977, provenientes en su mayor parte, de Holanda y, en menor medida, de Argelia, la URSS y el Mar del Norte.

Energía nuclear

Dentro de la política energética de Francia, la energía nuclear ocupa un papel preponderante, como opción para disminuir la dependencia del petróleo y lograr una producción energética interna que permita acercarse a la autosuficiencia, para así reducir la vulnerabilidad de los suministros y los desequilibrios en la balanza de pagos (las compras de petróleo representan más del 3% del PIB).

Francia dispone en su territorio metropolitano de reservas de uranio evaluadas en 100,000 toneladas, cantidad que consumida en reactores de agua ligera representa 800 Mtpe, es decir, el equivalente a una tercera parte del petróleo del Mar del Norte; pero este uranio utilizado en reactores de cría, podría suministrar 50,000 Mtpe, lo que equivale en energía a todo el petróleo del Medio Oriente.

Después de la crisis de octubre de 1973, el gobierno decidió acelerar el programa nuclear y proyectó, para la década de los ochentas, la construcción de 5,000 MWe, o sea, un mínimo de 5 reactores anuales. Este objetivo se concibió combinado con una perspectiva a largo plazo, para evitar cualquier escasez de uranio. La estrategia se definió previendo la utilización de los reactores de cría, tan pronto como lo permita el programa de desarrollo iniciado hace 15 años, cuyo resultado es el reactor Phenix, (el modelo piloto tiene una capacidad de 250 MW), que ha operado satisfactoriamente. En 1977 se iniciaron los trabajos del Super Phenix, prototipo de 1,200 MW, proponiéndose simultáneamente los trabajos de proyecto para reactores comerciales, cuya puesta en funcionamiento se prevé a partir de 1990.

Tabla 1: PRODUCCION DE PETROLEO EN FRANCIA

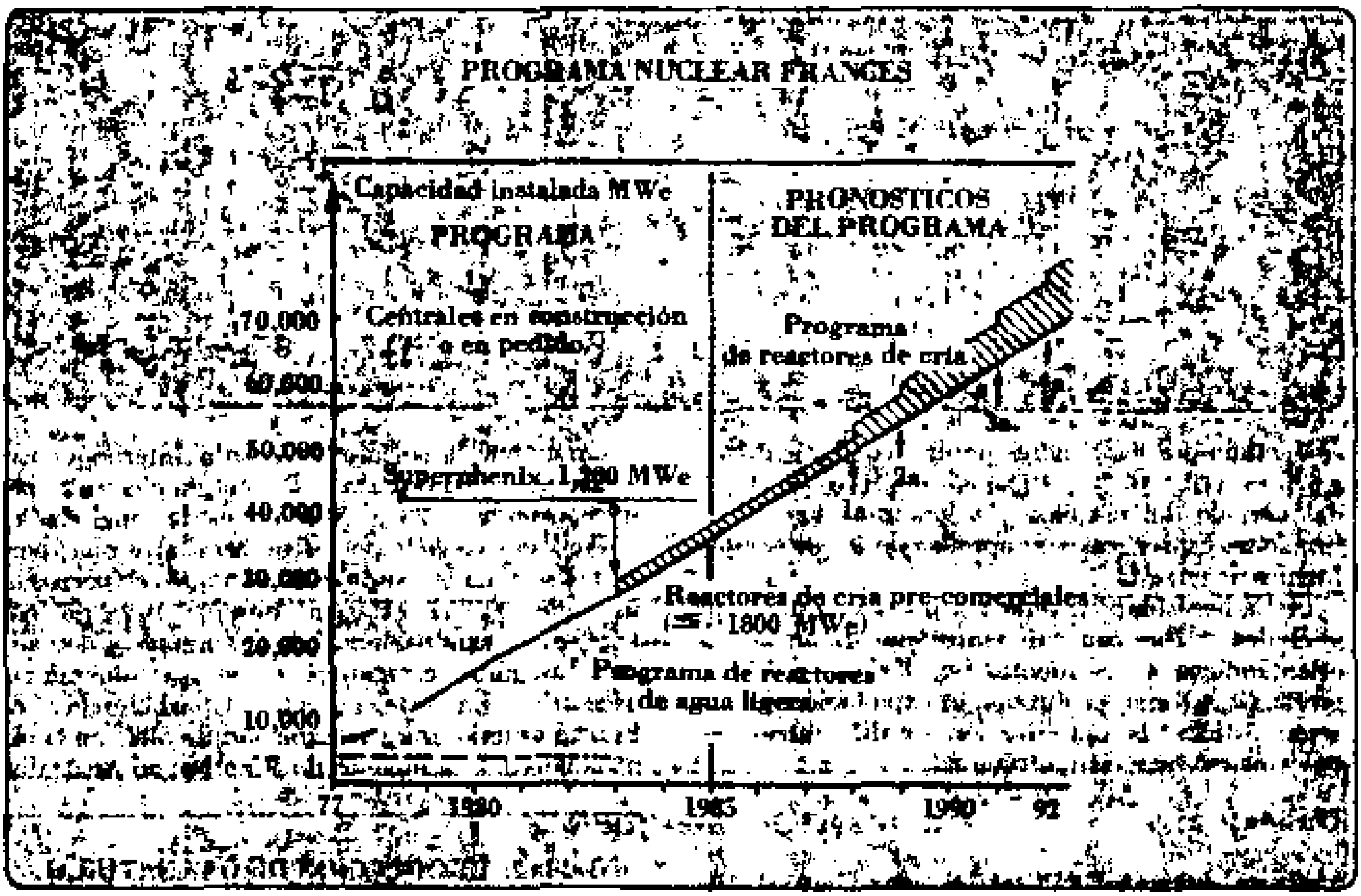
Año	Miles b/d	Millones ton/año
1940	1.4	0.1
1950	2.5	0.1
1960	38.6	1.9
1965	59.5	2.9
1968	54.7	2.7
1969	49.9	2.5
1970	45.8	2.3
1971	37.0	1.8
1972	30.0	1.5
1973	20.0	1.3
1974	23.0	1.1
1975	20.0	1.0
1976	20.0	1.0
1977	20.0	1.0
1978*	21.0	1.1

Fuente: *Enciclopedia Mundial del Petróleo, 1978.* / p. 263
* *Petroleum Economist*, enero de 1979. / p. 6

Política petrolera

La política petrolera francesa está definida por la ley de 1928, que instituyó un monopolio delegado de la importación de crudos y productos petroleros.

En 1924, fue fundada la Compagnie Francaise des Pétroles, con una participación del 35% del Estado, su principal accionista, que se reserva el 40% de los derechos de voto. La entidad fue concebida como el "instrumento de la política petrolera del país". En 1944 se creó el Bureau de Recherches des Pétroles, que, por fusión con la Régie Autonome des Pétroles, creada en 1938, dió origen a la compañía estatal Elf-Erap en 1965. Otra compañía semiestatal es la Societé Nationale des Pétroles de Aquitanie-SNPA, controlada en un 51% por el Estado y con 49% de participación privada.

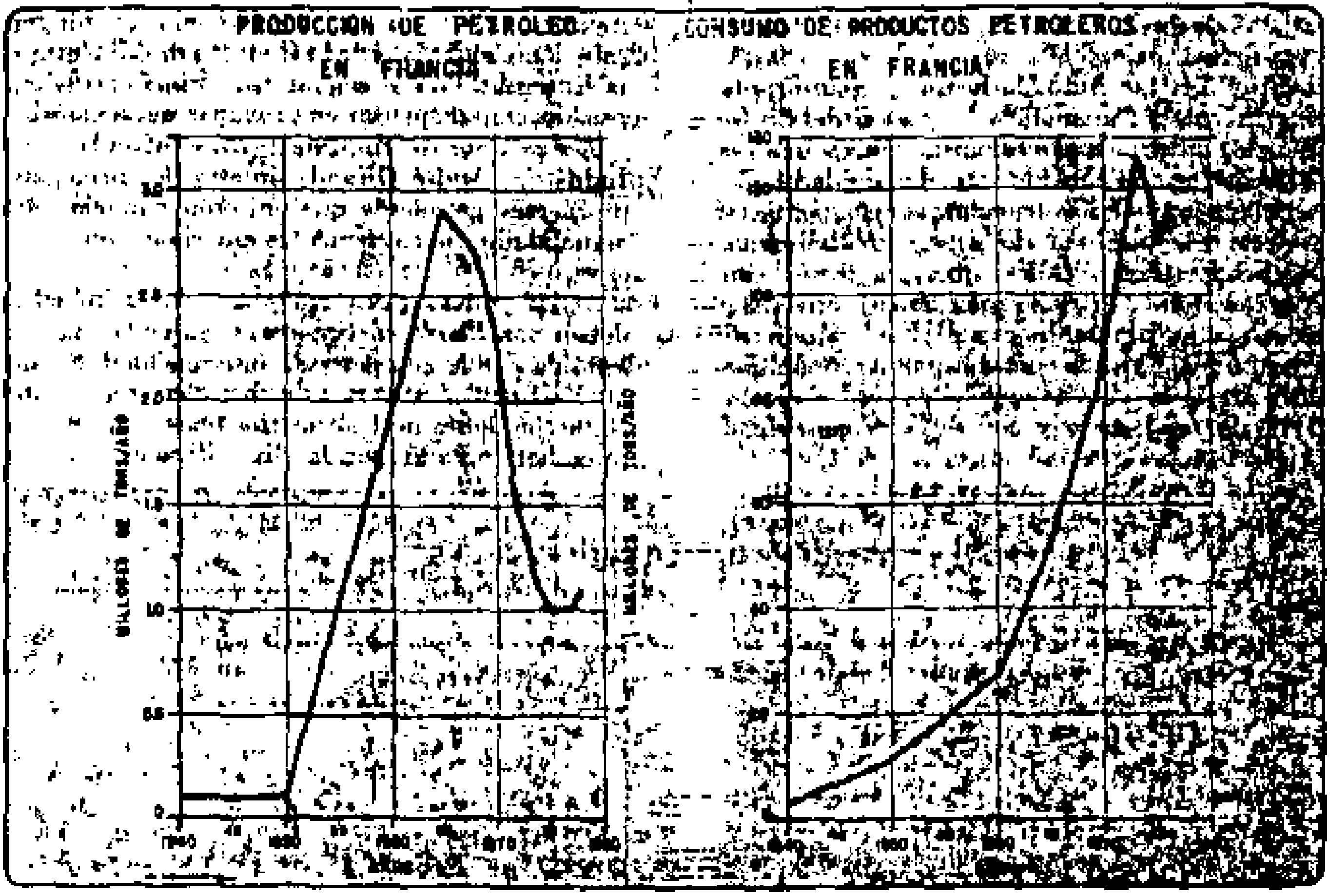


La ley de 1928 da margen para lograr la independencia energética del país. Entre sus postulados permite crear una industria nacional de refinación y una flota petrolera; desarrollar una industria de la exploración y de la producción de crudo y una industria parapetrolera; economizar 8.500 millones de francos en divisas al año y procurar 300,000 empleos directos e indirectos en el solo sector de transporte marítimo. No obstante, esta ley es sumamente atacada por la Comunidad Económica Europea, porque impone ciertas obligaciones en los intercambios intracomunitarios. La CEE no ha ofrecido empero ninguna solución y el fracaso de la Reunión de Ministros de la Energía de los 9, celebrada a principios del año pasado, impide pensar en próximas resoluciones.

A mediados de junio de 1978, el Ministro de la Industria, André Giraud, sintetizó los principales problemas petroleros que enfrenta Francia en la actualidad y cuyos elementos esenciales son:

a) La política petrolera y la política industrial deben conciliarse en Francia, cuya economía está influida por la competencia internacional. Si bien las compras francesas de petróleo representan 60,000 millones de francos, los países productores (que han optado por la diversificación y aceleración de su desarrollo económico) ofrecen un nuevo e importante mercado a la tecnología de los países industrializados. En consecuencia, la industria petrolera francesa, que dispone de una tecnología específica, puede y debe exportar.

b) Existe la necesidad de preparar, desde ahora, algunos acuerdos sobre puntos difíciles en materia energética, a pesar del ingreso al mercado del petróleo, del Mar del Norte, México y Alaska: "La actual abundancia de crudo no debe deslumbrarnos; en el horizonte 1985, nuevas alzas de precios podrían cuestionar la política energética



sustentada por los poderes públicos después de los trastornos de 1973". "Debemos preparar el fin del período del petróleo y orientarnos hacia utilizaciones específicas y adaptadas de las diferentes fuentes de energía".

c) La necesidad de velar porque la investigación y el desarrollo sean suficientemente financiados, orientándolos a las fuentes no clásicas, a la exploración en mar profundo, la explotación en las zonas árticas, la optimización de diferentes métodos de recuperación, etcétera.

Carbón

A principios de 1978, el Director General Adjunto de Charbonnages de France, delineó el rol del carbón en el abastecimiento energético del país. Como solución para disminuir los suministros externos de energía (77% del total consumido en Francia), la solución sería el uso simultáneo de la energía nuclear y el carbón, lo que permitiría reducir el aprovisionamiento del petróleo en 30%, manteniendo la participación del carbón en 20%.

Francia se caracteriza en cuanto al carbón, por su escaso potencial: dispone de reservas de 600 millones de toneladas y de una producción de 20 millones, situación que lleva al país a ser el segundo importador mundial, después de Japón.

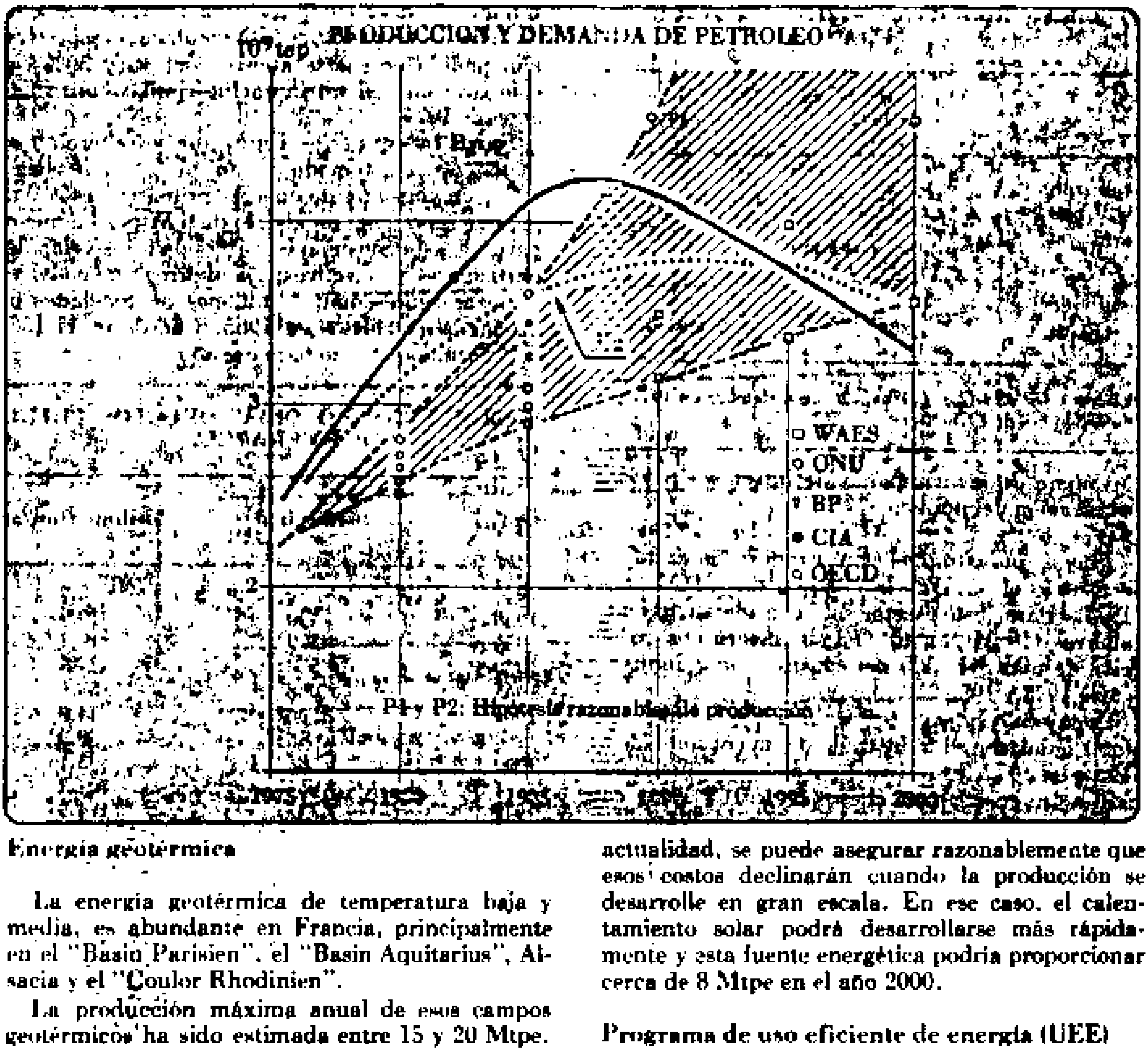
Existe un importante mercado interno consumidor, en el cual destaca la energía eléctrica, con un consumo de 23 a 24 millones de toneladas en 1977. Este mercado podría desarrollarse más; pero su abastecimiento supone importantes esfuerzos de inversión en el exterior, aunque bastaría con triplicar o cuadruplicar los desembolsos actuales para asegurar el control de aprovisionamiento necesario. En este aspecto, Charbonnages de France asumió una participación de 50% en la explotación del yacimiento de Wambo, en Australia.

Tabla 2: PRODUCCION DE GAS NATURAL EN FRANCIA

AÑO	MMPCD*
1972	735.8
1973	708.2
1974	831.8
1975	732.0
1976	686.8
1977	703.3

* millones de pies cúbicos diarios

Fuente: *Enciclopedia Mundial del Petróleo;* 1978. / p. 278



Energía geotérmica

La energía geotérmica de temperatura baja y media, es abundante en Francia, principalmente en el "Basin Parisien", el "Basin Aquitarius", Alsacia y el "Coulor Rhodinien".

La producción máxima anual de esos campos geotérmicos ha sido estimada entre 15 y 20 Mtpe. Esta fuente energética, será usada principalmente para generar vapor de agua para la calefacción residencial y para algunos usos industriales.

Debido a que la mayoría de los campos geotérmicos se encuentran bajo áreas densamente urbanizadas, el desarrollo de la energía geotérmica podría resultar razonable antes del año 2000, y esta fuente energética proporcionaría cerca de 10 Mtpe.

Energía solar

La energía solar en Francia podrá ser usada principalmente para el calentamiento de agua y para calefacción ambiental. Dos técnicas han sido probadas durante algunos años: la técnica de "Trombe" y la técnica de colectores planos. Aunque el costo de esas técnicas es muy elevado en la actualidad, se puede asegurar razonablemente que esos costos declinarán cuando la producción se desarrolle en gran escala. En ese caso, el calentamiento solar podrá desarrollarse más rápidamente y esta fuente energética podría proporcionar cerca de 8 Mtpe en el año 2000.

Programa de uso eficiente de energía (UEE)

Uno de los elementos claves de la política energética de Francia es la implementación de un programa tendiente a disminuir el consumo de energía, a través del uso eficiente de la misma en los distintos sectores demandantes.

La política nacional de UEE fue encomendada a la Agencia para las Economías de Energía (AEE), creada a tal efecto y destinada a la preparación, implementación y ejecución del programa en cuestión. Su acción se ejerce en todos los sectores consumidores de energía: industria, agricultura, transporte, residencial y servicios. La competencia de la AEE incluye todas las formas de energía y se ejercita utilizando conjuntamente la reglamentación, los estímulos financieros por la vía indirecta de la tributación y las tarifas de la energía, valiéndose también de la ayuda a las inversiones,

Tabla 3: RESERVAS DE HIDROCARBUROS EN FRANCIA

	31 de diciembre de 1977	31 de diciembre de 1978
Crudo (10^9 barriles)	43.0	56.0
Gas natural (10^9 ft^3)	4,800	6,500

Fuente: *Oil and Gas Journal*, 26 de diciembre de 1977 y 25 de diciembre de 1978

así como de las campañas de información y sensibilización del público.

Sector industrial.— En Francia, la industria consumió el 35% de la energía, con 61 Mtpe en 1977. Para este sector se consideran grandes ahorros (16 Mtpe), lo cual significará una reducción de más del 25% del consumo de la industria entre 1973 y 1985.

Sectores residencial y servicios.— Ambos sectores igualaron al industrial con un consumo de 61 Mtpe en 1977. El objetivo para 1985 es ahorrar 21 Mtpe, en relación al consumo de 103 Mtpe calculado en 1977.

El 70% de los requerimientos de estos sectores se centra en la calefacción. Las medidas para lograr un UEE se apoyan en la ley del 19 de julio de 1977, cuyo elemento más importante para disminuir el consumo de energía en el aislamiento térmico. Observando la reglamentación respectiva, han podido obtenerse ahorros del 40 y 50%, en comparación con un inmueble similar construido antes de 1974.

Sector transporte.— En lo que se refiere a este sector, se ha tomado como orientación, hasta 1985, un consumo de energía primaria de 44 Mtpe, que representa un ahorro de 6 Mtpe. La mayor parte de este consumo corresponde a los vehículos particulares y colectivos; los ahorros que conviene alcanzar representan 3 millones de toneladas de productos petroleros en 1985, vale decir, el 15% del consumo previsto para ese año.

Tabla 4: FRANCIA: CAPACIDAD DE REFINACION

Año	Miles de b/d	Millones ton/año
1940	152	7.5
1950	306	15.1
1960	769	37.9
1965	1,308	64.5
1969	2,092	103.2
1970	2,405	118.6
1971	2,527	124.6
1972	2,692	132.8
1973	2,949	145.5
1974	3.140	154.9
1975	3.342	164.8
1976	3,312	163.4
1977	3,517	182.9
1978	3,456	179.7

Fuente: *Enciclopedia Mundial del Petróleo*, 1978. / p. 274.

Tabla 5: CONSUMO DE PRODUCTOS PETROLEROS EN FRANCIA

Año	Miles b/d	Millones ton/año
1940	59	2.9
1950	220	10.9
1955	399	19.7
1960	558	27.5
1965	1,088	53.7
1968	1,500	74.0
1969	1,640	80.9
1970	1,888	93.1
1971	2,051	101.2
1972	2,315	114.2
1973	2,554	126.0
1974	2,435	120.0
1975	2,240	109.3
1976	2,385	117.3

Fuente: *Enciclopedia Mundial del Petróleo*; 1978. / p. 278

La acción de la AEE se orienta en dos niveles:

— Utilizar el vehículo particular estrictamente lo necesario e imponer la conducción racional del mismo, a fin de minimizar el consumo de carburantes y los gastos de uso.

— Producir unidades de bajo consumo de carburantes.

Los primeros resultados de la ejecución del programa de UEE significaron una notoria disminución del consumo de energéticos: 5 Mtpe en 1974; 12 Mtpe en 1975; 13 Mtpe en 1976 y 14.5 Mtpe en 1977.

A pesar de esto, hasta ahora los industriales y los distribuidores de la energía han invertido poco en UEE (cerca de la mitad de lo deseable) y han modificado muy poco su política comercial. Pero los resultados del programa en 1977 demuestran que los objetivos pueden lograrse adecuadamente.

Perspectivas energéticas de Francia al año 2000

Antes de la crisis energética de 1973-1974 los pronósticos de consumo de energía elaborados por el gobierno francés fijaban el límite máximo hacia 1985 en un nivel de 285 Mtpe. Poco después, al implementar algunas medidas para reducir el consumo, ese tope bajó a 265 Mtpe y, posteriormente, en 1975 el Consejo Nacional de Planificación decidió establecer como límite superior un consumo de 240 Mtpe para 1985, mismo que aparece bajo los supuestos de crecimiento económico alto en la alternativa "A" de las proyecciones de la demanda de energía primaria (ver Tablas Nos. 6 y 7).

Se reconoce, sin embargo, que ese objetivo resulta ser un tanto ambicioso, ya que para alcanzarlo se necesitan cambios importantes en el uso de la energía y en el comportamiento de los consumidores. Para ello las autoridades deberán combinar ajustes reglamentarios con incentivos financieros en proporciones que varíen de acuerdo a las necesidades de cada sector consumidor, como el industrial, el de transporte, el residencial, etc.

Se estima que, aproximadamente la cuarta parte del ahorro necesario, entre 10 y 15 Mtpe, puede ser alcanzado mediante la implementación de acciones que involucran un costo bajo de inversión. Otra parte importante del ahorro necesario se podrá obtener mediante la promoción de técnicas que ya han sido desarrolladas para este propósito, y asignando los recursos que requiere la investigación de nuevas técnicas de uso eficiente de la energía.

Otro de los aspectos que han sido considerados en la elaboración de los pronósticos de la demanda de energía es el relativo a la reducción de la dependencia de Francia en el suministro externo de combustibles fósiles. En la tabla No. 7 puede observarse que en el caso de la demanda de petróleo se proyecta reducir su participación de 65% en 1972 a 40% en 1985 y a 33% en el año 2000.

En lo que toca al carbón, las proyecciones involucran la tendencia al aumento de la participación de este energético, de acuerdo a la decisión de revisar el plan anterior de cerrar progresivamente las explotaciones de carbón en Francia, la cual estuvo basada en la baja competitividad de los precios de producción en relación con los de otros energéticos, con el objetivo de desarrollar al máximo la producción de este combustible promoviendo simultáneamente un programa complementario de exploración.

Por otro lado, se pretende aumentar el suministro de gas natural mediante el establecimiento de nuevos acuerdos con los países productores, para alcanzar los objetivos de abastecer en 1985 un volumen equivalente a 37 Mtpe y de elevar este nivel a 70 Mtpe para el año 2000.

En el caso de la energía nuclear, el incremento que se espera alcanzar en los próximos años resulta ser el más espectacular de todos, ya que se ha fijado como objetivo para 1985 la satisfacción del 25% de la demanda total de energía, sobre la base del desarrollo de un amplio programa nuclear que incluye la construcción de un elevado número de reactores de agua ligera. Numéricamente hablando, la parte más importante de los esfuerzos está siendo dedicada a la investigación tecnológica de los reactores de cría, lo que representa una forma

Tabla 6: **BASES PARA LAS PROYECCIONES DE DEMANDA DE ENERGIA**

	ALTERNATIVAS	
Variables	"A"	"B"
Tasa de crecimiento económico mundial	Alta (6%) (5% para Francia)	Baja (3.5%) (3% para Francia)
Precio del Petróleo	1977-1985 constante 1985-2000 creciente	1977-1985 constante 1985-2000 constante
Política Nacional	Vigorosa	Restringida
Incremento mundial de Reservas*	Alto 20,000 MB/A	Bajo 10,000 MB/A
Límite de Producción de la OPEP	Alto 45 MB/D	Bajo 40 MB/D
Combustible para sustituir Petróleo	Nuclear	Nuclear

1) Precio constante: durante todo el período se mantiene en US $11.50/b

Precio creciente: 1977-1985 US$11.50/b
1985-2000 US$17.50/b

2) Vigorosa: significa la implementación de medidas de uso eficiente y la eventual utilización de fuentes alternas de energía.

Restringida: significa una débil intervención del Estado en la aplicación de medidas de uso eficiente y en el volumen esperado de oferta de energía de acuerdo a los supuestos de precios y de crecimiento económico.

* millones de barriles anuales.

Fuente: WAES.— Energy Supply-Demand Integrations to the Year 2000

DEMANDA TOTAL DE ENERGIA PRIMARIA EN FRANCIA

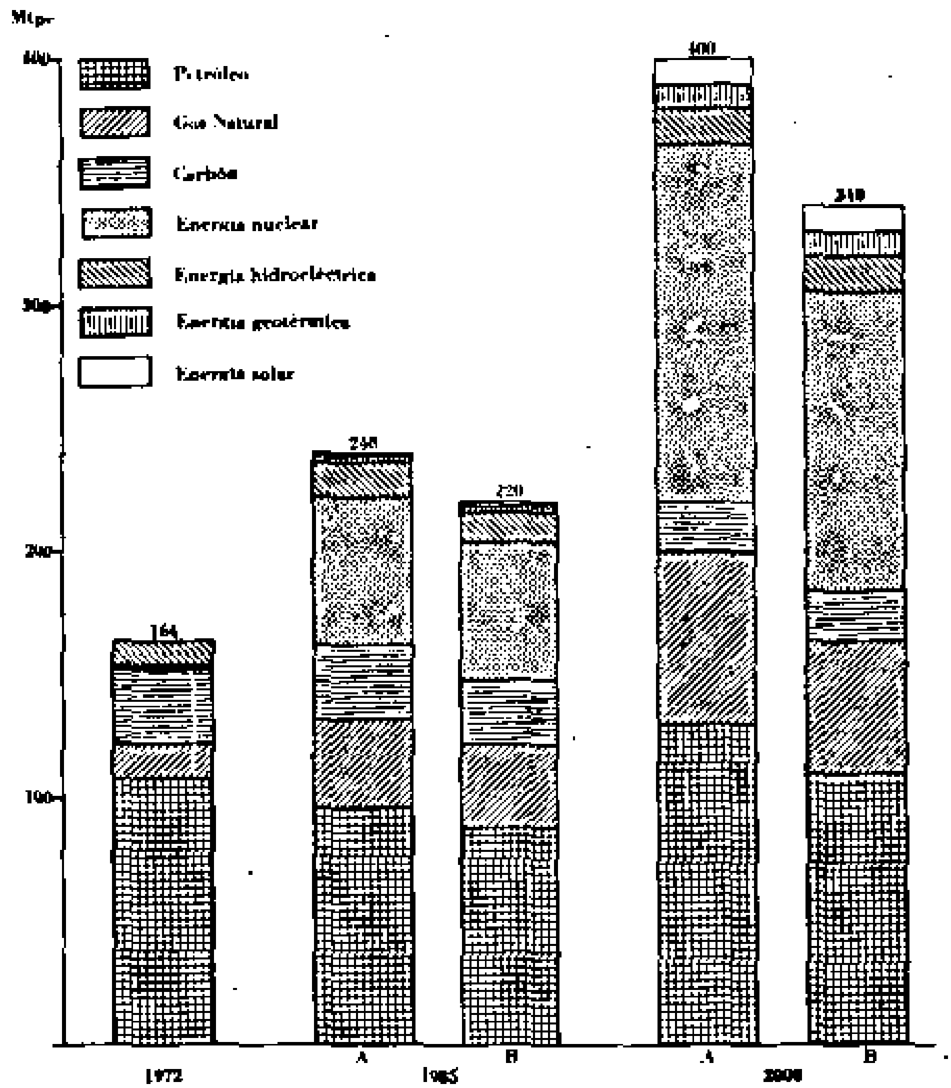


Tabla 7: DEMANDA TOTAL DE ENERGIA PRIMARIA EN FRANCIA

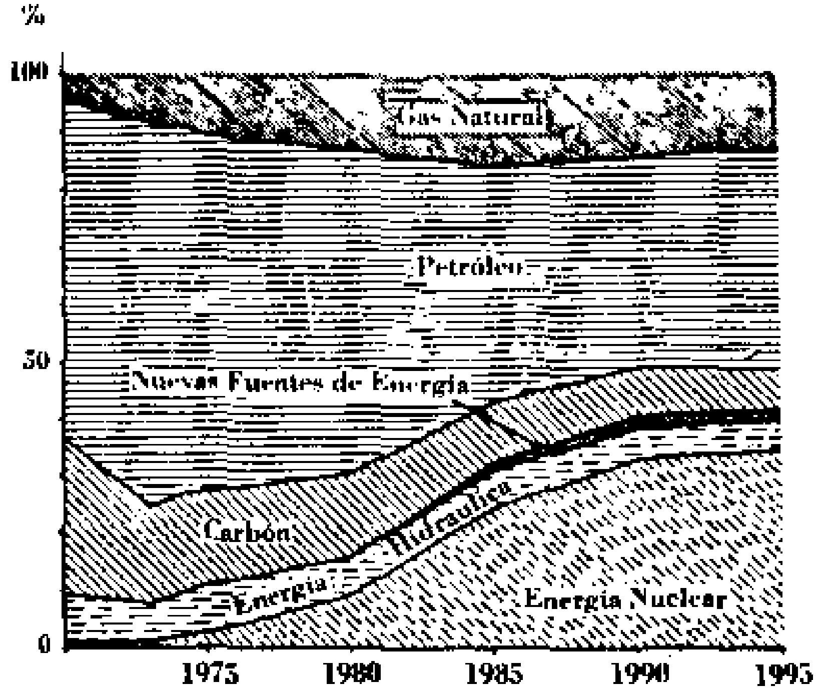
Millones de toneladas de petróleo equivalente

	1972 (Año Base)		1985				2000			
		%	"A"	%	"B"	%	"A"	%	"B"	%
Petróleo	107	65.2	96	39.5	88	39.5	130	32.5	110	32.5
Gas Natural	14	8.5	37	15.2	34	15.2	70	17.5	54	15.9
Carbón	31	18.9	30	12.3	27	12.1	20	5.0	20	6.0
Energía Nuclear	1	0.6	60	25.0	55	25.0	145	36.2	121	36.6
E. Hidroeléctrica	11	6.7	14	5.8	13	5.9	15	3.8	15	4.5
E. Geotérmica	—		3	1.2	3	1.3	10	2.5	10	3.0
E. Solar	—		3	1.2	3	1:3	10	2.5	10	3.0
Total:	164	100.0	240	100.0	220	100.0	400	100.0	340	100.0

Fuente: WAES.— Energy Supply-Demand Integrations to the Year 2000 — Cifras redondeadas

PERSPECTIVAS DEL BALANCE FRANCES DE ENERGIA

1970 - 1995



de asegurarse contra los posibles incrementos del costo del uranio y contra el posible agotamiento de las reservas en el futuro.

En virtud de lo anterior, las proyecciones realizadas involucran el objetivo de atender una demanda equivalente a 60 Mtpe en 1985, y el aumento de este nivel a 145 Mtpe para el año 2000, lo que significa una tasa de crecimiento medio anual de 19.5% durante todo el periodo.

En el mediano plazo existen otras posibilidades para complementar el suministro de recursos energéticos. El gobierno francés intenta dar un impulso especial al desarrollo de técnicas para el aprovechamiento de la energía solar y de los recursos geotérmicos de bajas temperaturas.

En la actualidad se están apoyando algunos proyectos concretos en esos campos, lo que permite suponer que la entrada en operación de este tipo de tecnologías permitirá satisfacer, en 1985, una demanda de 3 Mtpe tanto de aprovechamientos geotérmicos como solares y del equivalente a 10 Mtpe para el año 2000, por cada uno de esos conceptos.

Para el caso de la alternativa "B", que supone una tasa de crecimiento económico más moderada que en la alternativa "A", el análisis que se ha hecho anteriormente sigue siendo válido, ya que contiene básicamente los mismos supuestos, tanto en lo que se refiere a los lineamientos de política involucrados como en lo que toca al planteamiento de objetivos, con la diferencia de que el límite máximo para la demanda se ha fijado en un nivel menor que el correspondiente a la alternativa "A", que en 1985 asciende a 220 Mtpe.

FUENTES:

1) *Enciclopedia Mundial del Petróleo*, 1978, Pág. 121.
2) *CEA: Notes d'Information;* No. 4, abril 1978; "Programe nucléaire française et cooperation internationale" por M. André Giraud.
3) *Revue de l'énergie*, septiembre de 1978.
4) Berreby, Jean Jacques: *El petróleo en la estrategia mundial*, ediciones Guadarrama, Madrid, 1976, pp. 43-44.
5) *Revue de l'énergie*, julio-agosto de 1978
6) *Revue de l'énergie*, mayo de 1978
7) Syrota, J.: "*La politique française d'economie d'énergie*" ponencia presentada en el Seminario de Economías de la energía, México, agosto de 1978.
8) *Energy Technology II*, editado por el Dr. Thomas F.P. Sullivan, Government Institutes, Inc., Washington D.C., 1975.
9) *Energy Supply-Demand Integrations to the Year 2000*, Workshop on Alternative Energy Strategies, MIT, 1977.

RESERVAS DE URANIO EN SUDAMERICA

Brasil y Argentina están aumentando rápidamente el conocimiento de sus reservas de uranio mediante ambiciosos programas de exploración y desarrollo. Otros paises de Sudamérica se están moviendo también en ese sentido, en la medida en que se van materializando sus programas a largo plazo de reactores.

Brasil

El programa de prospección más impresionante es el brasileño, que comprende la inversión de 20 a 25 millones de dólares anuales, lo que hace uno de los esfuerzos de exploración de uranio más grande del mundo.

Brasil ha anunciado recientemente cifras que duplican las reservas conocidas e inferidas del país, llegando su potencia actual a 142,300 toneladas de U_3O_8; el gran aumento de reservas es el resultado de la evaluación de nuevos descubrimientos efectuados en diversas regiones durante 1977 y 1978.

Las reservas se estimaban en 66,800 toneladas en 1977, lo que ya representaba un gran aumento sobre las 20,380 toneladas que se calculaban en 1976.

La mayor parte del aumento en 1978 proviene de nuevas estimaciones en la región de Itataia, en el Estado de Ceara, en el norte del país. El resultado del programa de perforación de 10,000 metros, ejecutado este año, permitió a Nuclebras aumentar las reservas de Itatai de 18,000 a 71,000 toneladas de U_3O_8.

Por primera vez Nuclebras está dando, además, estimaciones de su más reciente descubrimiento, Lagoa Real, en el Estado de Bahia. Este descubrimiento le ha dado a Brasil 5,500 toneladas de nuevas reservas y las perforaciones en la región continúan.

Por otra parte, Nuclam —una compañía formada por Nuclebras y la firma alemana Urangesellschaft— ha mencionado sus primeras reservas, por un total de 10,000 toneladas, en un lugar cercano a Expinharas, en el estado de Paraiba. Estos trabajos de exploración fueron iniciados en 1976.

Una vez que las reservas de uranio de Brasil sean suficientes para cubrir las necesidades del programa nucleoeléctrico del país, el socio alemán en Nuclam tendrá opción por lo menos al 20% de la producción de uranio de la compañía.

La primera planta de proceso de Nuclebras, que comprende el desarrollo de una mina y una planta de beneficio cerca de Pozos de Caldas, en el estado de Minas Gerais, se está llevando a cabo en programa. En la mina se han removido 10 millones de metros cúbicos de tierra y se está a punto de extraer el mineral para almacenarlo. La planta de beneficio iniciará su operación a fines de 1979. El complejo de 70 millones de dólares manejará 250 toneladas de mineral por día y producirá 500 toneladas de U_3O_8 por año.

Las reservas de 142,300 toneladas son suficientes para alimentar durante 30 años a 35 reactores de potencia, cada uno de 1,300 MW. El programa actual de Brasil, que ya está algo atrasado, contempla la construcción de ocho reactores de 1,300 MW para estar en operación en 1990, además de un reactor de 640 MW.

De acuerdo con el balance de energía oficial de Brasil, recientemente actualizado por el Ministerio de Minas y Energía, la demanda y producción de U_3O_8 del país, es como sigue:

Año	Consumo (ton)	Producción (ton)
1979	15.4	122
1980	125.0	600
1981	122.0	600
1982	110.0	960
1983	108.5	1140
1984	245.0	1140
1985	367.5	1140
1986	606.0	1140
1987	821.0	1140

Argentina

Generalmente se considera que Argentina, que ha estado trabajando minas de uranio desde los años sesenta, y que tiene su primer reactor en operación desde 1974, está más adelantada que Brasil en su conocimiento del campo nuclear, aun cuando esta situación podría cambiar en unos cuantos años, en base al programa brasileño de 15,000 millones de dólares establecido con Alemania, que incluye tecnología de reactores y del ciclo de combustible.

El programa eléctrico de Argentina prevé 3,000 MW de capacidad nuclear para 1990 y 15,000 MW para el año 2000.

Como parte de un programa de autosuficiencia en uranio, Argentina está gastando cerca de 6 millones de dólares anuales en exploración. Las reservas conocidas actuales de U_3O_8 son de 25,000 toneladas, a las que se agregan 16,000 toneladas como probables.

Félix Rodrigo, Director de Exploraciones de la Comisión Nacional de Energía Atómica, dice que se espera un aumento substancial en las reservas de uranio en el futuro próximo. El programa para este año incluye prospección en una área de 100,000 km cuadrados, 55,000 metros de perforación exploratoria y 2,000 metros de túneles.

La CNEA enlista 50 depósitos conocidos de uranio, en 21 áreas diferentes. La zona más grande se llama Sierra Pintada, en la provincia de Córdoba y tiene una reserva de 18,000 toneladas. Diez compañías locales están compitiendo para ganar un contrato para minería en Sierra Pintada, en donde se espera tener producción en gran escala para fines de 1979.

Otros concursos similares se iniciarán próximamente para depósitos más pequeños, en Cosquín (reservas estimadas en 3,000 toneladas) y el Gigante (1,400 toneladas estimadas), también en la provincia de Córdoba.

Argentina tiene tres plantas de concentración trabajando con minerales de minas antiguas, cuya producción combinada es de 150 toneladas por año de U_3O_8. Una nueva planta de lixiviación está en construcción, la que agregará 55 toneladas más por año a partir de marzo de 1979. Se tienen también planes para otra planta de beneficio en el área de Sierra Pintada, para producir 700 toneladas de U_3O_8 a partir de 1983.

Por primera vez, autoridades del gobierno argentino han mencionado la posibilidad de participación extranjera en los trabajos de minería de uranio.

Chile

El programa de trabajos de minas de uranio en Chile se vió afectado durante 1978, cuando nadie atendió a la invitación del gobierno para el desarrollo de siete áreas potencialmente uraniferas; sin embargo, el propio gobierno está procediendo para recuperar uranio de aguas de lavado de minas de cobre.

La Comisión Chilena de Energía Nuclear (Cochen) tomó en sus manos el año pasado un proyecto para recuperar uranio en la Mina Sur de Chuquicamata (antiguamente conocida como Mina Exótica, de Anaconda). Una planta piloto produjo, a mediados de 1978, las primeras muestras de óxido de uranio. Se espera pronto la decisión de proseguir con la construcción de una planta de recuperación a escala industrial.

Cochen está negociando con la Wyoming Mineral, una subsidiaria de Westinghouse, otra planta de extracción de uranio a base de jales de minas de cobre.

Los planes nucleares de Chile han sido revividos: Cochen firmó un contrato en septiembre pasado con la Compañía Dames & Moore, de Los Angeles, para un estudio de selección de un sitio para una planta nucleoeléctrica de 600 MW; el estudio tendrá un costo de 300,000 dólares y deberá estar listo en junio de 1979.

Colombia

A principios de 1978 Colombia formó una nueva agencia estatal llamada Coluranio, para supervisar y controlar los esfuerzos del gobierno en la exploración y desarrollo en el campo del uranio. La propiedad de Coluranio está compartida entre la compañía estatal Ecopetrol, la compañía estatal de interconexión eléctrica y el Instituto Colombiano de Energía Nuclear, el cual estima las reservas de uranio ya conocidas en 40,000 toneladas de U_3O_8.

La primera acción de Coluranio consistió en la firma en marzo pasado, de un acuerdo con la compañía española Empresa Nacional de Uranio (ENUSA), para la exploración de 125,000 acres de territorio de jungla en el sureste del país. La inversión en la primera etapa comprende un total de 3 millones de dólares.

La compañía francesa Minatome, que el año pasado gastó en exploración en Colombia 3.4 millones de dólares, continuó sus trabajos al mismo ritmo, bajo un nuevo contrato con Coluranio. Tanto con los españoles como con los franceses, Coluranio es socio mayoritario con 51% de las acciones.

A pesar dé su empuje en exploración de uranio, Colombia no tiene planes para construir plantas nucleares sino hasta el siglo XXI, ya que el país cuenta con bastante potencial hidroeléctrico que aún no ha sido aprovechado.

Bolivia

Los esfuerzos exploratorios en Bolivia se iniciaron en 1973, cuando la compañía Homestake Mining descubrió depósitos de uranio cerca de Cotaje, en el estado de Potosí.

El año pasado se terminó el desarrollo de un programa de exploración efectuado por la compañía italiana Agip, en base a un contrato firmado en 1974 con la Comisión Boliviana de Energía Nuclear. El trabajo de exploración cubrió 50,000 km cuadrados, con resultados que, de acuerdo con una fuente minera local, fueron negativos. Sin embargo, en 1976 la Comisión solicitó de Agip la construcción de una planta experimental en la población de Cotaje, para una producción de 200 kg de concentrado de uranio por año.

El año pasado la Comisión instaló en Viacha, a 40 km de La Paz, un pequeño centro de investigación para trabajo experimental con reactores y generadores de neutrones.

Venezuela

Este país, rico en petróleo, no tiene urgencia de contar con generación de origen nuclear; sin embargo, espera tener su primer reactor en operación en la última década de este siglo.

La planeación está en manos del Consejo Nacional de Aplicaciones Nucleares, el cual tuvo un presupuesto el año pasado de 1.7 millones de dólares, de los cuales aproximadamente la mitad se están gastando específicamente en la exploración de uranio.

Hasta el momento, el trabajo se ha limitado a mediciones radiométricas en áreas relativamente accesibles, habiéndose concentrado la atención en la formación La Quinta, que se desarrolla a lo largo de los estados andinos de la parte oeste del país.

Fuente: *Nuclear Fuel*, noviembre, 1978, ININ.

INCENTIVOS A LA PRODUCCION DE GAS EN EU

La escasez de gas natural en EU provocó que la industria norteamericana redujera el consumo de éste como combustible. Dicha reducción tuvo como resultado un mayor consumo de crudo y no de carbón, con el consecuente incremento en las importaciones de petróleo. Mientras que en 1973 el gas natural abastecía el 36.1% del mercado energético industrial, el crudo el 21.9% y el carbón el 11.9%, en 1977 la participación del gas natural en dicho mercado se redujo al 32%, y la del carbón al 13.9%, pero la del petróleo crudo aumentó al 26.7%. Estas cifras han llevado a que J. Schlesinger, Secretario de Energía de EU declare que aquellas empresas que han dejado de usar gas natural se verán alentadas por el gobierno si vuelven a utilizarlo en lugar de quemar petróleo importado. El decreto sobre gas natural de aquel país que elimina los precios diferenciales entre los mercados interestatales y estatales, dará como resultado una mayor producción interna de gas natural en aquellos estados donde los productores se negaban a vender su producto dentro del mercado interestatal, regulado por las autoridades federales.

Business Week, 4 de diciembre, 1978, pp. 36-38.

JAPON REDUCIRA SU CAPACIDAD DE AMONIACO

La industria de fertilizantes nitrogenados de Japón proyecta cerrar 1.2 millones de TZA de su capacidad de amoniaco, lo que representa un 30% del total. Aproximadamente el 40% de la de urea será cerrada también como parte de un plan de reestructuración industrial. Estas medidas se deben en gran parte al incremento en los costos de producción y la erosión de la competitividad de los productos japoneses en los mercados de exportación. Cuando el cierre de plantas se haya terminado la capacidad total de amoniaco en Japón será de 2.7 millones de TZA y 2.2 millones de TZA de urea.

Fertilizer International, enero, 1979, p. 1.

IMPACTO DEL AUMENTO DE CRUDO DE OPEP

La decisión de los países de la OPEP sobre el aumento del precio del crudo que será de hasta un 14.5% en el curso de este año, introdujo un nuevo elemento en el plan económico de Carter que busca frenar la economía sin provocar una recesión. Funcionarios norteamericanos han declarado que este incremento de precios empeorará sólo marginalmente la inflación. Sin embargo, esta medida de la OPEP podría minar la credibilidad de las políticas económicas y energéticas de Carter. De acuerdo con Wharton School de Pennsylvania el aumento, que de momento es del 10%, provocará un crecimiento en la tasa de inflación de EU del 0.5% y reducirá la tasa de crecimiento en un 0.3%.

El problema más grave para Washington será decidir si se iniciará el programa de liberalización del precio interno del crudo que debería iniciarse este año. El nuevo precio de la OPEP añadirá de por sí, entre 2.5 y 3 centavos de dólar por galón a la gasolina y a otros productos petroleros, aún bajo las actuales políticas de control.

En caso de que el precio del petróleo no se hubiera incrementado, la Administración Carter calculó que el liberar el precio interno del crudo provocaría un aumento de entre 3 y 4 centavos de dólar/galón a la gasolina en 1980. Con el nuevo aumento, el efecto podría ser de 6 centavos de dólar/galón.

El inesperado aumento de la OPEP ha provocado que Washington preste más atención a la posibilidad de importar elevados volúmenes de crudo de México.

Business Week, 8 de enero, 1979, pp. 14-15.

SUSTITUTO DE GASOLINA

La empresa estatal austriaca Voest-Alpine-AG acordó con el Ministerio Filipino de Energéticos llevar a cabo un programa para desarrollar combustibles energéticos a partir de caña de azúcar.

El alcogas, una mezcla del 15% de alcohol anhidro (supuestamente etanol) y 85% de gasolina se examinará como sustituto de gasolina. El etanol se extraería de la caña de azúcar en Filipinas.

Dicho proyecto incluye la construcción de una planta de extracción del jugo de caña y destilación del alcohol para así mezclarlo con gasolina. Contaría con una capacidad de 100,000 litros/día de dicha mezcla. La inversión está calculada en 34 millones de dólares.

Chemical Week, 15 de noviembre, 1978, p. 79.

ENERGIE: L'OFFRE ET LA DEMANDE D'INFORMATION; Balmoutier, Françoise; colección "Energía sociedad" del IEJE (Instituto Económico y Jurídico de la Energía) de Grenoble, publicado en Ediciones del Centro Nacional de Investigaciones Científicas.

La autora realizó su investigación con un equipo del IEJE, en el seno de comisiones de trabajo europeas y francesas, estructurándola en torno del diálogo necesario entre productores y usuarios de la información, de la permeabilidad de los sistemas de documentación, de la difusión de los conocimientos, así como de la crítica de los datos y su tratamiento.

La obra se inicia con una breve prólogo y está constituida por cinco capítulos: I.— Características de la información energética; II.— Las fuentes de información; III.— La demanda de información; IV.— Los medios de acceso a la información y V.— Hacia una mejor integración.

Desde el primer capítulo, además de los diversos aspectos que cubre la información energética, se plantean los riesgos respecto de los datos económicos numéricos, que siempre exigen una interpretación. La información no se reduce a datos, pero está constituida por "un conjunto de datos (elementos factuales) y de ideas (elementos de reflexión) contenidos en un documento"; a su vez, la documentación constituye "el conjunto de procesos que permiten poner a disposición de un demandante o usuario, la información que necesita".

Considerando que las fuentes de información son innumerables, la autora no proporciona una nómina o un catálogo, sino un método de trabajo e indicaciones para seleccionar entre fuentes confiables y dudosas, así como un llamado a evaluar los datos obtenidos como premisa imprescindible en la labor de recopilación. El extraordinario volumen de información, entre la que figuran varios miles de publicaciones periódicas y gran cantidad de literatura de aparición irregular (libros o documentos de difusión restringida, anuarios, información "subterránea" e informadores particulares) obligan a recurrir no a un repertorio de documentos sino de fuentes. Estos repertorios son muy numerosos en el mundo, al extremo de que se ha hecho necesario publicar "repertorios de repertorios".

Un punto negro en esta masa de informaciones son las estadísticas, que difieren de un país a otro no sólo por las unidades de medición sino también por las nomenclaturas y las formas de obtención de los datos brutos, así como por el tratamientro que se les da.

En el capítulo III se aborda la demanda de información. Son los usuarios más destacados de la información, sobre todo de la concerniente a la energía, quienes deberán decidir respecto de la modalidad y calidad de los informantes. La autora enfatiza en la necesidad de escuchar al demandante, de conocer el uso que dará a la información solicitada y de colaborar oferente y demandante, para enriquecer y funcionalizar los servicios en cuestión. Gracias a la cooperación pluridisciplinaria podrá superarse la calidad de los servicios de información, que deberán apuntar esencialmente a la comprensión del interlocutor, para cumplir una función de intercambio y de pedagogía.

El capítulo IV, "Los medios de acceso a la información" es el más extenso y más técnico de la obra. Se accede a la información "gracias a todo un juego de productos, servicios y circuitos, concebido para remplazar esta función", se describe enseguida 13 tipos de productos y servicios documentales, cuyos "centros de análisis de la información" y "servicios" resultan importantes. Posteriormente se refiere a los "bancos de datos", que juegan un gran papel y que están muy de moda, pero cuyo funcionamiento es más delicado de lo que se imagina.

Especial atención dedica la autora a las redes en general y a ciertas redes en particular, entre las que destaca la de "Economía de la Energía", creada en 1970 con la colaboración de cuatro organismos franceses. Esta red ha servido de base al Comité para la Información y la Documentación Científica y Técnica de la CEE para su proyecto piloto, en el que cada centro de gestión nacional funciona como satélite del centro internacional de gestión: el proyecto piloto, largamente elaborado, comenzó a implementarse en 1977 y habría entrado en operación a fines de 1978.

No obstante ser una especialista técnica que domina su oficio, la autora reconoce gran importancia a la red de personas: "a pesar del escándalo de quienes creen en el progreso a través de la técnica, pensamos que estos sistemas informales, más parecidos al tam tam de la selva que a la informática, ofrecen muchas cosas positivas. . . En efecto, redes formales y redes informales deben apoyarse unas con otras; la utilización excluyente de cada una encuentra rápidamente sus límites".

Pasa enseguida la autora a describir la adaptación de la oferta a la demanda y sus circunstancias. Aunque la oferta es indudablemente abundante, es necesario hacerla más eficiente, mediante "productos anexos, tales como repertorios de interlocutores" y "productos complementarios, sobre todo en documentación elaborada". Para Françoise Blamoutier, el remedio al desorden actual reside "no ya en la creación de nuevos medios, sino en la organización más racional de los ya existentes y en la adición de los eslabones faltantes, o simplemente dispersos, valorizando significativamente los sistemas actuales, con un pequeño costo adicional".

En cuanto al quinto y último capítulo, éste subraya la constante de un gran desequilibrio entre el desarrollo y la complicación más o menos artificial de los sistemas, por una parte, y por la otra, el desarrollo y la calificación de los medios humanos. Esta es la oportunidad para reseñar, precisándolos, las principales proposiciones del libro, respecto de los circuitos, los instrumentos y los agentes de información, entre los cuales los usuarios deberán formarse como tales.

En reiteradas ocasiones, la autora menciona la necesidad de información del Tercer Mundo y la posibilidad de satisfacerla. En sus conclusiones, señala que, especialmente con el proyecto piloto sobre la energía, Europa puede obtener, en la participación del Tercer Mundo, un avance decisivo sobre EU: "El sector energético. . . puede llegar a ser el ejemplo de un nuevo modelo de la información y de su transferencia. . ."

Extraído de: *Revue de l'énergie*; Yves Mainguy: "Trois nouvelles études grenobloises éditées par le CNRS"; septiembre, 1978.

EU: IMPORTACION DE CRUDO, ORIGEN Y NIVEL DE PRECIOS

	Enero-Septiembre				PRECIOS $US/b					
	1978		1977		1978			1977		
	BPD*	%	BPD*	%	fas**	cif	flete	fas**	cif	flete
Saudi Arabia	1'080,428	16.72	1'446,090	20.60	12.81	14.02	1.21	12.28	13.56	1.28
Nigeria	846,356	13.09	1'179,316	16.80	14.12	14.87	0.75	14.24	15.05	0.81
Libia	725,115	11.22	725,193	10.33	13.80	14.52	0.72	13.84	14.67	0.83
Argelia	657,848	10.18	558,416	7.95	14.17	14.82	0.65	14.16	14.91	0.75
Indonesia	547,097	8.46	566,875	8.07	13.59	14.59	1.00	13.24	14.25	1.01
Irán	605,033	9.36	594,354	8.46	12.72	14.02	1.30	12.72	13.83	1.11
México	273,253	4.23	153,864	2.19	13.36	13.65	0.29	13.23	13.60	0.37
EAU	377,964	5.85	349,511	4.98	13.35	14.55	1.20	12.56	13.89	1.33
Canadá	241,994	3.74	308,227	4.39	13.56	13.59	0.03	13.41	13.44	0.03
Venezuela	253,781	3.93	358,475	5.11	12.20	12.72	0.52	12.47	12.96	0.49
Trinidad	147,289	2.28	136,962	1.95	14.41	14.83	0.42	14.60	15.20	0.60
Reino Unido	143,981	2.23	68,807	0.98	13.74	14.75	1.01	14.23	14.92	0.69
Noruega	135,245	2.09	58,472	0.83	13.91	14.60	0.69	14.33	15.08	0.75
Ecuador	46,668	0.72	61,266	0.87	12.70	13.29	0.59	13.05	13.51	0.46
Colombia	5,275	0.08	–	–	11.41	11.91	0.50	–	–	–
Katar	77,057	1.19	58,116	0.83	12.98	13.93	0.95	13.00	14.12	1.12
Otros	299,385	4.63	397,507	5.66	13.04	14.01	0.97	12.88	13.92	1.04
Total	6,463,771	100.00	7,021,452	100.00	13.44	14.30	0.86	13.26	14.17	0.91

BPD* - Barriles por día
fas** - Free alongside ship
cif - Cost insurance free

En el cuadro anterior se puede observar que el 84% del total de las importaciones de crudo realizadas por EU en 1977, provino en conjunto de países miembros de la OPEP, contribuyendo conjuntamente México y Canadá sólo con el 6.58% del total considerado en el año en cuestión.

Sin embargo, en 1978 la aportación de los países de la OPEP al volumen total importado por EU fue de 74.87% correspondiendo en esta ocasión a México y Canadá el 7.97%.

Lo anterior muestra en 1978 un decremento del 11.53% con respecto al crudo adquirido en 1977 a países miembros de OPEP, mientras que México y Canadá mostraron en conjunto un incremento de 11.50% bajo las mismas circunstancias.

Fuente: *Petroleum Economist*, diciembre de 1978.

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SIMPLIFIED FLOW SCHEMATIC
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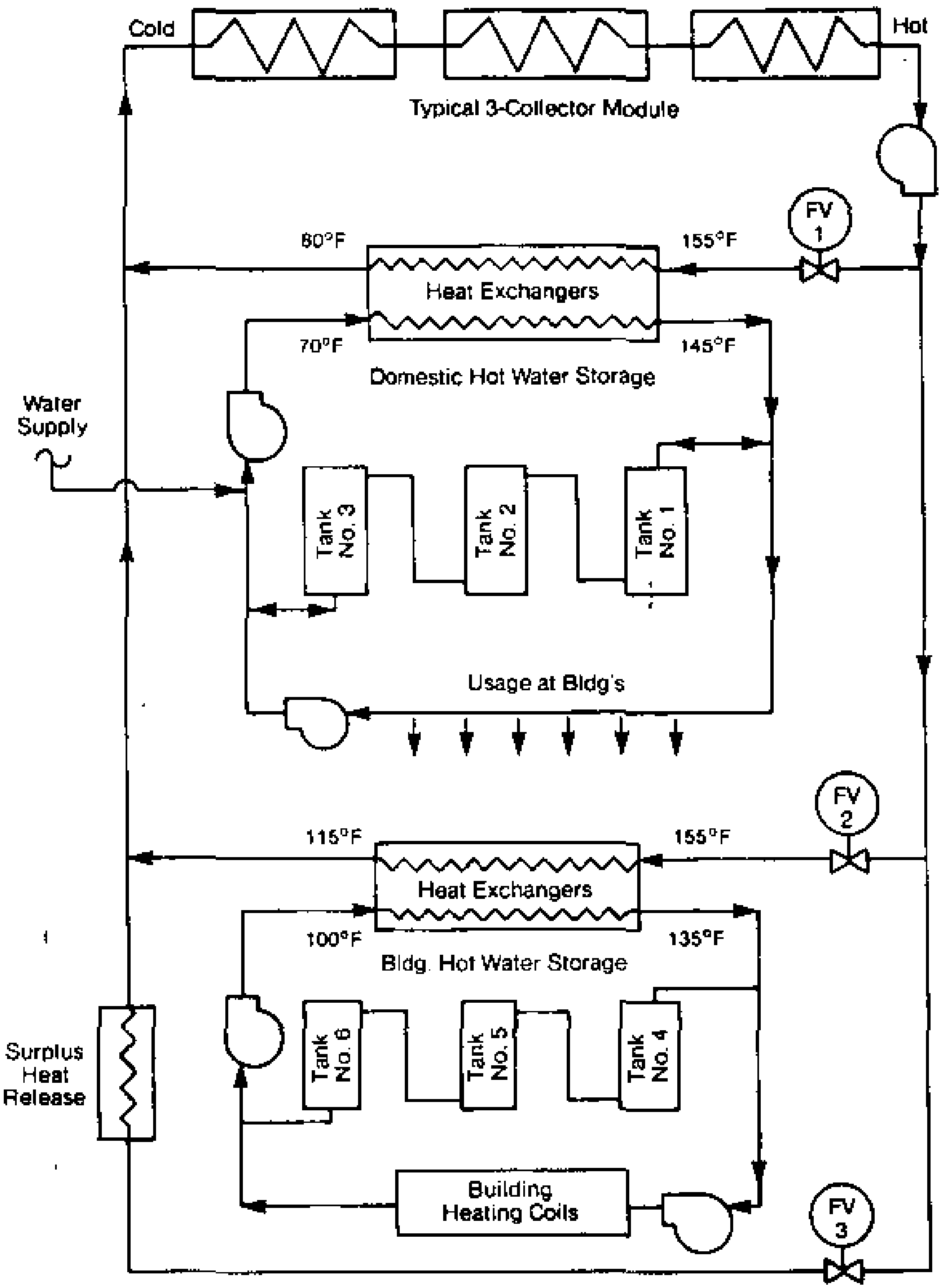

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

THE OIL CRISIS

ED. RAYMUND VERNON

W. W. NORTON INC. N.Y., N.Y. 1976

AGOSTO, 1979

basic necessity for the functioning of any industrial economy.[4] Thus energy supply problems caused by physical shortages or high prices are likely to affect directly the economic growth of the industrialized consuming countries.

On the basis of this recent experience, it can be argued that market forces, particularly through the price mechanism, are only going to be effective in establishing an equilibrium in the energy market over a long period of time, perhaps 25 to 30 years. In the meantime, political factors such as the policies and preferences of a few key countries could have a profound influence upon the long-term "solutions" worked out by market forces. The response of energy demand to price changes seems to be of less importance and slower than previously anticipated,[5] and it also seems to be fairly limited, particularly outside North America. This is partly because the discovery rate for oil has fallen in recent years and partly because substitutes seem to be increasingly capital-intensive.

This limited ability of the price mechanism to regulate the demand and supply for energy creates the potential for abrupt changes, primarily price discontinuities. It is the impact of organizational and political factors that is critical in the world energy market. In this century, the price of oil has only to a limited extent been determined by open transactions in a free market.[6] In fact, there is historically no systematic relationship between the price of oil and the costs of production.[7] In the past, the key organizational and political factors worked to the advantage of the industrialized consumers. As control of the oil market has moved

[4]Philip Connelly and Robert Perlman, *The Politics of Scarcity: Resource Conflicts in International Relations*, Oxford University Press, London, 1975, p. 26ff.

[5]Joel Darmstadter, Joy Dunkerley, and Jack Alterman, *How Industrial Societies Use Energy: A Comparative Analysis*, Resources for the Future, Washington, D.C., 1977, p. 183ff.

[6]Robert Engler, *The Brotherhood of Oil*, University of Chicago Press, Chicago, 1977, p. 16ff.

[7]Douglas R. Bohl and Milton Russell, "Some Economic Effects of the United States Oil Import Quota," in Ragaei El Mallakh and Carl McGuire (eds.), *U.S. and W[illegible] Energy Resources: Prospects and Priorities*, ICEED, Boulder, Colo., [illegible], pp. 1–19.

to the producers, the industrialized consumers increasingly run the risk of new price rises and even supply crises. To avoid economic and political disturbances in the short run, and to facilitate the achievement of an equilibrium in the long run, it is in the interest of the industrialized consumers to find a political solution to the world's energy problem, in the form of a negotiated international agreement. In order to be viable, such an agreement must also secure vital interests for the producers.

The initial reaction to the fourfold increase in the price of oil in 1973–1974 was that OPEC, the Organization of Petroleum Exporting Countries, had gone too far; there would be a glut of oil on the world market, and the price of oil would soon decline again.[8] This reaction reflected the point of view that the price increase was due to a successful cartel that would eventually break down because of overproduction, and thus in the long run oil prices would tend to approach the costs of production in the main producing areas.[9] This point of view has been replaced to a considerable extent by the view that there still is a large potential for raising the price of oil because it is a finite resource and the costs of substitutes are generally well above the present price. Also, there is a growing awareness that there are discrepancies in the projected patterns of supply and demand for energy.[10] These may create shortages, particularly for oil, in the 1980s and could stimulate new sudden price increases.

With the depletion of conventional petroleum resources, the late-twentieth-century world has a relatively short period of time to organize the move from low-cost to high-cost energy.[11] The failure to organize this move properly will provoke new and more serious energy crises, severe setbacks for the world economy,

[8]Edward R. Fried, "World Market Trends and Bargaining Leverage," in Joseph A. Yager and Eleanor Steinberg (eds.), *Energy and U.S. Foreign Policy*, Ballinger, Cambridge, Mass., 1975, pp. 231–275.

[9]Ibid.

[10]*World Energy Outlook*, OECD, Paris, 1977, p. 8ff.

[11]F. Parra, Ramos, and A. Parra, *World Supplies of Primary Energy 1976–1980*, Energy Economics Information Service Ltd., Workingham, Berkshire, England, 1976, p. 13, and Mason Willrich, *Energy and World P[illegible]*, The Free Press, New York, 1975, p. 27 ff.

and possibly international conflicts. Conventional oil production may peak around 1990 for physical reasons.[12] Not only are alternative sources in general much more costly, but they also take a long time to develop. Current investment in new sources of energy is largely insufficient to offset the anticipated decline in conventional oil production, let alone to cover incremental energy demand. There is thus a discrepancy between the technological horizon and the market horizon for energy that market forces alone are not able to resolve. Unless a strenuous effort is begun at once, both the industrialized and developing consuming countries are likely to experience a prolonged period at the end of this century during which energy is both expensive and scarce.

Most of the traditional oil-exporting countries are also in a difficult situation. Their economic and social development is a complex long-term process, and oil is their only real asset. The insufficient development of alternative sources of energy creates an increasing pressure upon the oil resources of these countries. They therefore risk entering the next century with depleted oil resources, financial assets eroded by inflation, and much larger populations. However, for some oil producers, increasing production will lead to financial surpluses, which they have not yet been able to invest successfully; this makes these surpluses less attractive. The decision facing a surplus member of OPEC can be seen as a portfolio decision: whether to invest in oil in the ground by holding back production or to produce above current economic requirements and to invest abroad.

Thus, given this overall situation, there is a case for a political solution to the problems of the world oil market.[13] The purpose of this study is to propose a negotiated international oil agreement that could help overcome the discrepancy between the technological capabilities and the market needs for energy, and at the same time help with the economic development of the oil-exporting countries. As a basis for this proposal, this study contains an analysis of the existing world oil market—both its economic and its political features—and a description of various ways it might evolve in the near future. At the outset, a brief sketch of the basic line of argument seems in order before turning to the analysis itself.

[12]Carroll L. Wilson (ed.), *Energy: Global Prospects, 1985–2000*, Report of the Workshop on Alternative Energy Strategies, McGraw-Hill, New York, 1977, p. 17.

[13]Neil H. Jacoby, "Oil and the Future: Economic Consequences of the Oil Revolution," *The Journal of Energy and Economic Development*, Autumn 1975, pp. 45–54, and Mason Willrich and Melvin A. Conant, "The International Energy Agency: An Interpretation and Assessment," in *The American Journal of International Law*, April 1977, pp. 199–223.

The point of departure will be an examination of the inherent instability of the world oil market, which results from the structure of the supply-and-demand relationship. This contributes to the high degree of politicization in the market. I shall then analyze the politics of both the OECD (Organization for Economic Cooperation and Development) and OPEC sides of the market. This discussion of their interests and potential for internal cooperation and conflict will be followed by an analysis of their interdependence.

Using this model of the political economy of the oil market, I shall look to future developments and the various ways oil politics might evolve. A solution to many of the future problems that are projected lies in the oil agreement I propose in the concluding chapter. It would regulate the market for the benefit of both producers and consumers, taking into consideration the current complexity of North-South relations.

The essentials of the international energy agreement proposed here can be reduced to a few elements. The most important one is a rational relationship between oil prices and oil supplies. There should be a gradual increase in the price of oil linked to the growth of consumption, and, up to a given level, OPEC should guarantee increased supplies. The negotiated price for oil should also be designed to reach the cost of alternative sources of energy when pressure on oil reserves reaches a certain point. This satisfies the need of both consumers and producers to stabilize the market and helps ensure an orderly transition to alternative sources of energy.

The second element involves encouraging oil producers to expand supplies while at the same time providing a method to offset the burden on the balance of payments of the oil consumers. This can be done by guaranteeing OPEC investments [illegible] OECD area against [illegible] currency depreciation, and nationalization. This not only [illegible] provide a means of absorbing balance-of-payments deficits and surpluses but will also give oil exporters assured sources of income and a direct interest in the economic health of the consumers.

The third element consists of giving the producers a direct interest in the energy consumption of the oil importers, combined with an intensified effort to develop alternative sources of energy. The oil producers should be given incentives to invest in downstream oil operations and in alternative sources of energy in the OECD area.

The fourth point, like the third, combines the OPEC concern with diversifying their sources of income and the desire of the oil consumers to make the producers more dependent on the OECD economies. This can be achieved by the OECD area offering technical and organizational assistance to the oil producers, along with greater access to OECD markets.

An international energy agreement that includes these elements could make the interdependence between the oil producers and oil consumers more balanced, help ensure the economic health of both OPEC and OECD countries, and reduce the political conflict potential of the world oil market.

As their vulnerability increases, the need of the industrialized consumers for an agreement regulating oil prices and oil supplies grows, and this weakens their bargaining position. It is therefore unlikely that the industrialized consumers will be able to obtain an agreement on oil without giving considerable attention to OPEC demands for linking an energy deal to assistance to the less developed countries (LDCs). This raises the question of whether an isolated energy agreement is politically possible or whether it could only be brought about as part of a comprehensive agreement, including economic development and commodities. In any case, an energy agreement that does not take at least the energy interests of the LDCs into consideration seems politically inconceivable. In the long run it could even be in the interest of the industrialized consumers to associate the LDCs with an energy deal. As consumers, the LDCs have interests that are increasingly similar to those of the industrialized consumers, and

the LDCs might in the long run have a mediating influence between oil exporters and the OECD area.

It is, of course, difficult to discuss oil politics without taking into account the situation in the Middle East. The persistence of the Arab-Israeli conflict is likely to produce an increasingly unstable world oil market and make an international oil agreement difficult to achieve. The solution discussed in this study presupposes that the Arab-Israeli conflict will have been settled by the early 1980s, either through negotiation or a new war.

TWO

The International Politics of Oil

THE RESOURCE BASE

Many economic analyses of the energy situation tend to treat the supply side lightly.[1] In reality, the distinction between supplies from renewable and finite sources is of fundamental importance. It affects both replacement costs and the supply of substitutes and has particular significance for the study of the world oil market.

The production and consumption of a renewable resource can be seen as a self-sustaining circular process in which the resource base and the supply potential do not get eroded by continuous use. Examples of renewable resources are hydroelectric power and solar energy. By contrast, the production and consumption of a nonrenewable resource is a process of depletion, the resource base and the supply potential declining with use.[2] Typical examples are oil and natural gas. Historically, with increasing demand, prices have gone up, technology has improved, exploration has increased, and new reserves have been brought forth.[3]

[1]William H. Miernyk, "Regional Economic Consequences of High Energy Prices in the United States," *The Journal of Energy and Development*, Spring 1976, pp. 213–239.

[2]Nicholas Georgescu-Roegen, "Energy and Economic Myths," *Southern Economic Journal*, vol. 41, no. 3, January 1975, p. 367.

[3]Hendrik A. Houthakker, *The Price of World Oil*, The American Enterprise Institute for Public Policy, Washington, D.C., 1975, p. 11ff.

Although this pattern might continue for a long time to come, the basic fact is that nonrenewable resources exist in finite quantities, whatever the price.

An important element of this observation is that all energy resources exist in different categories of availability and cost. The transition from one level to the other is not always smooth and is often characterized by discontinuities, or even abrupt changes. This means that the transition is often not an automatic and continuous process, but is marked by difficult periods of adjustment, with gluts or shortages occurring, affecting economic growth and the distribution of income. In economic terms, the price elasticity of supply for energy seems to vary considerably over time. That is to say that the amount that the price must rise to bring forth one more unit of energy varies enormously depending on the available source. For example, in the extreme, at certain periods increasing supplies are available at falling prices, whereas at other times supplies can decrease in spite of rising prices. In political terms this means that the relations of strength and the control of the industry can change dramatically over time. Thus the exploitation of a nonrenewable resource can be seen as a historical process in which at least two major phases can be distinguished: In the first, exploitation moves into more easily accessible areas; then there is a shift as the pressure upon the easily accessible areas builds up, and in the second phase exploitation moves into less easily accessible areas.

In the first phase, a finite resource is exploited where it is most accessible, and the cost of increasing production declines during this period. Because more is available at lower costs in new places, newcomers can establish themselves relatively easily, and it can be an advantage not to be tied up in older and more costly areas of production. This stimulates competition, and real prices tend to fall. In addition, it is difficult for the producers to establish an effective collusive agreement if they do not have control of the markets.[4]

In the second phase, when exploitation moves into less accessible areas, the cost of expanding production tends to increase. Since more is available only at higher costs, newcomers have more trouble establishing themselves, and it is advantageous to be producing in the older and less costly areas. Competition is thus impeded, and real prices tend to rise. Furthermore, it is relatively easy for producers to establish collusive agreements, even if they do not control the markets. An important part of this phenomenon is that the movement of real prices can be much more dramatic than the changes in the costs of production. In fact, there need not be any systematic relationship between the price and the costs of production.

In the first phase, when more is available at declining costs, the cost of substitutes is of little relevance, and the cost of production in the most accessible areas can be a useful point of reference, so that prices tend to decline toward this level.[5] In the second phase, when exploitation occurs in less accessible areas, the cost of replacement becomes more relevant, and the price approaches the cost of substitutes. To make the point succinctly: The historical shift from the first to the second phase of exploitation implies that the point of reference for pricing shifts from the cost of production to the cost of substitutes. However, the actual changes in price during these two phases depend upon a number of factors, such as the relationship between supply and demand and the degree of competition or collusion in the industry.[6] The basis for the political control of the industry also changes with the historical shift; in the first phase the control of the market is important, and in the second phase it is the control of supplies that matters.

The world's energy supplies are now running into such a period of discontinuous adjustment. The oil market had its historical shift in about 1970, when the discovery rate began to decline and consumption for the first time exceeded the expansion of new reserves through new discoveries. From 1950 to 1970 the average rate of discovery of new oil reserves in the world, excluding the U.S.S.R., Eastern Europe, and China, was about 2,500 million

[4] Jean Marie Chevalier, *Le Nouvel Enjeu Pétrolier*, Calmann-Levy, Paris, 197[illegible] ff, and Charles F. Doran, *Oil, Myth and Politics*, The Free Press, New York, [illegible]7, p. 29.

[5] Chevalier, op. cit., p. 20, and M. A. Adelman, *The World Petroleum Market*, The Johns Hopkins University Press, Baltimore, 1972, p. 195

[6] Paul Leo Eckbo, *The Future of World Oil*, Ballinger, Ca[illegible]ge, Mass., 1976, p. 2.

metric tons, equivalent to 18 billion barrels, a year. Since 1970 the discovery rate has been lower, about 2,100 million metric tons or 15 billion barrels a year.[7]

Oil discoveries have an uneven geographical distribution. The first major oil provinces were in the United States and Russia, and later even more important oil provinces, with lower costs of production, were discovered in the Middle East. The new oil provinces are smaller and scattered around the LDCs, Arctic areas, the continental shelves of Western Europe and North America, and in remote parts of the U.S.S.R. They all have costs of production that are higher than in the Middle East. In the tropical areas, that is, in many LDCs, costs of production are relatively low and lead times are relatively short. In the industrialized countries of the Northern Hemisphere, costs of production from new oil-producing areas are high and lead times generally are long.

The world's total recoverable oil reserves are now estimated to be approximately 88 billion metric tons, or 650 billion barrels.[8] This corresponds to about 34 years of production at present rates. This figure may be revised downward. In recent years, reserve estimates for most parts of the world have been reduced, particularly in the Western Hemisphere and the Middle East.[9] Since 1970, North American oil production has been declining. In the contiguous United States the resource base is so eroded that production seems likely to decline regardless of the price of oil, and the essential question here is the rate of decline.[10] In coming years several of the traditional oil producers in the Middle East and elsewhere may reduce their oil production, because reserves are being depleted.[11] It is also possible that Soviet oil production may peak around or shortly after 1980. Oil production is now increasing in a few areas, such as Alaska, the North Sea, and

[7]Carroll L. Wilson (ed.), *Energy: Global Prospects 1985–2000*, Report of the Workshop on Alternative Energy Strategies, McGraw-Hill, New York, 1977, p. 119ff.

[8]*International Petroleum Encyclopedia 1977*, The Petroleum Publishing Co., Tulsa, Okla., 1977, pp. 303–306.

[9]*Oil and Gas Journal*, December 27, 1976.

[10]*Petroleum Intelligence Weekly*, January 3, 1977.

[11]*World Energy Outlook*, OECD, Paris, 1977, p. 8.

Mexico. It is reasonable to assume that past rates of discovery can only be maintained through an extensive exploration effort, combined with an extremely high success rate.[12] It is also reasonable to assume that future discoveries of oil will be unevenly distributed geographically and that in many cases the costs of production will be extremely high.

In the immediate future, incremental oil production will have to come both from new, less accessible areas, such as Alaska and the North Sea, and from some of the traditional areas of production, such as Saudi Arabia. In a long-term perspective, it can be assumed that a ceiling will be reached on Saudi production. This will make the search for oil in less accessible areas and the development of substitutes even more urgent. This implies that long-term production costs can be seen as rising, but at present it is impossible to define the border between the short term and the long term in this respect. Consequently, price developments are also uncertain. Since the historical shift to the second phase has already taken place, the cost of substitutes is a useful point of reference in the long term. In the short term, other factors, such as the relationship between supply and demand and the preferences of important producers, especially Saudi Arabia, may be decisive. Thus, within the framework of a long-term upward trend, short-term and medium-term preferences and values can be decisive. In a word, politics are important to the price of oil.

A brief look at the history of the oil market illustrates the shift from the first to the second phase quite clearly. Energy costs can reasonably be assumed to have been declining from 1859 to 1970, as less expensive oil gradually replaced other forms of energy. This process accelerated after 1945, when not only the real price but even the nominal price of oil declined.[13] The result was a dramatic increase in the consumption and production of petroleum. Oil and natural gas accounted for 5 percent of the world's energy consumption in 1900 and for 62 percent in 1970.[14] Oil

[12]Wilson (ed.), *Energy: Global Prospects*, p. 125ff.

[13]Chevalier, *Nouvel Enjeu*, p. 19.

[14]Joel Darmstadter et al., *Energy in the World Economy*, The Johns Hopkins University Press, Baltimore, 1971, p. 106ff.

that accounted for 4 percent in [illegible] and for 44 percent in 1970. If oil consumption and production had continued to grow at past rates from 1970 to 1980, the total output of oil during this decade would probably not have been much less than the total quantity of oil produced and consumed from 1859 to 1970.[15]

The exponential growth rates of consumption and production in the first phase prepared the ground for the historical shift. About 1960 it became evident to the international oil industry that traditional oil-producing areas, such as the Middle East, would not be able to meet demand in the long run. So interest developed in new, less accessible areas like Alaska and the North Sea, where the cost of production then exceeded the price of oil. With the price increases, oil production in these less accessible areas has now become economical. Oil production in newer and more remote areas, such as the Siberian continental shelf, the Beaufort Sea, and even possibly the Antarctic, will require even higher oil prices.

In the second phase of oil production, the major point of reference for the price of oil is the cost of substitutes. The estimated cost of alternative sources of energy has grown over the past years because of unforeseen technical and environmental problems. A useful point of reference is the cost of synthetic oil. It is now estimated to be twice to three times the present price of oil, that is, in the range of $25 to $40 per barrel.[16] This now seems to be considered the ceiling for the future price of oil.

In the long term it is difficult to argue that the world is confronted with a shortage of energy or even of fossil fuels or hydrocarbons. Oil reserves could multiply if nonconventional sources are developed, such as tar sands, shale oil, and heavy oil. Coal might also provide an extensive basis for synthetic oil. The technology for the exploitation of these resources is improving; the main limitations are costs and capital. From this perspective, the world energy problem has less to do with the

[15]Christopher Tugendhat and Adrian Hamilton, *Oil—The Biggest Business*, Eyre Methuen, London, 1975, p. 215.

[16]Hannes Porias, "Alternate Sources of Energy: Possibilities and Constraints," in Ragaei El Mallakh and Carl McGuire (eds.), *U.S. and World Energy Resources*, ICEED, Boulder, Colo., 1977, pp. 75–86.

finite limits of conventional oil resources than the replacement of conventional oil and how this should be organized. A major difficulty with alternatives to oil is that not only are their costs rising but lead times are increasing as well. In addition, political constraints on the development of alternatives are growing. Examples are found in public concern over the safety of nuclear reactors and in environmental restrictions over the production and use of coal in many industrial countries. The combined impact of these factors may be such that in the short term the price elasticity of energy supplies may be very low; that is, incremental energy supplies might not be increased no matter how much prices rise in the short run. This clearly compounds the uncertainty over prices and supplies.

The amount of conventional oil available will determine the rate at which alternatives must be developed to ensure a smooth transition to other forms of energy. The actual rate of depletion of the conventional oil reserves is dependent on the future relationship between the rate of reserve expansion and the rate of growth of consumption. Estimates of future additions to world oil reserves are, of course, most uncertain, because they depend upon new discoveries and improved recovery from existing wells. The Workshop on Alternative Energy Strategies makes the following evaluation of possible additions to world oil reserves.

TABLE 1

Estimated Annual Additions to World Oil Reserves, In Billions of Metric Tons

	High	*Low*
1975–2000	2.8	1.4
2000–2010	1.7	1.1
2010–2020	1.0	0.8
2020–2025	0.6	0.4

SOURCE: Carroll L. Wilson (ed.), *Energy: Global Prospects 1985–2000*, Report of the Workshop on Alternative Energy Strategies, McGraw-Hill, New York, 1977, p. 126.

With the high rate of reserve expansion, the gross addition to world oil reserves could be 70 billion tons between 1975 and 2000, almost doubling the 91 billion tons of oil reserves that were available by the end of 1975. With the low rate of reserve expansion, oil reserves would grow by 35 billion tons between 1975 and 2000, increasing reserves by only slightly more than a third. These estimates for reserve expansion should, however, be measured against estimates for oil consumption to get a clear picture of future world oil reserves.

Here, four rates of reserve expansion will be assumed:

1. A very high rate, 25 billion barrels or 3.5 billion tons a year
2. A high rate, 20 billion barrels or 2.8 billion tons a year
3. A medium rate, 15 billion barrels, or 2.1 billion tons a year
4. A low rate, 10 billion barrels, or 1.4 billion tons a year.

Only the most optimistic of combinations, those with a very high rate of reserve expansion combined with a low rate of annual demand growth, prevent oil reserves from being seriously eroded in this century. With all other combinations, available oil reserves will be diminished considerably, particularly in the period after 1990. Some combinations, which cannot be ruled out, even give a physical deficit of oil by 2000. This means that the relationship between reserves and production is likely to decline considerably in the 1980s and 1990s, making for a potential shortage of oil by 1990 or perhaps even earlier. This would probably stimulate oil producers to adopt more restrictive depletion policies and encourage consumers to compete more agressively for available oil supplies. Such developments would inevitably call into question the availability of oil in an open world market.

THE DEPENDENCE ON OIL

At present the OECD area is heavily dependent on other countries for its oil. Furthermore, it is by far the world's biggest consumer of oil. In 1975 the OECD countries accounted for 66

TABLE 2
State of World Oil Reserves at Different Rates of Reserve Expansion and Demand Growth, in Millions of Metric Tons

Projected Reserves at a Very High Rate of Expansion

Growth rate of demand (%)	1975	1980	1985	1990	1995	2000
2	91,000	93,300	95,800	92,900	89,900	84,700
3	91,000	92,800	92,100	88,500	81,600	70,700
4	91,000	92,300	90,200	83,700	72,100	54,500
5	91,000	91,800	88,100	78,500	61,400	34,700

Projected Reserves at a High Rate of Expansion

Growth rate of demand (%)	1975	1980	1985	1990	1995	2000
2	91,000	89,800	87,800	82,400	75,100	67,200
3	91,000	89,300	85,100	78,000	67,600	53,200
4	91,000	88,800	83,200	73,200	58,100	36,700
5	91,000	88,300	81,100	68,000	47,400	17,200

Projected Reserves at a Medium Rate of Expansion

Growth rate of demand (%)	1975	1980	1985	1990	1995	2000
2	91,000	86,300	81,800	71,900	61,900	49,800
3	91,000	85,800	78,100	67,500	53,600	35,700
4	91,000	85,300	76,200	62,700	44,100	19,200
5	91,000	84,800	74,100	57,500	33,400	(−300)

TABLE [illegible] (Continued)
State of World Oil Reserves at Different Rates of Reserve Expansion and Demand Growth, in Millions of Metric Tons

Projected Reserves at a Low Rate of Expansion						
Growth rate of demand (%)	*1975*	*1980*	*1985*	*1990*	*1995*	*2000*
2	91,000	82,600	74,800	61,400	47,900	32,200
3	91,000	82,300	71,100	57,000	39,600	18,200
4	91,000	81,800	69,200	52,200	30,100	1,700
5	91,000	81,300	67,100	47,000	19,400	(−17,400)*

*Negative values indicate the extent to which demand will have exceeded reserves.

SOURCE: Author's own calculations.

percent of world oil consumption, but only 25 percent of production. Imports into the OECD area represented close to 45 percent of all oil produced in the world. The OECD area has 10 percent of the world's proven oil reserves, corresponding to 17 years of production and to 5 years of consumption at current rates. By contrast, in the rest of the world oil reserves correspond to 38 years of production and 87 years of consumption.[17]

This has triggered an intense debate about the nature of Western dependence on imported oil. There are profound disagreements over the outlook for the medium term, the period from 5 to 15 or 20 years ahead. First, there is disagreement about the impact of price hikes on the general level of energy consumption and, in particular, on the relationship between the rate of economic growth and the growth of energy consumption. Second, there is disagreement on the substitution of expensive imported oil for other forms of energy. The controversy can be summed up by two opposing arguments.

[17]*International Petroleum Encyclopedia 1977*, p. 303.

One view is that there are still large quantities of inexpensive energy available. The increase in the oil price will first lead to a reduced growth of demand and then to an increasing output of oil, from the discovery of new fields and from improved recovery in existing oil fields. The higher prices will also accelerate the development of alternative sources of energy whose costs will fall. There may even be a glut of energy, and particularly of oil. Excess capacity will cause OPEC to break down because of disagreements on the distribution of production and income.[18] Eventually, prices will fall and Western dependence on imported oil will be seen as transitory.[19]

The second argument points out that oil is a scarce resource. Other forms of energy either are technically undeveloped (solar energy, fusion), are very expensive (synthetic oil), or cause environmental and safety problems (coal, nuclear fission). The demand for energy does not seem to be too sensitive to price changes, at least within the known limits. Historically, there is a fairly close relationship between the level of energy consumption and the level of economic activity, even if there are important variations by country and over time.[20] Because probabilities of improving the discovery rate for oil, or of substantially improving the recovery rate from existing fields, are low, and because of the large costs and lead times for other forms of energy, there is unlikely to be a glut of oil, or of energy. On the contrary, there may be a shortage of energy until alternatives are sufficiently developed, and chances are that the price of oil will increase further.[21] The dependence of the Western industrial countries on imported oil is likely to continue for a considerable period of time, at even higher prices.[22]

[18]Eckbo, *Future of World Oil*, p. 269ff.

[19]Edward R. Fried, "World Market Trends and Bargaining Leverage," in Joseph A. Yager and Eleanor Steinberg (eds.), *Energy and U.S. Foreign Policy*, Ballinger, Cambridge, Mass., 1975, p. 269ff.

[20]Darmstadter et al., *Energy in the World Economy*, p. 27ff.

[21]Parra, Ramos, and Parra, *World Supplies of Primary Energy 1976–1990*, Energy Economics Information Service Ltd., Wokingham, Berkshire, England, 1976, p. 13.

[22]*World Energy Outlook*, p. 9.

The first argument fits well with neoclassical economics, and the second reflects certain neo-Malthusian assumptions. Differences in relative endowments and in ideological propensities may explain why neoclassical analyses and prescriptions are more accepted in North America than in Western Europe.

The choice of argument also has a practical importance in the choice of policies and solutions. If the first argument is right, the high relative price of energy and dependence on imported oil will last a short time, constituting a temporary disturbance for the OECD economies. This disturbance can be most properly countered by short-term measures designed to neutralize the effects of the high price of oil.[23] If, however, the second argument is more valid, the high relative price of energy and the dependence upon oil imports will last a long time and will reflect a structural change in the environment and the fundamental working conditions of the OECD economies. In this case the appropriate response is by measures designed to adjust the OECD economies to the high price of oil. Structural changes in the OECD economies, and possibly in the international financial system, may be required. This may also imply an international negotiated settlement to regulate the world oil market.

Choosing between the two arguments is risky because the implementation of the wrong policy could be costly. Applying long-term measures to a temporary phenomenon does more harm than good by keeping the relative price of oil at an artificially high level, thus reducing the possible rate of economic growth in Western countries and LDCs. Applying short-term measures to a structural problem may have dangerous consequences because it would keep the Western economies and possibly the LDCs in an artificially comfortable environment in which contradictions would build to create an extremely serious future energy shock.

The disagreement between the two positions essentially comes down to differences over the long-term price elasticities of demand and supply for energy. The "neoclassical" argument as-

[23]Eric Rhenman, *Organisationsproblem och långsiktsplanering*, Bonniers, Stockholm, 1975, p. 266.

sumes that both are high, which means that both supply and demand are responsive to changes in price. This is believed because it is rational economic behavior to consume less and to produce more energy at higher prices. The "neo-Malthusian" argument assumes that both are low, or in other words that demand and supply are not very responsive to changes in price. This assumption is based on the observation that consumers are largely indifferent to energy prices—giving a high priority to energy-intensive habits of consumption. In addition, the physical and technical possibilities for increasing energy output are limited. So the major points of discord relate to consumer behavior in the face of rising prices, the probability of finding new oil fields or improving recovery from existing ones, and the prospects for alternative energy sources.

The two arguments are not mutually exclusive in a dynamic perspective. It can reasonably be argued that in a medium-term perspective the neo-Malthusian position provides the best image of reality and that the neoclassical pattern will only assert itself over the long run. As a result, policy makers should not assume that the forces of the market will cause OPEC to break down and oil prices to fall again as neoclassical analysis suggests.[24]

Two observations support this dynamic view of the neo-Malthusian and neoclassical positions. First, the high price of oil set by OPEC is essentially a function of external conditions, namely the historical shift of the exploitation to less accessible areas. By doing away with OPEC, the process might be delayed somewhat but not fundamentally changed. Eventually there will be a transition to other forms of energy and the market will adjust to this in the long run.

Second, the direct substitution of other forms of energy for oil is difficult for many reasons. Oil is in many ways an ideal primary energy source. It is relatively clean, is transportable, and allows consumers considerable flexibility. These technical qualities have fostered specific patterns of consumption and have

[24]Ragaei El Mallakh et al., *Implications of Regional Development in the Middle East for U.S. Trade, Capital Flows and Balance of Payments*, ICEED, Boulder, Col., 1977, p. 9.

increased the use of energy in modern economies. This can be seen by the rapid increase in Western oil consumption in the postwar period, which is not due to the replacement of coal by oil as much as it is the result of new patterns of oil consumption. The use of the automobile, petrochemical products, and oil-based heating systems are the best examples of these new patterns. The direct substitution of oil by other primary sources of energy is possible in only some cases. Coal can replace oil for heating, and both coal and nuclear power can be used to produce electricity, but there are no primary forms of energy that can substitute for most transportation and petrochemical uses of oil. A good substitute for oil must have essentially the same characteristics of flexibility, transportability, and so forth. This suggests synthetic oil, which is extremely expensive and much less efficient than primary sources of energy. The widespread substitution of oil by coal and nuclear, geothermal, solar, and other forms of energy, implies extensive changes in production processes, patterns of consumption, and methods of transportation. This means large investments and high capital costs, and it would only be economical at very high oil prices.

Given these realities, it is no wonder that it is hard to find good substitutes for oil, and this explains the low price elasticity of demand generally observed.[25] Oil, quite simply, is a necessary input in many modern production and consumption processes. The importance of oil is not reflected by its small part of the gross national product,[26] but it nonetheless functions as a catalyst without which other inputs would be much less effective.[27] It should be recalled that substantial conservation efforts require a long time. For example, reducing by half the amount of energy needed for producing ammonia has taken 60 years.[28] The replacement of one form of energy by another as the dominant one is a long historical process too. It took 70 years for oil to move from providing 4 percent to providing 44 percent of the world's energy. In the medium term there are obviously limits to the ability of substitutes or conservation to replace oil. This unavoidable dependence on oil, which necessarily follows, makes the availability of oil a critical political question for all countries and places us squarely in the neo-Malthusian dilemma, at least, for the short run.

[25]Neil H. Jacoby, "Oil and the Future: Economic Consequences of the Oil Revolution," *The Journal of Energy and Economic Development*, Autumn 1975, p. 15.

[26]Chauncey Starr, *Energy Planning—A Nation at Risk*, Electric Power Research Institute, Palo Alto, Calif., 1977, p. 2.

[27]William W. Hogan and Alan S. Manne, *Energy-Economy Interactions: The Fable of the Elephant and the Rabbit*, Energy Modeling Forum, Stanford University, Stanford, 1977, p. B-2ff.

THE POLITICIZATION OF OIL

The critical position of oil in the world's energy balance and the uneven distribution of reserves give oil a lot of economic, strategic, and political importance. The oil price and the control of supplies are thus potentially conflicting political issues. In addition, oil becomes linked directly or indirectly to other issues. Since most countries are net importers of oil and rely heavily on this oil for total energy supplies, the price of oil and its control can have direct implications for their freedom of action in economic and foreign policy. Oil is thus linked to such matters as the rate of economic growth, the level of employment, the rate of inflation, trade policy, and general foreign policy orientation. It is also linked to the political cohesion of the world's political blocs and to the development of the LDCs.[28a] Consequently, matters relating to oil have a high priority in the industrial, economic, trade, and foreign policies of both oil-importing and oil-exporting nations, whether they are developed or developing economies.

The political importance of oil means that changes in the international oil market can have consequences for the international distribution of power. The best example is provided by the Arab oil-exporting countries, which in the 1970s have dramatically improved their ability to pursue foreign-policy goals. Another example is the United States, which by organizing the

[28]Porias, "Alternate Sources of Energy," p. 84.

[28a]Willrich, *Energy and World Politics*, p. 180ff.

industrial oil-consuming countries in the International Energy Agency (IEA) hoped to offset any loss to its own position of leadership in the Western world inflicted by the new conditions in the oil market.[29] Thus the structure and organization of the world oil market not only serve purposes of rationality and efficiency but are also in part mechanisms of political control.[30]

For both OECD and OPEC countries there can be internal conflicts over priorities related to oil and other social, economic, trade, and foreign policy goals. This can create difficult choices. Restricting or expanding oil imports can directly affect domestic political goals in OECD countries. Conversely, the world's oil exporters are concerned about the rate of depletion of their finite resources. Several of the traditional oil-exporting countries might not be able to sustain past or present levels of production, and others may prefer to keep the major national asset in the ground, deferring income to future generations.[31] The way they exploit their oil plays a decisive role in determining how and when they influence the market. Securing supplies and controlling demand are of primary importance to the governments of consumer countries, and the management of reserves is critical to the governments of the oil-exporting countries if they seek to maximize their income or promote other political goals. As a result the production, distribution, and consumption of oil are to a large extent, and increasingly, subject to government intervention and regulation.

The international oil industry has an oligopolistic structure because it is dominated by a limited number of private international and state-owned oil companies. Their long-term interests and policies often determine their short-term behavior.[32] In addition, the oil companies and the governments normally have close relations of consultation and cooperation. The major agents on the international oil market are thus a limited number of

[29] Martin Sæter, "Oljen og de politiske samarbeidsformer," *Internasjonal Politikk*, no. 2B, 1975, pp. 397–421.

[30] Ibid., p. 397.

[31] *World Energy Outlook*, p. 8ff.

[32] Anthony Sampson, *The Seven Sisters*, Hodder and Stoughton London, 1975, p. 3ff.

companies and governments, often with clearly defined long-term interests. Consequently, the patterns of oil production, distribution, and consumption are less the result of market forces than is the case with many other commodities. Instead, political intervention and long-term considerations have a greater impact, and the nation-state is a more important agent.[33]

The oil crisis of 1973–1974 demonstrated the complexity and wider political significance of the oil market. The Western-dominated system of relations between OECD and OPEC countries, and between the OECD area and the Third World, was shaken. The Arab oil embargo was explicitly linked with the conflict in the Middle East and with the position of the OECD countries toward Israel. This in turn directly affected relations between the United States and Western Europe. The cooperative policy of the European Community (EC) toward the Arab and the Mediterranean countries was in conflict with the Atlanticist policy of consolidation of the United States.

The foundation of the IEA affected the EC plans for a common energy policy and the process of economic and political integration in the EC. The IEA can be seen not only as an attempt to solve the energy problems of the OECD countries on a common basis but also as an attempt to mold the OECD countries into an institutional framework controlled by the United States.[34] One purpose was to prevent extensive bilateral deals between the other OECD countries and the oil exporters, because this could dilute the cohesion of the OECD area and reduce the political influence of the United States. Another purpose was to preserve the position of United States–based multinational oil companies in supplying OECD countries with oil. An extensive network of bilateral deals between the other OECD countries and the oil producers would probably affect the structure of international oil trade, reducing the role of the multinationals and benefiting the national oil companies of the producing and consuming countries. The solution for the United States, to defend its interests, was to attempt to speak for all the industrialized

[33] Tugendhat and Hamilton, *Oil*, p. 250ff.

[34] Ibid., p. 409.

consumers. This in part explains why the United States, which is much less dependent on imported oil than Western Europe and Japan, has, at least verbally, taken a much more aggressive attitude toward OPEC.

Another dimension in the split within the OECD over how to respond to OPEC concerns Israel. The United States has consistently supported Israel in the Middle East and was reluctant to back down simply because of the oil embargo. The other OECD countries tended to compromise with the Arab oil producers more easily. France's support for the Palestinians and its bilateral arrangements with Arab countries are probably the best example of this type of response. It is clear that just as the Atlanticist policy was in the best interest of the United States, the cooperative policy of the EC was likewise a response of self-interest. The relatively low dependence of the United States on foreign oil allowed it to continue its support of Israel while the Europeans, with a greater dependence on Middle East oil, preferred to avoid confrontations with the Arab oil producers over Israel. The Europeans also knew that the United States was not going to abandon Israel. In this context they could use their softer stance in an attempt to placate the Arab oil producers and make bilateral deals with them to help provide for their immediate energy needs. In the future this split could have dramatic consequences for the cohesion of the OECD area, especially in the event of a new war or prolonged tension in the Middle East that threatens the security of supplies. If the United States felt that it had to intervene directly this might even lead to several European countries leaving the North Atlantic Treaty Organization (NATO).

Similarly, splits could develop over policies toward the Third World and the structure of a new international economic order, especially if OPEC countries directly linked negotiations over North-South relations to oil prices and supplies. Some European governments—that of France, for example—believe that a more generous attitude toward Third World demands could have a beneficial impact on the security of their oil supplies. The Scandinavian countries and the Netherlands support a more generous attitude toward Third World demands, for ethical and ideological

reasons. Thus a split could develop within the OECD area between generous and less generous friends of the Third World, with the first perhaps hoping to have preferential treatment from OPEC and preferred access to LDC markets and resources.

It is significant that the links to other important economic and political problems have increasingly been made explicit, whereas only a few years ago they were only implicit. The United States has on several occasions stressed the link between oil and security in relations with Western Europe. In order to make Western Europe accept common institutions for energy policy, the United States used security policy and the presence of American troops in West Germany as a means of pressure.[35] Another recent example of the open linkage of issues was at the OPEC meeting in Doha in December 1976, where Saudi Arabia explicitly linked the price of oil to Middle East peace developments and to the results of the Conference on International Economic Cooperation (CIEC) held in Paris in 1976–1977.[36]

OIL REGIMES

The dramatic character of the oil crisis of 1973–1974 overshadowed some of the long-term economic problems with the demand and supply of energy. The crisis produced in a few months important economic and political changes in the world oil market. These changes were a kind of "oil revolution,"[37] a transition from the First Oil Regime to the Second Oil Regime.

The First Oil Regime was characterized by an integrated pattern of organization, based in the major consuming countries, and a low price for oil. During the First Oil Regime the center of the world's oil production gradually shifted from North America to the Middle East. Decreasing exploitation costs and the political dominance of important producing areas by major consuming countries made this shift possible. The industrialized

[35] Ibid., p. 402.

[36] Louis Turner, "Oil in the North-South Dialogue," *The World Today*, February 1977, p. 57.

[37] Tugendhat and Hamilton, *Oil*, p. 179ff.

consuming countries became increasingly dependent on a limited number of developing countries for their oil. Within the First Oil Regime the basis of the regime's existence was eventually eroded because power shifted to countries whose interests the regime did not serve. The combination of rapidly growing demand and rising exploitation costs (shown by the investments in areas like Alaska and the North Sea) proved fatal to the First Oil Regime because it opened the way for a price increase and institutional change through OPEC control of production. This loss of the economic and political basis of the regime explains the abruptness of the transition, once the catalyst of the Middle East dispute set it off.

The Second Oil regime is characterized by a fragmented pattern of organization and a much higher price for oil. The center of world oil production is the Middle East, but for physical and political reasons it is not clear if growing demand can be met by supplies from this area. Efforts are being made to find and produce oil in new oil provinces, but it is unlikely that oil from these new areas will be able to keep pace with demand for long. Thus the need to develop alternative sources of energy will become more and more urgent.[28] The Second Oil Regime, like the first, erodes the basis of its own existence through its inability—for physical and political reasons—to guarantee sufficient supplies of oil.

Assuming that in the short run the industrial consuming countries fail to achieve much greater energy self-sufficiency, a sudden collapse of the Second Oil Regime can be anticipated. One of the following three options seems probable:

- The oil-producing countries will supply the quantities of oil demanded on the world market at gradually higher prices so that alternative sources of energy eventually become more competitive.
- The oil-producing countries will supply the quantities of oil demanded, but at sharply increasing prices, provoking a new recession in the OECD area.

[28] Ibid., p. 380.

- The oil-producing countries will not supply the quantities of oil demanded on the world market but will use oil as a means to achieve other political goals by rationing exports and selecting favorite clients.

It is clearly in the interest of the OECD countries to avoid the last two possibilities, even if this means the end of the Second Oil Regime through an accelerated development of alternative sources of energy or through direct military intervention in the oil-producing countries. It is in the interest of both producers and consumers to have a gradual transition from the Second Oil Regime to a third one; indeed, such a transition appears to be inevitable. A historical trend for incremental energy supplies can be assumed, moving from cheap conventional oil, by way of more expensive oil, to extremely expensive synthetic oil. This trend can also provide the basis for a transition from one oil regime to another. These three regimes are schematically presented in Table 3.

Regardless of how we arrive at the Third Oil Regime, it is clear that the energy problems that caused the oil revolution have not vanished, and the Second Oil Regime has not yet been tested in a situation of rapidly increasing demand. Therefore, the political and physical limits to the energy supplies of the OECD countries

TABLE 3
The Three Oil Regimes

	Oil Regime		
	First	*Second*	*Third*
Incremental resource base	Conventional oil	Alternative oil	Synthetic oil
Marginal costs	Falling	Rising	Rising
Price	Low	High	Very High
Structure	Integrated	Disintegrated	?
Control	Consumers	Producers	?

could be tested again.[38] In practical terms this means that their bilateral relations with OPEC countries and the development of alternative sources of energy are of primary concern to the OECD area. The crucial question for this study is whether the OECD countries and OPEC are better off with or without a negotiated settlement. To resolve this question we need a clearer picture of OECD-area needs and the likely OPEC response to them.

TABLE 4
Distribution of World Oil Reserves and Oil Production in 1975, in Millions of Metric Tons

	Reserves	*Production*	*Ratio of reserves to production*
North America	5,656	489	11.5
Western Europe	3,531	27	130.7
Middle East	55,247	977	56.5
Latin America	5,551	219	25.5
Asia	2,879	110	26.1
Africa	9,343	249	37.5
Communist nations	15,239	592	25.7

SOURCE: *International Petroleum Encyclopedia 1976*, The Petroleum Publishing Co., Tulsa, Okla., 1976, pp. 12–13, and *Basic Petroleum Data Book*, American Petroleum Institute, Washington, D.C., 1975, section IV, table 1.

[38]*World Energy Outlook*, p. 8ff.

TABLE 5
World Petroleum Trade Balances for 1976, in Millions of Metric Tons

Region	*Petroleum production*	*Petroleum consumption*	*Trade balance*
North America	489.1	908.3	− 419
Western Europe	46.5	691.1	− 645
Australia, New Zealand	22.8	37.7	− 15
Japan	0.5	254.5	− 254
OECD area total	558.9	1,891.6	− 1,333
Middle East	1,137.8	88.5	+ 1,050
*Asia**	115.5	121.2	− 6
Africa	291.0	54.2	+ 237
Latin America	228.4	189.1	+ 39
China	91.0	66.0	+ 27
U.S.S.R. + Eastern Europe	527.3	460.0	+ 67
World excluding OECD	2,391.0	979.0	− 1,414
World including OECD	2,949.9	2,870.5	

*Excluding Japan, Australia, and New Zealand.

SOURCE: *International Petroleum Encyclopedia, 1977*, The Petroleum Publishing Co., Tulsa, Okla., 1977, pp. 392–393, 277–279.

TABLE 6
World Energy and Oil Consumption, 1900–1974

Year	World energy consumption (millions of metric tons of oil or the equivalent)	Yearly growth rate	Oil consumption (millions of metric tons)	Yearly growth rate	Cumulative Oil consumption by period (millions of metric tons)	Cumulative oil consumption (millions of metric tons)	Period as a percentage of total
1900	532		21				
1913	945	4.52	57	7.98	451	451	1.3
1929	1,190	1.45	179	7.41	1,645	2,096	4.6
1937	1,260	0.72	227	3.01	1,592	3,688	4.4
1950	1,750	2.56	438	5.19	4,070	7,758	11.4
1958	2,632	5.23	816	8.09	4,674	12,432	13.0
1967	3,976	4.69	1,551	7.35	9,917	22,349	27.7
1974	5,579	4.96	2,511	7.12	13,412	35,821	37.6

SOURCE: John Chesshire and Keith Pavitt, *Social and Technological Alternatives for the Future—Energy*, Science Policy Research Unit, University of Sussex, Brighton, England, 1977, p. 9.

TABLE 7
World Petroleum Consumption and Production 1950–1975, in Millions of Metric Tons

	Consumption			Production		
Year	*World*	*WECC**	*OECD*	*World*	*WECC**	*OECD*
1950	478	436	368	514	476	274
1960	1,051	907	753	1,036	875	388
1970	2,281	1,948	1,608	2,216	1,831	562
1973	2,789	2,355	1,949	2,740	2,284	578
1975	2,742	2,239	1,804	2,622	2,039	527

*World excluding the Communist countries (U.S.S.R., Eastern Europe, and China).

SOURCE: *International Petroleum Encyclopedia, 1977*, pp. 392–393, 277–279.

TABLE 8
World Oil Reserves and Oil Production 1950–1975, in Millions of Metric Tons

Year	*World oil reserves*	*World oil production*	*Ratio of reserves to production*
1950	10,458	520	20.1
1960	39,676	1,049	37.8
1970	72,576	2,295	31.6
1973	90,864	2,786	32.6
1975	97,458	2,664	36.5

SOURCE: *International Petroleum Encyclopedia, 1977*, pp. 12–13, and *Basic Petroleum Data Book*, section IV, table 1.

TABLE 9
Rates of Growth of Oil Consumption

	World	WECC*	OECD
1950–1960	8.2%	7.6%	7.4%
1960–1970	8.1	7.9	7.9
1970–1973	6.9	6.5	6.6
1950–1973	8.0	7.6	7.5
1960–1973	7.8	7.2	7.6

*World excluding the Communist countries (U.S.S.R., Eastern Europe, and China).

SOURCE: Chesshire and Pavitt, *Social and Technological Alternatives for the Future—Energy*, p. 8.

TABLE 10
Cumulative Volume of Oil Consumed, in Millions of Metric Tons

	World	WECC*	OECD
1950–1959	6,989.2	6,198.8	5,174.5
1960–1969	15,299.3	13,078.5	10,859.6
1970–1973	10,112.1	8,583.0	7,099.0
1950–1973	32,400.6	27,860.3	23,133.1
1960–1973	25,411.4	21,661.5	17,958.6
1970–1980†	33,199.7	28,079.0	23,189.8

*World excluding the Communist countries (U.S.S.R., Eastern Europe, and China).

†Hypothetical at growth rates of period 1960–1969.

SOURCE: Chesshire and Pavitt, *Social and Technological Alternatives for the Future—Energy*, p. 8.

THREE

OECD Demand

Under the First Oil Regime low prices and increasing supplies of oil gave most OECD governments inexpensive and assured energy supplies without disturbing important economic and foreign policy goals. Cheap foreign oil covered their incremental energy demands and substituted for more expensive domestic sources of energy, without weighing heavily on their balance of payments. Their control of the oil industry implied that increasing dependence on oil imports was not associated with political dependence on the oil-exporting countries. For example, as recently as during the Six-Day War in 1967, oil supplies from the Middle East were generally uninterrupted. Thus the First Oil Regime allowed OECD governments to ignore the problem of potential oil shortages.

In the post-1974 period, under the Second Oil Regime, continued economic growth in the OECD countries could be less compatible with other important goals of economic and foreign policy. High oil prices could have a negative effect on the balance of payments and, indirectly at least, stimulate inflation. Increasing dependence on oil imports could also limit freedom of action in foreign policy. At the same time, though, high levels of unemployment and stagnant real incomes in many OECD countries make it difficult for governments to pursue a policy of economic austerity over a long period. Many OECD governments, if not most, may thus have to sacrifice internal or external policy goals to cope with their energy problems.

The crucial question is: To what extent does the oil revolution actually mark a historic break in energy demand trends? In 1974 and 1975 there was an absolute decline in the energy consumption of the OECD area, caused almost entirely by the drop in oil consumption. This decline was due less to the price increase than to the economic recession and to the exceptionally mild winters. Since the end of 1975 energy consumption, including the use of oil, has increased again as economic growth has picked up. Future growth rates will depend on national and international market forces, on the domestic political pressures put on governments, and on their freedom of action in the relationship between economic policy and energy policy.

THE FACTORS OF DEMAND

The important economic factors behind oil imports are the rate of economic growth, the domestic output of energy, and the energy coefficient (the relationship between the economic growth rate and the growth of energy consumption). In terms of economic analysis, oil imports are the residual, or what is left over, of the economy's energy requirements, after domestic energy production has been absorbed.

The important political factors that influence oil imports are the goals of national economic and energy policies and the impact of business and public interest groups on these policies. Oil imports can be seen as unmet national energy needs, which are one element in the balancing of a nation's economic and energy goals in such a way that excessive domestic opposition is avoided.

These two approaches to the analysis of oil imports are complementary. One stresses the importance of economic processes, the other the importance of political decisions. Both underline the fact that oil imports represent that part of essential national energy needs that cannot be satisfied domestically. This implies that relatively small economic or political changes can have quite important effects on the level of oil imports. Let us now turn to the specific economic processes that influence demand for oil in the OECD area.

The energy coefficient is critical, and the OECD economies can reasonably be expected to have a lower one in the post-1974 period than before 1973. In other words, pre-1973 economic growth rates can now be achieved with a smaller growth rate of energy consumption. Historically, there is a close relationship between the rate of economic growth and the growth of energy consumption, but there are important differences over time and between countries.[1] There has in some cases been a tendency for the energy coefficient to fall with greater industrial maturity.[2] Today the consumption of energy in relation to gross national product is twice as high in the United States as in West Germany or France.[3] Geographical size is not the only explanation for this. Both the price of energy and the content of economic growth are important factors here. Thus past relationships between economic growth and the growth of energy consumption cannot be uncritically projected into the Second Oil Regime. In economic terms, it is rational behavior to use less energy at high prices, and politically many governments are encouraging energy conservation.

There are also arguments against the trend toward declining energy coefficients. Consumers appear to give a high priority to habits of consumption that are energy-intensive, particularly with rising living standards.[4] Also, there is a widespread consumer indifference to rising costs and the insecurity of energy supply.[5] Industry is now reluctant to conserve energy by changing production processes and by new investments in energy-saving

[1]Darmstadter et al., *Energy in the World Economy*, The Johns Hopkins University Press, Baltimore, 1971, p. 37.

[2]John Chesshire and Keith Pavitt, *Social and Technological Alternatives for the Future—Energy*, Science Policy Research Unit, University of Sussex, Brighton, England, 1977, p. 6ff.

[3]Joel Darmstadter, Joy Dunkerley, and Jack Alterman, *How Industrial Societies Use Energy: A Comparative Analysis*, Resources for the Future, Washington, D.C., 1977, p. 21ff.

[4]D. K. Verleger and D. P. Sheehan, "A Study of the Demand for Gasoline," in Dale W. Jorgensen (ed.), *Econometric Studies of U.S. Energy Policy*, North Holland Publishing Company, Amsterdam, 1976, pp. 179–234.

[5]Anthony Sampson, *The Seven Sisters*, Hodder and Stoughton, London, 1975, p. 29.

equipment because of uncertainty over future energy prices and because the cost of energy conservation could be very high. In addition, many firms simply offset higher energy costs by higher prices. Finally, expenses for energy still make up only a small proportion of users' budgets, so price increases in many cases can continue to be absorbed.

Little is known about long-term energy coefficients at high income levels after a sharp price increase such as the one experienced in 1973. The OECD assumes an average energy coefficient of 0.84 over the period 1974–1985, at constant oil prices.[6] This is a decline of 24 percent in the energy coefficient of the pre-1973 period, when real oil prices were about one-third of what they are today.

We can reasonably suppose that the growth of domestic energy production in the OECD countries will be higher in the post-1974 period than before 1973. The question again is how much, and again little is known about the long-term price elasticity of energy supply in advanced industrial countries after a sharp price increase. In economic terms, it is rational to produce more energy at higher prices. Politically, many governments actively encourage domestic energy production to offset balance-of-payments deficits and reduce supply insecurity. In practice, however, the responsiveness of OECD energy production to the price increase seems to be modest.[7] There is the problem of rising costs, which applies to all forms of energy produced in the OECD area. Politically, there is increasing environmental concern, and uncertainty in the private sector. This is reflected in a general reluctance to channel large funds into the energy sector and in resistance to particular forms of energy production, such as nuclear power, coal, and offshore petroleum. Thus it is questionable to what extent market forces alone will be able to bring about a significant growth in energy production.

The potential production of oil in the OECD area will be influenced by new discoveries and by the energy policy of a few countries. There are definite possibilities of finding additional reserves of petroleum in the OECD area. These possibilities are greatest in the new oil provinces—on the continental shelves of the United States, Canada, Great Britain, and Norway, as well as in the Canadian Arctic and Alaska. These regions are typical provinces of "alternative" oil, with high costs and lead times of 4 to 10 years.[8] Before 1985 these new fields are not likely to contribute substantially to the oil production of the OECD area. Another problem is the potential effect of changes in energy policy in key countries, particularly in the United States. For Americans the major question is the potential impact of deregulation of oil and gas prices on reserve estimates and supplies. In Canada the possibility of stopping the decline in oil production before 1985 seems remote. In Norway the question is the potential effect of a less restrictive production policy. In Great Britain the uncertainty concerns reduced output stemming from a possible depletion policy, once self-sufficiency is achieved.

In the period 1960–1973 the energy production of the OECD area expanded at an average yearly rate of 2.5 percent. For the period 1974–1985 the OECD assumes an average yearly growth in energy production of 3.5 percent, implying a strenuous effort in the form of political resolution and capital mobilization. If a much stronger effort is made, the OECD assumes that the growth rate could be 4.5 percent.[9]

REGIONAL CONTRASTS

The prospects for energy production are different in the various OECD regions, depending on local physical, economic, and political conditions. In the 1960s domestic energy production had a high yearly growth rate in North America, was stagnant in Western Europe, and was negative in Japan. By contrast in the 1970s domestic energy output has had a very low growth rate in North America, an exceptionally high growth rate in Western Europe,

[6] *World Energy Outlook*, OECD, Paris, 1977, p. 27.
[7] Ibid., p. 8ff.

[8] Christopher Tugendhat and Adrian Hamilton, *Oil—The Biggest Business*, Eyre Methuen, London, 1975, p. 332ff.
[9] *World Energy Outlook*, pp. 8–9.

TABLE 11
Average Yearly Growth Rates of Energy Production, 1960–1980, in Percentages

Region	*1960–1970*	*1970–1980*	*1974–1980*	*1960–1980*
North America	4.5	1.0	1.2	2.7
Western Europe	—	6.3	8.6	3.1
Japan	− 2.2	4.5	5.5	1.1

SOURCES: *Oil—The Present Situation and Future Prospects*, OECD, Paris, 1973, and *World Energy Outlook 1977*, OECD, Paris, 1977.

and a high growth rate in Japan. During the 1960s the differences in endowment of natural resources were decisive: North America had economically recoverable reserves of coal, oil, and gas, whereas Western Europe and Japan had declining coal industries and little or no oil and gas. In addition, the regulation of oil imports kept oil prices higher in North America than on the world market, which stimulated production. During the 1970s differences in energy policies seem more decisive: In Western Europe and Japan resolute energy policies are being implemented, while in North America, particularly in the United States, energy policies are more difficult to implement. Also, in the United States price regulation keeps oil prices lower than on the world market, which tends to discourage production. In addition, the economically recoverable reserves of oil and gas, at least in the traditional areas of production in North America, are declining; Western Europe, on the other hand, is tapping its new offshore reserves.

These differences in the growth of energy production give remarkable contrasts in the growth of oil imports (see Table 12). The contrasts are particularly striking over the years immediately following the oil crisis—the period 1974–1980. This period is characterized by an almost stagnant output of energy but rapidly increasing oil imports in North America and rapidly growing energy production with a slight drop in oil imports for Western Europe. To a certain extent these differences are explained by factors that are independent of the oil crisis, including investment

TABLE 12
Average Yearly Growth Rates of Oil Imports, 1960–1980, in Percentages

Region	*1960–1970*	*1970–1980*	*1974–1980*	*1960–1980*
North America	5.2	11.6	9.9	8.4
Western Europe	12.6	0.4	− 2.1	6.3
Japan	19.9	6.2	4.8	12.9

SOURCES: *Oil—the Present Situation and Future Prospects*, and *World Energy Outlook 1977*, OECD.

in the North Sea oil industry and the diminishing conventional reserves of oil and gas in North America. The rapidly increasing oil imports of North America, and of the United States in particular, contrast not only with the declining oil imports of Western Europe but also with policy declarations made by the United States government on the need to reduce dependence on imported oil.[10] A look at differences in governmental attitudes and policies will help explain the contrasting situations of North America and Western Europe with regard to oil imports.

First of all, there is the question of how the government bureaucracies of the United States and of most countries in Western Europe evaluate the long-term price elasticities of demand and supply for energy. As noted above, the neoclassical point of view seems to be more widespread in the United States, while the neo-Malthusian view is prevalent in Western Europe. This explains why many European governments have taken stronger action on energy. The ambitious energy-conservation and nuclear programs of France and West Germany are good examples.[11] Their relatively high dependence on imported oil may also be an important additional factor here.

Second, there is the question of how the political systems of

[10] U.S. Executive Office of the President, *The National Energy Plan*, Washington, D.C., 1977, p. 9ff.

[11] Horst Mendershausen, *Coping with the Oil Crisis*, The Johns Hopkins University Press, Baltimore, 1976, p. 67ff

the United States and Western Europe function on energy issues. The implementation of ambitious energy policies in Western European countries is not only a result of government resolution but also a function of the relatively centralized political systems, which give governments a high degree of domestic control. Correspondingly, the problems of energy policy in the United States not only are a result of government indecision but also to a large extent derive from the decentralized political system, which leaves the government less control in domestic matters and gives economic and political interest groups considerable influence.[12]

The contrast also reflects different historical traditions. In Western Europe there is a long tradition of governmental control in economic life. This, in part, explains why there is less opposition within these countries to governmental initiatives in energy policy. However, in Western Europe governmental resolution in energy matters might eventually be undermined by opposition parties that are willing to accept greater dependence on imported oil in order to achieve faster economic growth and reduce unemployment. They might also receive the support of the opponents of nuclear programs as well as others who are dissatisfied with governmental energy and economic policies.

The outlook for the United States merits special attention because it is the world's largest oil importer and because changes in its oil imports are critical to the demand for oil on the world market. By comparing the energy situation of the United States with that of Western Europe and Japan we can still argue that the United States, at least theoretically, has considerable freedom of action in the relationship between economic policy and energy policy. Its combination of a high level of energy consumption in relation to population and gross national product (GNP) and large unused energy supplies makes it possible for the United States to pursue a relatively high rate of economic growth with declining imports of oil. In fact, about half of the OECD-area potential for cutting oil imports lies with energy

[12]Gabriel A. Almond, "A Comparative Study of Interest Groups and the Political Process," in Harry Eckstein and David E. Apter (eds.), *Comparative Politics*, The Free Press, New York, 1963, pp. 397–408.

conservation and expanded domestic energy production in the United States.[13] This means that American energy policy is of crucial importance to Western Europe and Japan. Put simply, the level of United States oil imports in many ways decides how much oil is left for the rest of the world.

The North American level of energy consumption in relation to GNP has traditionally been considerably higher than Western Europe's or Japan's.[14] Energy consumption in relation to GNP is now about 50 percent higher in the United States than in Western Europe, and almost twice as high as in France and West Germany. This reflects the historically great American abundance of energy that has fostered more energy-intensive patterns of production and consumption. The United States alone, with approximately 6 percent of the world's population, consumes about 33 percent of the world's energy.[15] One explanation is that since 1945 the rate of investment in the domestic economy has been much lower in the United States than in most West European countries; therefore there is a higher proportion of energy-intensive industrial equipment in the United States. However, most of the discrepancy can be accounted for by differences in patterns of consumption, primarily in the transportation sector and to a smaller extent in the residential and commercial sectors.[16] Essentially, American tastes for driving and temperature control make up most of the difference.

Over the past few years estimates of petroleum reserves and production potential in the United States have been revised downward. The *National Energy Outlook 1976* is not as optimistic about production potential as the 1974 *Project Independence Report*,[17] and the 1977 Congressional Research Service study, *Project Interdependence*, is even less optimistic.[18] The

[13]*World Energy Outlook*, p. 36.

[14]*The National Energy Plan*, p. 2.

[15]Ibid., p. 2.

[16]Darmstadter, Dunkerley, and Alterman, *Industrial Societies*, p. 25ff.

[17]U.S. Federal Energy Administration, *National Energy Outlook 1976*, Washington, D.C., 1976, p. 70ff.

[18]U.S. Library of Congress, *Project Interdependence: U.S. and World Energy Outlook Through 1990*, Washington, D.C., 1977, p. 15ff.

National Petroleum Council assumes in a study published late in 1976 that the potential for expanding reserves increases in direct proportion to the rise of crude oil prices.[19] However, production from existing fields is likely to decrease substantially over the next 10 to 15 years even with high oil prices. But at higher prices the decline of production from existing fields is likely to be less extreme than at current prices. Tertiary recovery, through thermal techniques and improved water and gas drives, could perhaps add 40 billion barrels, or 5.6 billion tons, to United States oil reserves.[20] Not all of these methods are technically feasible or commercially viable yet. Consequently, the oil production of the United States increasingly depends upon the discovery and development of new fields. A high rate of development will be needed to halt the decline in United States oil production. This new oil is likely to be quite expensive, implying high capital needs and much more capital mobilization for the energy sector.

Even with shrinking conventional oil supplies, it is difficult to argue that the United States is faced with a genuine shortage of energy. The country has large deposits of oil shale, coal, and uranium. In principle, these reserves could cover the energy consumption of the United States for a very long period of time.

Thus the United States has several alternatives for solving its energy problems. This freedom of action leads to difficult choices and political conflict over energy issues. The range of alternatives can be an obstacle to an effective energy policy, complicating the basic trade-off between conservation and an expansion of energy supplies.

From a purely economic point of view, there are ample opportunities for energy conservation in the United States because the level of energy consumption in relation to economic performance is considerably higher than in Western Europe or Japan.[21] In this comparative perspective conservation is the most sensible medium-term solution. Relatively small changes in patterns of gasoline consumption and in habits of temperature control would

[19]*Enhanced Oil Recovery*, National Petroleum Council, Washington, D.C., 1976, p. 27ff.

[20]*World Energy Outlook*, p. 41.

[21]Darmstadter, Dunkerley, and Alterman, *Industrial Societies*, p. 21ff.

conserve considerable amounts of energy and reduce oil imports. This point of view was also reflected in President Carter's national energy plan of 1977, which emphasized conservation more strongly than the expansion of domestic energy supplies.[22] In Carter's 1977 plan the key method proposed to stimulate conservation was to increase prices through taxation. The plan was well received in Western Europe[23] because, from a European point of view, it has been difficult not to associate the low energy prices in the United States with a certain amount of irresponsibility in an age of energy scarcity. In addition, rising American oil imports are often seen as a threat to Western Europe's economic stability.[24] Thus, both the aim, to reduce excessive energy consumption, and the method, taxation, appeared most reasonable to a West European public.

However, for historical and political reasons, energy realities are perceived differently in the United States. First, the United States has developed on a basis of inexpensive and abundant energy, which gave it a historical tradition of energy-intensive patterns of consumption. Mobility and temperature control are part of the "American dream." This is reflected in the decentralized pattern of settlement, low standards of insulation, and poorly developed public transportation systems. Second, because of the historically high level of energy consumption, there are important pressure groups that have an interest in maintaining past patterns of energy consumption rather than opting for energy conservation.

Thus, the President's energy plan inevitably has clashed with structural features and with strong vested interests. The ability of a price increase alone to check the growth of gasoline consumption seems dubious. In practice, demand for gasoline in the United States seems to be relatively unresponsive to gradual price changes.[25] In fact, demand seems to be affected more by

[22]*The National Energy Plan*, p. 25ff.

[23]*Le Monde*, April 22, 1977.

[24]Jean Carrié, "Les Incidences de la crise énergétique sur l'économie de l'Europe et des Etats-Unis," *Politique Etrangère*, no. 1, 1975, pp. 85–97.

[25]Verleger and Sheehan, "Demand for Gasoline," in Jorgensen, *Econometric Studies*, p. 213ff.

changes of income than by changes of price. It is also doubtful to what extent a price increase by itself can induce industry and, in particular, electric utilities to switch from oil to coal. The obstacles here are the environmental regulations on the use of coal, in particular on the sulphur content of emissions, and local resistance to coal mining.

In addition to price measures, a thorough reorganization of the transportation sector, including considerable investment, public subsidies, and perhaps direct regulations, might be needed. Possible measures include massive investments and subsidies for mass transit, a revitalization and reorganization of the railroad system, a mandatory program for air transport, and eventually a limitation on long-distance road transport of freight. Such measures are reasonable from a European point of view, but in the United States they imply profound changes and affect powerful vested interests. Thus it seems that a substantial reduction of gasoline consumption requires a transportation policy that is alien to American traditions and is politically divisive. In the absence of such comprehensive planning, though, it is possible that some of the energy-saving measures will lead in the long run to greater gasoline consumption, as savings to the public might lead to more driving by private individuals.

Given these prospects, energy issues are likely to be an important dimension of conflict in the American political system for a long time to come. The dispute over the 1977 energy plan essentially represents a confrontation between two different philosophies that has important consequences for the distribution of power. Two arguments against the 1977 energy plan are perhaps relevant. One is that Americans will maintain their habits of petroleum consumption at almost any price.[26] The other is that the taxation of energy consumption will bring about a higher degree of centralization of the United States economy, giving the federal government more power in economic matters and thus changing the overall balance of power in the American political system.

In this way, the battle on energy issues is not limited only to

[26] *Wall Street Journal*, November 1, 1977.

energy but extends to the issues of how the economy is organized and how political power is distributed. These broad implications may well reduce the ability of the American political system to work out a consistent energy policy, at least in the short and medium terms. Taxation implies a centralization of energy and economic decision making in the federal government and is based on the assumptions that the price elasticity of supply is low and that the prospects for expanding oil and gas output are limited, even at much higher prices. Giving the private sector control, by allowing the energy industry to raise prices and to benefit from tax breaks, presupposes that the price elasticity of energy supplies is sufficiently high to make market forces provide more energy, including more oil and gas. The weighing of these two points of view is likely to create political conflicts for years to come and to limit the ability of the United States to check the growth of oil imports.

Regardless of these political obstacles, the market seems to be making some contribution to energy conservation in the United States.[27] In 1976 and 1977, as economic growth picked up after the recession, the relationship between the rate of economic growth and the growth of energy consumption was considerably lower than in the past.[28] In fact, it seems that the energy coefficient of the United States has been reduced to approximately 0.6. This might indicate a profound change in patterns of energy consumption in the United States, mainly in response to the price increase, and in this case the freedom of action of the United States in economic and energy policy will have improved substantially.

However, it is difficult to draw conclusions on the basis of two years of experience. This decline in the energy coefficient may be cyclical rather than structural. Historically, the relationship between economic growth rates and the growth of energy consumption has varied considerably from one year to another. Also,

[27] *World Energy Outlook, April 1978*, Exxon Background Series, Exxon, New York, 1978, p. 8.

[28] "Energy: Where Did the Crisis Go," *New York Times*, April 14, 1978, Section 3, pp. 1, 9.

since 1973 the growth of the American economy seems to have been directed more toward the service sector than toward the industrial sector. Industrial production has expanded less than the GNP since 1973, which explains, to a certain extent, the low energy coefficients for 1976 and 1977. Finally, it is likely that the United States will have fairly low energy coefficients over the years when its conservation gains are achieved. But, after the level of energy consumption in relation to economic output has been reduced, energy coefficients could increase again when the potential for conservation has been realized.

Western Europe does not have the same freedom of action in dealing with the relationship between economic policy and energy policy. Historically, the economies of Western Europe have relied on scarce and relatively expensive energy. As a result, energy conservation has been taken seriously for a long time, and thus the European capacity to conserve energy while maintaining economic growth is relatively small compared with that of the United States. West European energy markets are already characterized by severe restrictions on consumption and the stimulation of production. The oil imports of Western Europe began to decline slightly in the mid-1970s because of North Sea oil and gas. European supplies of energy will expand further mainly through the development of nuclear power and North Sea petroleum. Some energy can be conserved in the industrial sector by investments in energy-saving equipment and changes in production processes. However, West European industry might argue that further energy conservation creates competitive disadvantages relative to American industry. A more important change in the relationship between energy consumption and economic growth could be achieved if growth in Western European economies shifts more substantially toward the service sector, but that implies a diminishing role for Western Europe as an industrial manufacturer.

Western Europe's energy record in the aftermath of the oil crisis is better than that of the United States.[29] Conservation efforts have been more substantial, and so has the expansion of

[29] *World Energy Outlook*, p. 45ff

domestic supplies of energy. However, the ambitious nuclear programs have increasingly aroused political opposition, causing a slowdown in the expansion of nuclear energy. Also, the limited domestic supplies of hydrocarbons are somewhat insecure. In the Netherlands any expansion of gas production seems politically difficult, even if new reserves are found. In Great Britain a more restrictive depletion policy might be implemented when self-sufficiency in oil is attained (around 1980).

In Norway there might be considerable potential for increasing supplies of oil and gas.[30] Reserve estimates for the southern zone (south of 62°N) are conservative because relatively little drilling has taken place so far. The northern zone contains a large proportion of Western Europe's continental shelf, and geological data indicate the possibility of finding petroleum. If oil and gas are found there, the reserve estimates could be increased quite considerably and Norway might become a more important producer of oil in the late 1980s. The problem with the exploitation of these potential reserves is that Norway has limited economic needs and a small population that enjoys a high standard of living. Thus plans for substantially increasing production are likely to lead to serious political controversies. Events like the blowout in the North Sea in the spring of 1977 intensify such controversies. It is symptomatic that plans for exploratory drilling in the North were postponed afterward. However, Norwegian oil policy and particularly the low level of production could become major sources of friction between Norway and its allies and trading partners.[31] In addition, with a low rate of economic growth in Western Europe, Norway might produce more oil for economic reasons.

Of the major OECD countries, Japan has the least freedom of action in dealing with trade-offs between economic policy and energy policy. In 1975 oil imports represented 76 percent of Japan's total energy requirements, against 55 percent in Western Europe and 14 percent in North America. Even more than in

[30] Ibid., p. 46ff.

[31] U.S. Federal Energy Administration, *The Relationship of Oil Companies and Foreign Governments*, Washington, D.C., 1975, p. 143ff.

Western Europe, in Japan the economy has expanded on the basis of scarce and relatively expensive energy. This means that much of the conservation effort has already been carried out. As a result, the scope for conserving energy in the industrial sector through new equipment and changes in processes of production is limited. Also, industry might claim that strict measures of conservation lead to competitive disadvantages in international trade. The potential for expanding domestic energy supplies in Japan is almost exclusively linked to nuclear development.

OECD-AREA TENSIONS

The United States enjoys much greater flexibility than most of its allies and trading partners in the trade-off between economic policy and energy policy. Given the energy bind of the Europeans and the Japanese, a substantial increase in the oil imports of the United States is not only likely to cause economic problems for the entire OECD area, it will also produce substantial political divisions among them.[32] A close look at American policy on oil imports in the early 1970s demonstrates clearly the freedom of action of the United States and the anxiety this can generate in the OECD.

Before 1973 oil imports to the United States were controlled, and domestic oil prices were higher than on the world market. Consequently, energy prices were higher in the United States than in Western Europe or Japan, which was a competitive disadvantage for United States industry and an incentive for domestic oil production. This difference in prices could be eliminated if the United States lifted import controls and permitted domestic oil prices to move to the level of the world market, or if world market prices increased up to or beyond the level of American prices. The second possibility is not as implausible as it sounds: in fact, there are signs that from 1971 to 1973 the

[32] Sey[illegible] Brown, *New Forces in World Politics*, Brookings Institution, Washington[illegible], 1975, p. 36ff.

United States encouraged OPEC to raise its oil prices.[33] There are also signs that after the oil crisis the United States government discreetly supported the price radicals of OPEC, primarily Iran.[34] In addition to the desire to raise world prices, another reason for this stance could be that much of the financial surplus of OPEC was channeled to the United States. If the government of the United States really did encourage higher prices for oil after the oil crisis, this contrasts with two other important initiatives of the Nixon administration: Project Independence and the creation of the IEA. It might seem inconsistent that the Nixon administration would simultaneously launch an ambitious and expensive energy program, create an organization of oil consumers, and encourage OPEC to raise oil prices.

The contradiction here may be more apparent than real, and the link between these three facts could be logical. The Nixon administration could have proposed Project Independence to pacify domestic public opinion, knowing all along that the goal of energy self-sufficiency was unrealistic. The IEA could have been started to maintain American leadership, and to prevent the countries of Western Europe and Japan from making bilateral deals with OPEC countries. Finally, the Nixon administration could have encouraged high oil prices to maintain good relations with Iran, knowing that with higher world oil prices the competitiveness of American industry would improve.

This is why some Western Europeans have openly asked whether the United States under the Nixon and Ford administrations has played a two-sided game in oil politics, promoting its own interests at the expense of its allies.[35] The explanation is probably not so simple. The United States has different and sometimes very contradictory interests with regard to oil, and it therefore, perhaps, pursues policies related to oil that seem inconsistent. However, this explanation may not be sufficient to calm West European apprehensions.

[33] V. H. Oppenheim, "Why Oil Prices Go Up (1). The Past: We Pushed Them," *Foreign Policy*, no. 25 (1976–1977), pp. 24–57.

[34] "Pétrole: Les Tricheurs de Washington," *Le Nouvel Observateur*, no. 632, 1976, pp. 36–37.

[35] Ibid., p. 36.

Oil imports function as a safety valve in the United States energy sector; importing oil is the least controversial short-run solution to American problems of energy policy. But greater United States oil imports will increase the demand for oil on the world market, and this in turn will encourage OPEC to make new increases in the price of oil. Given these circumstances, apprehensive Western Europeans ask whether there is a plot behind the increasing oil imports of the United States.[36] They argue that the United States has a real interest in increasing its oil imports in a medium-term perspective. By maintaining price controls on oil and gas, and letting oil imports increase, the United States achieves the following:

- An average level of energy prices below that of Western Europe or Japan, which gives a competitive advantage to American industry
- A slower rate of depletion of domestic oil and gas reserves, which means greater future reserves
- Eventual pressures on the world oil market, which lead to price increases that make the exploitation of alternative sources of energy economical and put the United States in a more favorable position, given its technology and resources

It is perhaps doubtful that the decentralized political and financial system of the United States would permit such a calculated manipulation of the situation. But this does not rule out the possibility that the present stalemate in United States energy policy, and the rising oil imports resulting from it, could work out to be in the long-term interest of the United States. Therefore, West European fears are quite legitimate. In a tighter supply situation this could be a major source of friction between the United States and most of its allies. One symptom is that already considerable pressure is being put on the United States in international forums, such as OECD and IEA. The Secretary General of the IEA has recently stated that the ability of the Western world to

[36] "L'Absence de politique énergétique américaine fait le jeu de l'OPEP," *Le Monde*, March 23, 1976.

TABLE 13
The Consumption of Various Types of Primary Energy in 1976, in Millions of Metric Tons of Oil or the Equivalent

	Total	*Coal*	*Hydro-electric*	*Nuclear*	*Natural gas*	*Oil*	*Oil imports*
North America	1,998	365	113	46	580	894	354
Western Europe	1,208	235	74	27	175	697	607
Japan	346	52	21	7	11	255	254

SOURCE: *Energy Statistics 1974–76*, OECD, Paris, 1977.

limit its reliance upon imported oil depends on the United States.[37] This can be interpreted in two ways. First, the size of the United States makes its oil imports decisive, and second, its example is crucial. If the United States does not promote energy conservation and an expansion of domestic energy supplies, most countries of Western Europe and Japan will have stronger reasons to go ahead with conservation and nuclear programs, but chances are that the psychological impact of the United States will slow down energy programs in other OECD countries. Ultimately these differences can only lead to increasing friction between the governments.

It can easily be argued by Japan or Western Europe that for them oil imports are a vital necessity for economic life but for the United States they are a luxury, an excess consumption of energy. An oil cutback for Japan and Western Europe would lead to a total disruption of economic life, whereas for the United States it probably would only mean restrictions on private driving.[38]

A closer look at the energy balances should make this clear (see Table 13).

[37] Ulf Lantzke, "IEA Head: U.S. Key to Energy Economy," *Oil and Gas Journal*, April 18, 1977, pp. 25–26.
[38] Jean Carrié, *Les Incidences de la crise énergétique*, pp. 85–97.

in North America, oil imports represent only 18 percent of total energy consumption. For Western Europe the proportion is 51 percent, and for Japan 74 percent.

TABLE 14
End Uses for Oil for Selected Sectors in 1974, in Millions of Metric Tons

	Total for all sectors	*Industry*	*Transportation*	*Road transport*
North America	777	98	428	356
Western Europe	667	141	158	121
Japan	238	61	38	29

SOURCE: *Energy Statistics 1973–75*, OECD, Paris, 1977, pp. 76–77, 86–89, 100–101, 106–107, 112–113.

In North America the total oil consumption of the transportation sector alone exceeds the volume of oil imports (see Table 14). In Western Europe and Japan the oil consumption in transportation represents only a small proportion of the oil imports. In 1974 the total oil consumption in the OECD area was 1,781 million tons, of which 639 million tons, or 36 percent, were consumed by the transportation sectors. Road transport alone took 530 million tons, or 30 percent. It should be noted that the transportation sector of the United States took 394 million tons, and United States road transport alone 330 million tons. This corresponded to 19 percent of the total oil consumption of the OECD area, and to 28 percent of the OECD oil imports.

OECD-AREA OPTIONS

The range of possibilities for the OECD countries as a group is illustrated on the theoretical level by the future relationships between three basic economic components that determine the demand for oil imports. These are the rate of economic growth, the energy coefficient (the relationship between the growth of energy consumption and the rate of economic growth), and the growth of domestic energy production. Table 15 gives the net oil imports to the OECD area by 1985 according to different combinations of these three basic components.

On paper the OECD area has considerable freedom of action in reconciling economic and energy policies. It can maintain a

TABLE 15
OECD Oil Imports by 1985

Energy coefficient	*Growth of domestic energy production (%)*	*Rate of economic growth* 2 %	3 %	4 %	5 %
1.1	2.5	1,426	1,977	2,590	3,270
	3.0	1,262	1,813	2,462	3,106
	3.5	996	1,641	2,254	2,934
	4.0	909	1,460	2,073	2,753
1.0	2.5	1,168	1,821	2,359	2,952
	3.0	1,004	1,657	2,195	2,788
	3.5	832	1,485	2,032	2,616
	4.0	651	1,304	1,842	2,435
0.9	2.5	1,240	1,669	2,138	2,649
	3.0	1,076	1,503	1,972	2,485
	3.5	904	1,333	1,802	2,313
	4.0	732	1,152	1,621	2,132
0.8	2.5	1,150	1,522	1,924	2,359
	3.0	986	1,358	1,760	2,195
	3.5	814	1,186	1,588	2,023
	4.0	633	1,005	1,407	1,842
0.7	2.5	1,043	1,379	1,719	2,096
	3.0	879	1,215	1,555	1,922
	3.5	707	1,043	1,383	1,750
	4.0	526	862	1,202	1,569

SOURCE: These figures were derived by extrapolating from the 19[illegible] figures.

high rate of economic growth without overly increasing oil imports if appropriate policy measures are taken. For example, a rate of economic growth of 5 percent could by 1985 give only a modest growth in oil imports, provided the energy coefficient falls to 0.7 and the domestic energy production expands at 4 percent a year. Yet a relatively low rate of economic growth could create a considerable increase in oil imports, if energy policy is unchanged. For example, a rate of economic growth of 3.0 percent and an energy coefficient of 1.0 combined with an expansion of domestic supplies of energy at a rate of 2.5 percent a year would require oil imports to be 50 percent higher in 1985 than in 1975.

Even if the examples chosen here are extreme, the comparison shows that there is a certain flexibility in the OECD area as a whole in dealing with the trade-offs between economic policy and energy policy. The major problem is the economic and political costs to governments of energy policy measures. In reality, most OECD governments have the choice between the following options in the relationship between economic policy and energy policy:

- Sustaining economic growth, with a limited effort in the energy sector, thus increasing oil imports.
- Sustaining economic growth, with a significant effort in the energy sector to check the growth of oil imports. Such an effort is likely to be economically costly and to provoke serious political opposition. Its potential for success is higher in the United States than in most other OECD countries, given the greater potential for conservation and for increasing domestic energy supplies.
- Restricting economic growth in order to check oil imports.

The first option preserves economic growth and thus satisfies most domestic goals, but at the cost of increasing oil imports and international vulnerability. The second and third options decrease national exposure to the world oil market but impose domestic costs in the form of an all-out energy policy or economic stagnation.

As noted above, the energy policy of the United States, through its impact upon the level of oil imports, is a decisive factor in the energy choices and economic policies of most other OECD countries.[39] Consequently, increasing United States oil imports will not only put pressure on the American balance of trade, making the United States more vulnerable to diplomatic pressure from oil-exporting countries, but will also mean more political pressure from Western Europe and Japan. These pressures, however, function to a considerable extent as "externalities" in the American political system. They are perceived as problems by those dealing with foreign relations, but most of the United States economy is sheltered from them, and thus their political weight is limited. Therefore, growing external pressure could certainly lead to stronger initiatives on energy policy by the executive, but because of domestic opposition the chances of these programs becoming law will be fairly limited unless a major international energy crisis develops.

Clearly, the future prospects for oil supplies on the international market are a decisive factor for the formulation of energy policy in the United States and in most other OECD countries. Therefore, a look at the OPEC response to OECD needs is crucial to a complete picture of the world oil market in the medium-term future.

[39] Guy de Carmoy, *Energy for Europe*, American Enterprise Institute for Public Policy Research, Washington, D.C., 1977, p. 96ff.

North America and around 0.9 in Western Europe and Japan. The growth of domestic energy production is low in North America (2.75 percent a year) and higher in Western Europe (5.5 percent a year). In Japan the consumption of energy from domestic sources, mainly nuclear, and from nonoil energy imports, grows at an annual rate of 7 percent. In the Third World economic growth is higher. The noncommunist countries outside the OECD and OPEC—called the "rest" in these scenarios—have an average economic growth rate of 5 percent, and an energy coefficient of 1.2 because of the early phase of industrialization. Their domestic output of energy collectively grows at a rate of 6 percent a year. The picture thus given is represented in Table 23.

OPEC Response

The low growth of the OECD economies forces OPEC countries to limit their import growth after 1980. Until 1980 the growth of imports in real terms is 10 percent a year in the countries with large populations and small reserves and 20 percent a year in the countries with small populations and large reserves. After 1980 the import growth rates are halved (5 percent a year in the first group, 10 percent a year in the second group). Other exports grow at a rate of 10 percent a year. By 1980 this creates negative trade balances for almost all OPEC countries, the most notable exceptions being Kuwait and Saudi Arabia. Almost all of the OPEC trade deficit countries produce at full capacity, and domestic oil consumption grows at an annual rate of 8 percent. Both of these factors severely limit the future export potential of several countries.

Price Politics

Because most of the OPEC countries in the first group have negative trade balances, their exports do not cover their income requirements and they have limited political weight in determining prices. Therefore, the price of oil can be assumed to remain relatively stable until at least 1985. After 1985 there is increasing pressure on Saudi Arabia, through a combination of growing demand and a reduction of output in some of the countries of

TABLE 23

Scenario One: Energy Consumption and Production in the 1980s and 1990s, in Millions of Metric Tons of Oil or the Equivalent

	1975	*1980*	*1985*	*1990*	*1995*	*2000*
Total Energy Consumption						
North America	1,804	2,183	2,458	2,767	3,114	3,508
Western Europe	1,138	1,315	1,503	1,717	1,962	2,241
Japan	329	418	521	649	809	1,005
*OECD Total**	3,361	3,916	4,481	5,133	5,886	6,757
Rest†	752	1,006	1,347	1,802	2,412	3,227
World‡	4,113	4,923	5,828	6,935	8,298	9,984
Domestic Output of Energy						
North America	1,559	1,831	2,097	2,402	2,751	3,151
Western Europe	521	681	890	1,163	1,520	1,987
Japan§	89	125	175	246	344	483
*OECD total**	2,209	2,637	3,162	3,811	4,616	5,620
Rest†	499	668	894	1,196	1,600	2,142
World‡	2,708	3,305	4,056	5,007	6,216	7,762
Oil Imports						
North America	295	352	360	365	365	357
Western Europe	617	634	613	554	441	254
Japan	240	293	346	403	464	525
*OECD total**	1,152	1,279	1,319	1,322	1,270	1,136
Rest†	253	339	453	606	811	1,086
World‡	1,405	1,618	1,772	1,929	2,082	2,222

*Excluding Australia and New Zealand.
†Including Australia and New Zealand.
‡Excluding the Soviet Union, Eastern Europe, and China.
§Including consumption of imported energy other than oil.
SOURCE: Author's projection.

TABLE 24

Scenario One: OPEC Oil Exports in the 1980s and 1990s, in Millions of Metric Tons of Oil

	1975	*1980*	*1985*	*1990*	*1995*	*2000*
The Distribution of Oil Exports						
Group I	651	857	808	681	516	294
*Group II**	754	761	954	1,246	1,566	1,924
Saudi Arabia	544	537	741	1,027	1,348	1,715
Saudi Excess Capacity at Different Production Ceilings						
750	193	201	−91†	−304	−638	−1,023
1,000	433	451	241	−54	−388	−773
1,250	693	701	491	196	−138	−523

*Includes Saudi Arabia.

†Negative values indicate the extent to which the demand for exports exceeds the production ceiling.

SOURCE: Author's projection.

the first group. Also, the countries of the first group have significant current account deficits and accumulate large foreign debts. Consequently, they press for a substantial increase in the price of oil, which would improve their situation. A coalition of countries, including Kuwait, threatens a cutback of supplies that might be greater than Saudi Arabia's excess capacity, if Saudi production limits are not set at high levels, for example, at a billion metric tons a year. As a result, sometime between 1985 and 1990 Saudi Arabia yields to the price pressure and the oil price is increased by perhaps 50 to 100 percent over a short time. This helps to improve the financial situation of most other OPEC countries but is detrimental to the world economy.

Political Tensions

The constant price of oil, in real terms, creates tension within OPEC. The countries with large populations and small reserves reach their ceilings of output around 1980, with the exception

of Iraq, making them borrowers on the international financial market. Lending to these countries is encouraged, both by Saudi Arabia and by the West, to appease their demands for a higher oil price. However, this is increasingly resented by these countries for political reasons and because the service of the debts becomes a burden. Saudi Arabia is increasingly seen as being closely committed to the cause of the OECD countries, and particularly as acting hand in glove with the United States. Consequently, Saudi Arabia becomes isolated in OPEC, in the Middle East, and in OAPEC.

From the West, Saudi Arabia gets only small rewards. Tension in the Middle East conflict is reduced, but no viable solution to the Palestinian problem is found. In North-South relations only limited progress is made, as the OECD countries claim that their low rates of economic growth prevent considerable concessions to the Third World. In addition, the IEA, under United States leadership, tries to keep member countries together by closer cooperation on the development of alternative sources of energy, offering economic relief to some of the most adversely affected countries. The IEA also tries to prevent price increases by presenting OPEC with a common front and threatening retaliations in the form of trade restrictions.

The low rate of economic growth, particularly in North America and Western Europe, creates unemployment, social tensions, and political instability. Increasingly, economic policies and the priority given to keeping oil imports low are questioned. Some countries adopt protectionist measures to insulate their economies. The LDCs maintain relatively high rates of economic growth, around 5 percent a year, which are facilitated by the constant real price of oil. The poorest LDCs accumulate substantial foreign debts.

In the OPEC countries the process of economic and social change is continued, but those countries with large populations and small reserves, where development efforts are most significant, run into financial and economic problems because of their balance-of-trade deficits. This threatens their political stability. In addition, all OPEC countries are adversely affected by the low rate of economic growth of the OECD area. The countries of the first group find few outlets for their new industrial exports.

and their nonoil exports grow at a slow pace. Thus they must consider limiting their imports, even though this will have adverse effects upon their economic development. The countries of the second group continue to accumulate financial assets, but the return on their investments in the West is low partly because of low rates of economic growth there.

When the price shock hits, after 1985, both the OECD countries and the LDCs are particularly vulnerable. This time the OECD countries are confronted with a drastic rise in the price of oil after a prolonged period of economic stagnation, not as in 1973–1974 after a period of sustained growth. Therefore, the inflationary and the recessionary effects are worse. Also, the OECD countries have not been able or willing to finance a strong effort to develop alternative sources of energy because of their low rates of growth. Furthermore, this effort has been inhibited by the stagnant real price of oil. The LDCs are also adversely affected because they are now much more dependent on imported oil for development, and in many cases their current account deficits reach alarming proportions. This adds to international financial instability. According to this scenario, prospects are that the new price rise in the late 1980s will severely damage a world that is still highly dependent on oil, leading to prolonged economic stagnation as well as financial and political instability.

SCENARIO TWO: HIGH OECD ECONOMIC GROWTH

Demand for OPEC Oil

Economic growth picks up in the OECD countries. It averages 4 percent a year in North America and Western Europe and 6 percent a year in Japan. The energy coefficient is reduced, averaging 0.8 in North America and 0.9 in Western Europe and Japan. The growth of domestic energy production is the same as in the previous scenario: 2.75 percent a year in North America, 5.5 percent a year in Western Europe. In Japan energy consumption from domestic sources and nonoil imports grows at 7 percent a year. The rest have the same performance, 5 percent econ[illegible]c growth, an energy coefficient of 1.2 and an average gro[illegible]ate of domestic energy output of 6 percent a year.

TABLE 25

Scenario Two. Energy Production and Consumption in the 1980s and 1990s, in Millions of Metric Tons of Oil or the Equivalent

	1975	*1980*	*1985*	*1990*	*1995*	*2000*
Total Energy Demand						
North America	1,894	2,287	2,677	3,132	3,608	4,293
Western Europe	1,138	1,379	1,646	1,964	2,344	2,795
Japan	329	438	569	741	964	1,253
*OECD total**	3,361	4,104	4,892	5,838	6,976	8,344
Rest†	752	1,006	1,347	1,802	2,412	3,227
World‡	4,113	5,110	6,239	7,641	9,387	11,572
Domestic Output of Energy						
North America	1,599	1,831	2,097	2,402	2,751	3,151
Western Europe	521	681	690	1,163	1,520	1,987
Japan§	89	125	175	246	344	483
*OECD total**	2,209	2,637	3,162	3,811	4,616	5,620
Rest†	499	668	894	1,196	1,600	2,142
World‡	2,708	3,305	4,056	5,007	6,216	7,762
Oil Imports						
North America	295	455	579	731	917	1,143
Western Europe	617	698	756	801	824	811
Japan	240	313	394	495	619	770
*OECD total**	1,152	1,467	1,730	2,028	2,360	2,724
Rest†	253	339	453	606	811	1,086
World‡	1,405	1,805	2,183	2,634	3,171	3,810

*Excluding Australia and New Zealand.
†Including Australia and New Zealand.
‡Excluding the Soviet Union, Eastern Europe, and China.
§Including consumption of imported energy other than oil.
SOURCE: Author's projection.

OPEC Response

The higher growth rates of the OECD economies make the OPEC countries more confident in their economic policies, and they maintain fairly high rates of imports growth. Imports continue to grow in real terms at 10 percent a year in the countries of the first group and at 15 percent a year in the countries of the second group. Exports other than oil grow at a rate of 10 percent a year. This makes all OPEC countries, excluding Saudi Arabia and Kuwait, have negative trade balances by 1980. Domestic oil consumption increases at an average of 8 percent a year in all OPEC countries.

Price Politics

The increasing demand for oil strengthens the position of the price radicals and, even before 1985, presents Saudi Arabia with a serious dilemma: whether to establish a depletion policy and let prices go up or to try to moderate prices and allow pressure to build on its oil resources. The economic growth of the OECD countries and their sizable contribution to incremental demand lend support to demands among OPEC members for a price rise. The real price of oil remains constant until 1980. Soon after 1980 there is a major confrontation on oil prices in OPEC. An important element is that Kuwait is having a negative balance of trade. Before its financial resources are eroded by deficits, Kuwait prefers to use them as leverage, and offers to finance output reductions in other OPEC countries. Saudi Arabia yields to the increase rather than strain its oil resources further. There is an OPEC agreement on a price escalation, and over a period of five years the real price of oil is doubled.

Political Tensions

The rising price of oil has an adverse effect on the trade balances of most OECD countries and LDCs. There is also a growing concern over the size and availability of oil supplies and a sense of increased vulnerability and dependence. The IEA, under United States leadership, tries to keep member countries together

TABLE 26
Scenario Two: OPEC Oil Exports in the 1980s and 1990s, in Millions of Metric Tons

	1975	1980	1985	1990	1995	2000
The Distribution of Oil Exports						
Group I	651	863	819	681	516	311
*Group II**	754	942	1,364	1,953	2,655	3,499
*Saudi Arabia**	544	718	1,141	1,732	2,437	3,266
Saudi Excess Capacity at Different Production Ceilings						
750	197	20	−409†	−759	−1,727	−2,594
1,000	447	270	−159	−509	−1,477	−2,344
1,250	697	520	91	−259	−1,227	−2,094

*Includes Saudi Arabia.
†Negative values indicate the extent to which export demand exceeds the Saudi production ceilings.
SOURCE: Author's projection.

by closer cooperation on the development of alternative energy sources and helps finance the effort in the most adversely affected countries. The IEA also tries to prevent further price increases by coordinating diplomatic pressure and presenting OPEC with a united front. But the IEA is increasingly split between countries wanting concerted action against OPEC and countries tempted to make bilateral deals with cartel members to secure supplies and compensate for the high price.

In the OECD countries the rising price of oil accelerates inflation, and increasing current account deficits limit the freedom of most governments in economic policy. Stagflation is the likely outcome. Among the OECD members a breakdown of free-trade policies might even develop as a last resort to protect national interests at the expense of international economic growth. This economic stagnation augments social and political tensions in many OECD countries, leading to increasing political instability.

The high price of oil forces most LDCs to run very high current account deficits. Rapid change in some LDCs brings more radical groups to power, demanding compensation from both OECD and OPEC countries for the high oil price. The higher oil price places obvious strains on Southern unity. Some of the most desperate LDCs threaten to go bankrupt in order to clear their debts. Others make special agreements with the Soviet Union in order to get economic assistance and perhaps oil at a reduced price. Finally, the high price of oil induces wealthier LDCs to develop nuclear power, causing a spread of nuclear military technology.

In OPEC there is an increasing split between Saudi Arabia and the other member countries, with the Saudis being more and more isolated over price questions. For most members the principal effect is huge financial wealth and an increasing political weight in international relations. Domestically, the pressure on oil reserves and the process of economic and social change lead to increasing political instability. Like the OPEC members, the Soviet Union and, to a smaller extent, China gain more international influence through the rising price of oil.

Thus the high demand situation hits the consumers hard. Not only is the economic health of the OECD area endangered but many LDCs are in serious trouble, which undermines Southern unity. The international financial position of the importers is so weak that economic growth levels are not likely to be maintained and recession is probable. The OPEC position is basically one of strength, but there are definite possibilities of OPEC splits over Israel and the Third World, in addition to the political polarization of Saudi Arabia. It is hard to say at what point these tensions will change the oil regime or how much OPEC will exploit its greater political leverage. Certainly the close bilateral ties between Saudi Arabia and the United States will be jeopardized. Within OPEC there is a possibility that a two-tiered cartel will develop if the countries of the first group and their sympathizers grow too impatient with the Saudis. In any case, the bilateral relations between the United States and Saudi Arabia will deteriorate and the rapidly increasing price of oil will have

magnified the international financial problems of OECD and LDC countries to the point of seriously stunting economic growth. The main positive influences will be in the wealth of the oil producers and in the stimulation of the production of alternative sources of energy.

SCENARIO THREE: HIGH OECD ECONOMIC GROWTH WITH A RESOLUTE ENERGY POLICY

Demand for OPEC Oil

Economic growth picks up and an active energy policy is implemented by the OECD countries. The aims are to check dependence on oil imports through conservation and the expansion of domestic energy supplies and, at least implicitly, to retrieve part of the oil rent from OPEC. Rates of economic growth are 4 percent in North America and Western Europe and 6 percent in Japan. The energy policy reduces the energy coefficient to 0.7 in North America and 0.8 in Western Europe and Japan. The rate of growth of energy production is 4 percent in North America and 7 percent in Western Europe. In Japan energy consumption from domestic production and nonoil energy imports increases at a yearly rate of 9 percent. The rest remain the same as in the previous scenario, with a rate of economic growth of 5 percent, an energy coefficient of 1.2, and an aggregate growth rate of energy production of 6 percent.

The OPEC Response

The OPEC countries, fearing the adverse impact of the OECD energy policy on the demand for oil, reduce the growth of their imports after 1980 to only 5 percent a year in the countries of the first group, and 10 percent a year in the countries of the second group. Several of the countries of the first group produce at less than full capacity. As in the previous scenario domestic oil consumption increases at an annual rate of 8 percent and exports other than oil grow at an average rate of 10 percent a year.

TABLE 27

Scenario Three: Energy Consumption and Production in the 1980s and 1990s, in Millions of Metric Tons of Oil or the Equivalent

	1975	*1980*	*1985*	*1990*	*1995*	*2000*
Total Energy Consumption						
North America	1,894	2,278	2,615	3,002	3,447	3,957
Western Europe	1,138	1,374	1,608	1,883	2,204	2,580
Japan	329	435	580	696	879	1,112
*OECD total**	3,361	4,087	4,774	5,580	6,530	7,648
Rest†	752	1,006	1,347	1,802	2,412	3,227
World‡	4,113	8,093	6,120	7,383	8,942	10,876
Domestic Output of Energy						
North America	1,599	1,945	2,367	2,880	3,504	4,263
Western Europe	521	731	1,025	1,437	2,016	2,828
Japan§	89	137	211	324	499	767
*OECD total**	2,209	2,813	3,602	4,641	6,019	7,858
Rest†	499	668	894	1,196	1,600	2,142
World‡	2,708	3,481	4,496	5,837	7,619	9,999
Oil Imports						
North America	295	332	248	122	−57	−306
Western Europe	617	643	583	445	188	−248
Japan	240	298	340	371	381	344
*OECD total**	1,152	1,274	1,171	939	511	−209
Rest†	253	339	453	606	811	1,086
World‡	1,405	1,612	1,624	1,545	1,323	876

*Excluding Australia and New Zealand.
†Including Australia and New Zealand.
‡Excluding the Soviet Union, Eastern Europe, and China.
§Including consumption of imported energy other than oil.
SOURCE: Author's projection.

TABLE 28

Scenario Three: OPEC Oil Exports in the 1980s and 1990s, in Millions of Metric Tons

	1975	*1980*	*1985*	*1990*	*1995*	*2000*
The Distribution of Oil Exports						
Group I	651	857	808	681	516	294
*Group II**	754	756	816	865	807	583
Saudi Arabia	544	532	593	644	589	369
Saudi Excess Capacity at Different Production Ceilings						
750	206	218	157	106	161	381
1,000	456	468	407	356	411	631
1,250	706	718	657	606	661	881

*Includes Saudi Arabia.
SOURCE: Author's projection.

Price Politics

The low level of demand on the world oil market strengthens Saudi Arabia's position in OPEC and also creates serious tension in OPEC. The OPEC countries have little freedom of action as their trade balances become negative. There is great pressure on Saudi Arabia to accept a price hike. As the swing producer, Saudi Arabia has taken responsibility for balancing supply and demand to keep oil prices constant. As a result, however, Saudi Arabia might also have a negative balance of trade between 1980 and 1985. Consequently, the constant price of oil no longer serves Saudi Arabia's interests, and the position of OPEC has been further damaged by OPEC or IEA attempts to retrieve part of the oil rent. Thus Saudi Arabia agrees to a major price rise. The view prevalent in OPEC countries is that constant oil prices have hurt them and helped the OECD countries. They want to get as much as possible from oil while they still can, doubling the price in the early 1980s.

Political Tensions

Expanded energy production and conservation in the OECD countries is costly, but vulnerability to OPEC declines. Investment in the energy sector increases several times, new energy is expensive, and the conservation measures mean more investment and higher energy prices. There is a high import duty on oil from outside the OECD area. High taxes on energy consumption are designed to promote conservation and to finance some of the necessary investment. There are numerous direct restrictions on the uses of energy, such as the direct control of prices to prevent the high costs of energy from being offset through price increases by industry. Many of the schemes require subsidies that are followed up with strict governmental controls. The mobilization of capital for energy development limits investment in the rest of the economy and slows the growth of consumption. The energy effort is coordinated by the IEA, under United States leadership, and some financial assistance is channeled to energy projects in poorer member countries. United States coordination of the energy effort is also designed to foster political unity among the member countries.

In the OECD countries the principal effect of the energy effort is greater governmental intervention in economic life. Because of this and the high costs of energy self-sufficiency there is growing opposition to it in the OECD countries. Opposition comes from trade unions, which desire a higher growth of private consumption, and from the parts of industry that suffer from the capital squeeze. The wisdom of the effort is questioned because of the domestic sacrifices and the difference between the internal IEA energy price and the international oil price.

The LDCs are affected in two opposite ways. The relatively moderate oil price enables some LDCs to increase oil imports without inordinate strains on their current account balances. On the other hand, the strict energy programs in the OECD area have adverse effects on the exports of most LDCs, on the demand for raw materials, and on the volume of economic aid. On the whole, the LDCs are in a less desperate situation than with the high-demand scenario, so the spread of nuclear technology is also more limited. The position of the poorest LDCs, however, is still precarious because of their inability to pay for energy and the loss of aid.

In the OPEC countries the principal effect is increasing political frustration. This scenario could potentially be very disruptive for the cartel. In desperation countries might try to underbid each other, and the cartel could collapse. On the other hand, OPEC might react collectively with a drastic price increase, hoping to break up IEA solidarity by offering special agreements to countries that abandoned the common import duty on non-IEA oil. Such a move would place the OECD governments in a difficult dilemma. The new international price of oil plus the import duty would probably create serious economic and political problems in the consuming countries. Abandoning the import duty would be a way out of these problems, but it would hamper the transition to other forms of energy and would dilute consumer solidarity.

THE ILLUSIONS

One of the most important negative effects of the Second Oil Regime is that it distorts our perception of the urgency of the world's energy problems. Since the oil crisis of 1973–1974 the world economy has adapted itself to higher oil prices and to the new structure of the oil market. Consequently, in the late 1970s there is a semblance of stability and a tendency among the public and the politicians to ignore the serious structural deficiencies of the oil market, both in its resource base and in its political organization.

There is a reluctance to accept the fact that the world, for the first time since the beginning of intensive industrialization, is facing increasing real costs for energy, and that the 1980s and perhaps the rest of this century will be a period of expensive and possibly scarce energy. There is still a widespread belief that there are no real supply constraints for energy and that those supply problems that exist are contrived by the oil industry or OPEC. As a result, there is a reluctance to conse[illegible] energy,

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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

LA DISTRIBUCION DE LA RADIACION GLOBAL EN MEXICO EVALUADA MEDIANTE LA FOTOINTERPRETACION DE LA NUBOSIDAD OBSERVADA POR SATELITES METEOROLOGICOS.

AGOSTO, 1979

Palacio de Minería Calle de Tacuba 5, primer piso. México 1, D. F. Tel: 521-40-20

NOMENCLATURA

ε Nubosidad (fraccional)

S_o Duración de la insolación astronómica

ϕ Latitud

δ Declinación solar

S Duración de la insolación real

S_r Duración de la insolación relativa

k Fracción del cielo que se encuentra despejado

h Altura solar

ω Angulo horario

t' Intervalo de tiempo contado a partir del medio día (tiempo solar verdadero)

τ Período de rotación terrestre

$\pm t_o$ Instantes de salida y puesta del sol

ω_o Angulo horario de salida o puesta del sol

A Elemento de superficie unitaria orientada normalmente a los rayos solares.

R_o Distancia media tierra-sol

t Tiempo solar verdadero

R Distancia tierra-sol

I_o Constante solar

I^* Radiación extraterrestre

R^* Razón entre la distancia tierra-sol y la distancia media tierra-sol.

A_H Proyección horizontal del elemento de superficie A.

I_H	Radiación solar incidente sobre una superficie horizontal.
Q_o	Radiación extraterrestre diaria
Q_{Max}	Radiación global máxima
w	Espesor de agua precipitable
β	Coeficiente de turbidez atmosférica
Q	Radiación global
Q'	Radiación global para $h<8°$
t_1	Instante en que $h=-8°$
t_2	Instante en que $h=+8°$
$\bar{Q}$	Radiación global media (decadaria o mensual)
$\bar{Q}_{Max}$	Radiación global máxima (promedio decadario o mensual)
$\bar{S}$	Duración de la insolación real (promedio decadario o mensual).
$\bar{S}_{Max}$	Duración máxima de la insolación (promedio decadario o mensual).
a	Constante
b	Constante
n	Número de días en el mes
n_1	Número de días despejados en el mes
n_2	Número de días parcialmente despejados en el mes
$\bar{S}_{d_o}$	Promedio diario del total de horas de insolación astronómica en el mes.
H_i	Total de horas de insolación astronómica del día i.
$\bar{S}_m$	Promedio mensual de horas con cielo despejado
$\bar{S}'_m$	Promedio mensual de horas con cielo parcialmente despejado.

05

S_1 Total mensual de horas de insolación real.

S_{0r} Total mensual de horas de insolación astronómica.

$\bar{Q}_m$ Promedio diario de la radiación global mensual.

$\bar{Q}_a$ Promedio diario de la radiación global anual.

Resumen

Con el propósito de conocer las características regionales de insolación en la República Mexicana, en este trabajo se estima, la distribución espacio-tiempo de la incidencia de la radiación solar global en el país. El método de aproximación empleado, se basa fundamentalmente en las formulaciones de Fritz y Angstrom, aunque en este caso, ante la escacez de datos sobre la duración real de la insolación, ésta ha sido determinada a partir de la nubosidad obtenida por E. Mendoza, J. Luna y T. Gómez, mediante la fotointerpretación de los satélites meteorológicos Nimbus III y ESSA-8 para el período 1969-'71.

La insolación real calculada en días despejados y parcialmente despejados, ha sido correlacionada con la radiación global, mediante la aproximación casi lineal propuesta por G. Lamboley y P. Brichambaut.
Los resultados obtenidos, se presentan anual y mensualmente en mapas en los que las líneas de isorradiación global media diaria, muestran gran continuidad con las líneas encontradas por Bennett para los Estados Unidos de Norteamérica.

Introducción

Considerando al sol como una esfera incandescente de plasma y radiando como un cuerpo negro a la temperatura de 5800°K, éste emite alrededor de $6.6 \times 10^4 Kw.m^{-2}$. Esto implica una transformación de materia en energía, equivalente a 4×10^9 Kg por segundo. De esta enorme densidad superficial de energía, la cual es radiada continuamente hacia el espacio, la tierra intercepta al través de su sección diametral de $1.275 \times 10^{14} m^2$ alrededor de 1.73×10^{17} watts.

La radiación solar incidente sobre un elemento de superficie horizontal en el límite de la atmósfera superior (radiación extraterrestre), solamente depende de la época del año y la latitud geográfica, mientras que la radiación solar que finalmente llega hasta el suelo, es resultado de una atenuación producida principalmente por los gases constituyentes de la atmósfera, los cuales dan lugar a fenómenos de reflexión, dispersión y absorción.

México, localizado entre los paralelos de latitud 14°30' y 32°42'N, respectivamente, se encuentra dentro del cinturón latitudinal de insolación anual máxima, comprendido entre los ±35°de latitud. De aquí que un estudio de las características de insolación en nuestro país, resulte por demás interesante dadas las grandes perspectivas que ofrece la conversión térmica y fotovoltaica de la radiación solar, como substituto de las fuentes convencionales de energía, cada día mas escasas y costosas. Además, el uso de esta fuente latente de energía, al no producir materiales de desecho contaminantes, ayudará a mantener el equilibrio ecológico cada día mas crítico y el cual es urgente preservar.

La determinación precisa de la radiación solar incidente en la superficie de la tierra durante un cierto período, puede llevarse a cabo mediante mediciones pirheliométricas regularmente realizadas con delicados instrumentos que exigen una calibración rigurosa. Dado que en México, solamente tresestaciones han venido realizando casi regularmente este tipo de mediciones con la precisión requerida por las normas pirheliométricas internacionales (1), podrá fácilmente inferirse el problema que se presenta al intentar hacer un estudio riguroso de la climatología solar del territorio nacional, de manera que permita analizar con confiabilidad las características regionales de insolación.

A falta de mediciones de la intensidad de la insolación, una apreciable y fidedigna colección de datos sobre la duración real de la insolación s, proporcionada por una extensa y bién distribuida red de heliógrafos en el país, permitiría realizar también un estudio completo de la distribución espacio-tiempo de la radiación global Q (directa + difusa). Sin embargo, aunque parte de esta red ha funcionado en varios sitios de México, los períodos de funcionamiento han sido bastante discontinuos, desconociéndose además el nivel de mantenimiento que se les haya suministrado. Por la discontinuidad misma de la mayor parte de los datos existentes, éstos no representan un acopio con la regularidad suficiente como para incluírseles con la validez requerida, dentro de un estudio climatológicamente confiable. Cabe la excepción de la serie de datos sobre la duración de la insolación publicados por el Instituto de Geofísica de la U.N.A.M. {2}, sin embargo, éstos corresponden solamente a tres localidades del país (Ciudad Universitaria-México,D.F., Orizabita,Hgo. y Chihuahua, Chih.).

Debido al alto costo del instrumental pirheliométrico, pocos paises han logrado extender una red considerable de estaciones meteorológicas con este tipo de instrumental, por lo que el problema de la determinación de la radiación global Q, ha sido tratado en base a formulaciones empíricas por varios autores {3,4,5,6,7,8}. Este tipo de formulaciones han permitido solucionar el problema con un alto grado de aproximación en muchos de los casos, sobretodo cuando se dispone de suficiente información sobre la duración real de la insolación S, o sobre la nubosidad ε.

Para determinar la radiación global Q, resultan de fundamental importancia otros parámetros intimamente relacionados con ésta; como lo son: la duración de la insolación astronómica S_o, la radiación extraterrestre Q_o y la radiación global máxima Q_m calculada para condiciones extraordinarias como son: cielo despejado, mínimo contenido atmosférico de vapor de H_2O y CO_2 y mínimo coeficiente de turbidez atmosférica β {9}.

En este trabajo se plantea un método para la estimación climatológica de la radiación global Q, basado no en datos de superficie, sino en datos observacionales de los satélites meteorológicos Nimbus III y ESSA-8, sobre la nubosidad regional imperante en el país durante tres años (1969-71), período que es climatológicamente aceptable.

Estos datos fueron tomados en la magnífica investigación realizada por E.Mendoza, J.Luna y T.Gómez {10}, en la que se reportan los porcentajes mensuales de días despejados y parcialmente despejados para 117 localidades de México (Apéndice), siendo cada localidad representativa de una región de aproximadamente 130 km^2. El mosaico formado, cubre todo el país con excepción de las Islas Revillagigedo en el Oceano Pacífico.

A diferencia de los trabajos anteriormente desarrollados por diversos autores acerca de la determinación de Q y en los que se ha hecho uso de la aproximación clásica de Angstrom introduciendo el número de horas de insolación real S registradas por heliógrafos {3}, {4}, {5}, en este trabajo, la duración de la insolación real se ha aproximado mediante el cómputo mensual del número de horas de insolación posible en días despejados y parcialmente despejados; como se analizará mas adelante, a éstos últimos se les ha asignado una nubosidad promedio del 50%, o sea $c=0.5$.

Los resultados obtenidos por este procedimiento, mostraron una diferencia del 6% anual con respecto a la serie casi completa de datos pirheliométricos del período 1969-71, medidos en México,D.F. (Ciudad Universitaria) y reportados en "Solar Radiation and Radiation Balance Data" {11}.

Debido a la falta de series completas de datos pirheliométricos en otras localidades Mexicanas (Chihuahua,Chih. - Orizabita, Hgo.) tuvo que hacerse una comparación con respecto a valores reportados por Bennett {12}, para localidades fronterizas con los Estados Unidos de Norteamérica y colindantes con localidades Mexicanas. Tal es el caso de Brownsville, Tex. (E.U.) y Matamoros,Tam. (Mex.), donde la diferencia fué de sólo 1.5% anual y de Yuma,Ariz. (E.U.) y Mexicali,B.C.N. (Mex.) en donde la diferencia alcanzó solamente el 2.5% anual, aunque estas localidades se encuentran un poco mas separadas.

Aunque no pudieron efectuarse mayor número de verificaciones por la escacés de datos, los mapas elaborados de radiación global, indican que las líneas de iso-radiación trazadas, concuerdan remarcadamente en las zonas fronterizas con los Estados Unidos de Norteamérica {12}, lo cual, aunado a la grán aproximación lograda en las localidades comparadas, muestra la bondad de los resultados alcanzados mediante el método de aproximación empleado.

I Descripción del Método

a) Consideraciones Sobre la Nubosidad

En el transcurso de un día, la duración astronómica de la insolación S_0, es función de la duración del día mismo, ya que depende de la latitud ϕ del lugar y de la declinación solar δ. La duración de la insolación real S, depende además de la nubosidad ε registrada, tal que el cociente S/S_0, al excluir los factores astronómicos, expresa la duración relativa de la insolación S_r, medida en fracciones de la máxima insolación posible, o sea la astronómica S_0.

Como la duración relativa de la insolación S_r, es completamente dependiente de la nubosidad ε, lo es también de la fracción k del cielo que se encuentra despejado; es decir: $k=1-\varepsilon$.

Al fotointerpretar cuadro por cuadro la nubosidad regional diaria, E.Mendoza, J.Luna y T.Gómez, clasificaron los días despejados, nublados y parcialmente nublados, conforme al siguiente criterio:

1) Cielo despejado → 0% de nubosidad
2) Cielo nublado → 100% de nubosidad
3) Cielo parcialmente cubierto → 0% < nubosidad < 100%

por lo que aquellos días con una nubosidad comprendida entre el 1 y 99%, fueron clasificados como parcialmente nublados, del mismo modo que pudo habérseles clasificado como parcialmente despejados. Conociendo únicamente el porcentaje mensual de éstos, no puede distinguirse que tan nublados o despejados fueron, por esta razón, al hacer el cómputo de las horas mensuales de insolación posible en estos días, se ha tomado un valor promedio de nubosidad del 50%. De esta manera se ha formado la siguiente tabla, donde la nubosidad se ha expresado en fracciones:

TABLA I.- Nubosidad

Porcentaje mensual de:	ε
días despejados	0.0
días parcialmente despejados	0.5
días nublados	1.0

b) La Duración de la Insolación Astronómica

El ángulo formado por el horizonte de una localidad de latitud ϕ y la posición del sol en un instante t del día, determina la altura solar h. Esta puede obtenerse fácilmente recurriendo a la relación de trigonometría esférica aplicada a la esfera celeste {13}

$$\operatorname{sen} h = \operatorname{sen} \phi \operatorname{sen} \delta + \cos \phi \cos \delta \cos \omega \qquad (1)$$

donde ω, es el ángulo horario, definido como el ángulo formado entre los planos del meridiano del lugar y el que pasa por el sol y el centro de la tierra. Este puede expresarse como:

$$\omega = \frac{2\pi\ t'}{\tau} \qquad (2)$$

siendo t', el intervalo de tiempo contado a partir del medio día solar verdadero (sol en h max) y τ el período de rotación terrestre. En los instantes de salida y puesta del sol, +to y -to respectivamente, se tiene que:

$$h = 0° \qquad (3)$$

y el ángulo horario ω_o correspondiente viene a ser:

$$\cos \omega_o = -\tan \phi \tan \delta \qquad (4)$$

como ω_o sólo tiene valores reales en el intervalo:

$$-1 \leq \tan \phi \tan \delta \leq +1 \qquad (5)$$

y debido a que δ fluctúa entre los valores máximos: $\pm$ 23° 27', correspondientes a los solsticios, la relación (4) se satisface durante todo el año sólo para latitudes comprendidas entre:

$$-(90°-\delta) \leq \phi \leq +(90°-\delta) \qquad (6)$$

Considerando que el ángulo rotado por la tierra en una hora es de 15° (360/τ), el ángulo horario ω_o expresado en horas, puede representarse como:

$$\omega_o = \frac{1}{15} \cos^{-1} (-\tan \phi \tan \delta) \qquad (7)$$

en consecuencia, la duración astronómica de la insolación, $S_o=2\omega_o$, queda expresada como:

$$S_o \text{ (hr)} = \frac{2}{15} \cos^{-1} (-\tan \phi \tan \delta) \qquad (8)$$

c) La Radiación Extraterrestre:

En ausencia de la atmósfera, el flujo de radiación solar extraterrestre que incide sobre un elemento de superficie unitaria A, orientado normalmente a la dirección de los rayos solares, y a la distancia media Tierra-Sol (R_o) es la llamada constante solar I_o. El valor más aceptado actualmente de ésta, es de:

I_o=1.94 cal.cm-²min-¹ ±2%(variaciones del ciclo solar)
=1353 watt cm-²

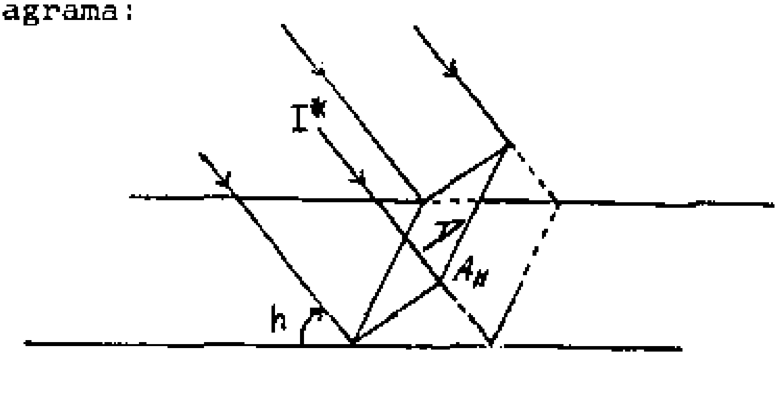
Sea I* el flujo de radiación extraterrestre incidente sobre el mismo elemento de superficie A, pero en cierta época del año cuando la distancia Tierra-Sol es R, en consecuencia, podemos relacionar a I_o e I* mediante la expresión:

$$4\pi\ R_o^2\ I_o = 4\pi\ R^2\ I^* \qquad (9)$$

es decir, el flujo de radiación que pasa al través de una esfera de radio R_o, es el mismo que pasará al través de una esfera de radio R, haciendo $R^* = R/R_o$, tenemos que:

$$I^* = \frac{I_o}{R^{*2}} \qquad (10)$$

El flujo de radiación extraterrestre I* que incide sobre una superficie horizontal, puede obtenerse observando el siguiente diagrama:



Si h es la altura solar en un instante dado, el flujo de radiación I* que pasa al través de A (normal a los rayos solares), será el mismo que incida sobre A_H, por lo que denotando a éste último por I_H, se tiene:

$$I^* A = I_H A_H \qquad (11)$$

como: $$A = A_H \text{ sen } h \qquad (12)$$

entonces: $$I_H = I^* \text{ sen } h$$

y de la expresión (1):

$$I_H = I^* (\text{sen } \phi \text{ sen } \delta + \cos \phi \cos \delta \cos \omega) \qquad (13)$$

como +to y -to representan las instantes de salida y puesta del sol, de (10) y (13) tenemos que la radiación extraterrestre diaria Q_o, es:

$$Q_o = \frac{I_o}{R^{*2}} \int_{-to}^{+to} (\text{sen } \phi \text{ sen } \delta + \cos \phi \cos \delta \cos \omega_o) dt \qquad (14)$$

Substituyendo ω_o por la expresión (2), tenemos finalmente que la radiación extraterrestre que incide sobre una superficie horizontal durante un día, es:

$$Q_o = \frac{I_o}{30 R^{*2}} \left(to \text{ sen } \phi \text{ sen } \delta + \frac{\tau}{2\pi} \cos \phi \cos \delta \text{ sen } \left(\frac{2\pi to}{\tau} \right) \right) \qquad (15)$$

$$\text{cal.cm}^{-2}\text{día}^{-1}$$

d) Radiación Global en Días Despejados

La radiación global máxima, Q_{Max}, que puede esperarse durante un día despejado, con un bajo coeficiente de turbidez atmosférica y un mínimo espesor de agua precipitable w del orden de 0.5 cm (atmósfera casi seca) {14}, puede ser calculada mediante la aproximación de Fritz {15}, {16},quien basándose en las investigaciones de Klein {17}, logró relacionar los valores instantaneos de la altura solar h con la radiación global máxima de la siguiente manera:

$$Q = 1.76 \text{ sen } h - 0.07 \quad \text{para } h > {}^{o}8$$
$$Q' = 1.20 \text{ sen } h \quad \text{para } h < 8^{o} \qquad (16)$$

Similarmente al cálculo de Q_o, la radiación global máxima durante el día será:

$$Q_{Max} = \int_{-t_0}^{t_1} Q' \, d_t + \int_{t_1}^{t_2} Q \, d_t + \int_{t_2}^{+to} Q' \, d_t \qquad (17)$$

donde t_1 representa el instante cuando h= -8°y t_2 cuando h= +8°.

e) Obtención de la Radiación Global Mensual en las Localidades Estudiadas.

Tal como se anticipó al principio de este trabajo, consideraremos primeramente la relación existente entre la radiación global Q y la duración real de la insolación S, Angstrom {3}, sugirió que esta relación se podía expresar linealmente como:

$$\frac{\bar{Q}}{\bar{Q}_{Max}} = a + b \frac{\bar{S}}{\bar{S}_{Max}} \qquad (18)$$

donde $\bar{Q}$, $\bar{Q}_{Max}$, $\bar{S}$ y $\bar{S}_{Max}$ son los valores medios en los períodos considerados (decadarios o mensuales); a y b son constantes a determinar de acuerdo con el siguiente criterio:

i) Cuando: $\bar{S} = 0$; $\bar{Q} = a\,\bar{Q}_{Max}$, determinándose así el valor de a, al efectuar el cociente de $\bar{Q}$ para cielo completamente cubierto y $\bar{Q}_{Max}$ para cielo completamente despejado

ii) Si: $\bar{S} = \bar{S}_{Max}$; en consecuencia $\bar{Q} = \bar{Q}_{Max}$, por lo que en este caso, a + b = 1 ; a y b se determinan experimentalmente en los períodos durante los cuales, $\bar{Q}$ y $\bar{S}$ son determinados. Se ha observado que estos valores varían según la latitud, el albedo de superficie y el espesor de agua precipitable w.

P. de Brichambaut y G. Lamboley (18), al analizar la radiación global media $\bar{Q}$, en función de la fracción de insolación media $\bar{S}$, para un considerable número de casos, encontraron que la expresión de Angstrom (18), no es del todo lineal, y sugieren reemplazar la expresión (18) por los valores de la curva siguiente (Grafica 1) indicando que la precisión que puede ser obtenida es del 8% o mejor si se dispone al menos de datos de tres años consecutivos.

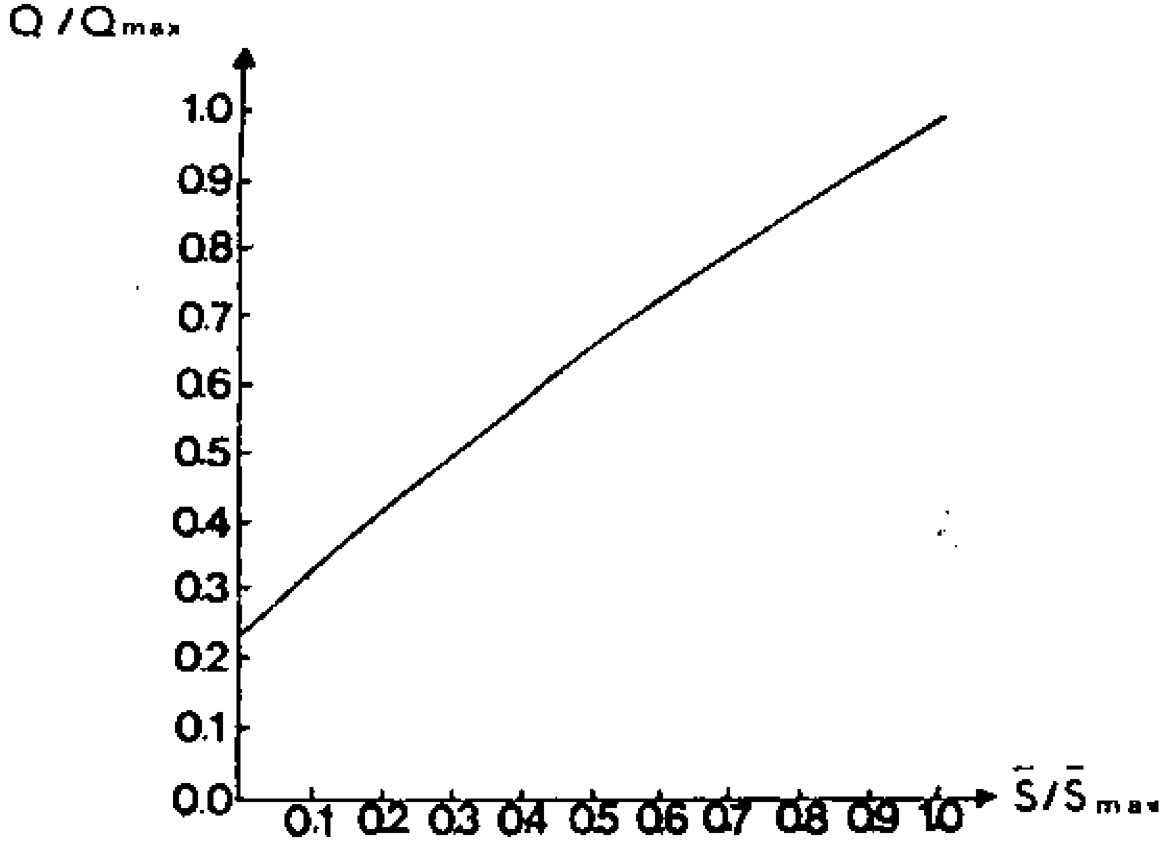


FIGURA 1 . RELACION ENTRE LA DURACION DE LA INSOLACION Y LA RADIACION GLOBAL.

Como en el presente caso, se carece de datos sobre la duración real de la insolación S, ésta se ha calculado en la forma siguiente.

Sean:

n, el número de días del mes.

n_1, el número de días despejados en el mes.

n_2, el número de días parcialmente despejados en el mes.

y, $\bar{S}_{d_o}$ el promedio diario del total de horas de insolación astronómica en el mes, es decir:

$$\bar{S}_{d_o} = \frac{\sum_{i=1}^{n} H_i}{n} \qquad (19)$$

donde H_i representa el total de horas de insolación astronómica del día i. Considerando que durante los días completamente despejados, ε=0.0, entonces aproximando:

$$S_{Max} = S_o$$

el número medio mensual de horas con cielo despejado será:

$$\bar{S}_m = n_1 \bar{S}_{d_o} \qquad (20)$$

Como en los días parcialmente despejados se ha considerado que S depende de ε (Tabla 1), entonces, en primera aproximación, el número medio mensual de horas con cielo parcialmente despejado, $\bar{S}'_m$, será:

$$\bar{S}'_m = n_2 \bar{S}_{d_o} \bar{\varepsilon} \qquad (21)$$

En consecuencia, el total mensual de horas con cielo despejado, que en este caso vendría a representar, el total mensual de horas de insolación real, queda expresado por:

$$S_t = n_1 \bar{S}_{d_o} + n_2 \bar{S}_{d_o} \bar{\varepsilon} \qquad (22)$$

designando por S_{o_t}, el total mensual de horas de insolación astronómica, es decir:

$$S_{o_t} = \sum_{i=1}^{n} H_i \qquad (23)$$

la insolación relativa, S_r, podrá obtenerse a partir del cociente

$$S_r = \frac{S_t}{S_{o_t}} \qquad (24)$$

Este valor, S_r, se ha relacionado con la radiación global relativa Q/Q_{Max}, utilizando la curva propuesta por P. de Brichambaut y G. Lamboley [18], para la cual se interpolaron 20 puntos. De esta manera se obtuvieron para las 117 localidades de referencia estudiadas, los promedios diarios de la radiación global mensual, $\bar{Q}_m$, así como también el promedio diario anual, $\bar{Q}_a$.

Tanto para el cómputo de las duraciones de la insolación, como para las radiaciones terrestres y global, se recurrieron a los valores decadarios de la declinación solar y la distancia Tierra-Sol, de acuerdo con las tablas siguientes:

TABLA II Declinación Solar	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC
1a decena	-22°	-16	-6	+6	+16	+22	+23	+17	+7	-5	-16	-22
2a "	-21	-13	-2	+10	+19	+23	+21	+14	+3	-9	-18	-23
3a "	-19	-9	+2	+13	+21	+23	+20	+11	-1	-12	-21	-23

TABLA III Distancia Tierra - Sol (variación)	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC
1a decena	+3%	+3	+2	0	-2	-3	-3	-3	-2	0	+2	+3
2a "	+3	+2	+1	-1	-2	-3	-3	-3	-1	+1	+2	+3
3a "	+3	+2	0	-1	-3	-3	-3	-2	-1	+1	+3	+3

II Resultados

Los resultados obtenidos de la distribución anual y mensual de la insolación en México, se muestran en los trece mapas siguientes. Las líneas conectan puntos con igual intensidad de la radiación global (media diaria), y fueron trazadas a intervalos de 25 $cal.cm^{-2}$ $día^{-1}$, salvo en los casos en que por claridad, se optó por interpolar más.

Todos los cómputos realizados y que condujeron a la elaboración de mapas, fueron procesados por una computadora Borroughs/B7700 del Centro de Servicios de Cómputo de la U.N.A.M.

El mapeo de los resultados mensuales muestra que durante casi todo el año (excepto Julio, Agosto y Septiembre), existe un marcado gradiente Este-Oeste en las regiones del norte y centro del país, donde los valores máximos calculados se encuentran desplazados hacia el Oeste. Las regiones fisiográficas comprendidas son: la parte norte y central de la Sierra Madre Oriental, la Altiplanicie Mexicana, la Sierra Madre Occidental y Península de Baja California.

Durante los meses de: Enero, Febrero, Marzo, Abril, Mayo, Octubre, Noviembre y Diciembre, es notable también el gradiente establecido en las regiones comprendidas entre la parte sur de la Sierra Madre Oriental y la Sierra Madre del Sur, donde los valores máximos se localizan sobre esta última región.

En el Istmo de Tehuantepec y Región del Sureste, se registran en el transcurso del año, gradientes de importancia, aunque por sus fluctuaciones tanto longitudinales como latitudinales, no son tan uniformes como los dos anteriormente mencionados.

En la Región de la Península de Yucatán, puede observarse fácilmente la existencia de un gradiente latitudinal, ya que durante los tres primeros meses del año, los valores de las líneas de iso-radiación aumentan hacia el sur; en contraste, durante los nueve meses restantes aumentan hacia el norte, invirtiéndose así la dirección de este gradiente.

La distribución anual de la insolación, la cual se muestra en el primer mapa, puede resumirse en el siguiente cuadro:

DISTRIBUCION ANUAL DE LA INSOLACION

Categoría	Características	Porcentajes aprox. que ocupan de la sup. total del territorio nacional.	Extensión territorial (aprox.) (Total=1,972,547Km^2)
I	Regiones con más de 500cal.cm^{-2}día^{-1}	38	749,570 Km^2
II	Regiones comprendidas entre 500 y 400 cal.cm^{-2}día^{-1}	57	1,124,350 Km^2
III	Regiones con menos de 400 cal.cm^{-2}día^{-1}	5	98,627 Km^2

Dentro de la primera categoría, el valor máximo-maximorum anual calculado, fué para la región de San Javier, B.C.S., (25°51'N, 111°35'O.) con 549 cal.cm-^{2}día-^{1} (6.38 kwh.m-^{2}día-^{1}). En la tercera categoría, el valor máximo-minimorum calculado, fué para la región de Cosamaloapan, Ver. (18°22'N,95°48'O.) con 363cal. cm-^{2}día-^{1} (4.22 kwh.m-^{2}día-^{1}). Considerando que el promedio diario de la radiación extraterrestre anual en el primero de los sitios, fué de 775 cal.cm-^{2}día-^{1}, la insolación relativa anual es de casi el 71%, mientras que en el segundo sitio fué de casi el 45%. Recurriendo a la clasificación climática de Köppen, el primero de estos sitios corresponde al segundo grupo; subtipo BWχ'; caracterizado por un clima desértico o muy árido con lluvias poco abundantes que pueden presentarse en cualquier época del año. El segundo sitio corresponde al primer grupo, subtipo Aω, caracterizado por ser cálido, subhúmedo con lluvias de Verano.

Del mismo mapa puede observarse que la zona de máxima insolación anual, es la parte sur de la Península de Baja California, aunque curiosamente, de la siguiente tabla puede observarse que mensualmente, sólo dos valores máximos-maximorum se encuentran en esta zona.

TABLA IV

Mes	Localidad	Radiación Global Máxima-Maximorum Mensual calculada (cal.cm-²día-¹)
ENE	San Luis de la Loma,Gro.	511
FEB	Cihuatlán, Jal.	591
MAR	San Luis de la Loma,Gro.	616
ABR	Chilpancingo, Gro.	692
MAY	Punta Peñasco, Son.	725
JUN	Punta Peñasco, Son.	716
JUL	Guerrero, Tam.	702
AGO	Jesus María, Nay.	667
SEP	Cerro Giganta, B.C.S.	600
OCT	La Paz, B.C.S.	513
NOV	Chilpancingo, Gro.	531
DIC	Juquila, Oax.	509

Esto se debe a que durante el año, en las localidades de referencia de la parte sur de la Península de Baja California, los valores mensuales permanecieron altos y fluctuaron en menor proporción que en las localidades enlistadas.

Respecto a las zonas de mínima insolación anual, éstas se encuentran localizadas en: la Llanura Costera del Golfo de México, abarcando también la parte oriental de la Mesa Central, Región de los Valles, Itsmo de Tehuantepec y la parte occidental de la Región del Sureste. Como puede observarse los valores de contorno de las líneas de iso-radiación fluctúan entre 450 y 375 cal. cm^{-2} $día^{-1}$.

En la tabla siguiente se muestran los valores máximos-minimorum mensuales que se calcularon:

TABLA V

Mes	Localidad	Radiación Global Máximo-Minimorum Mensual calculado (cal.$cm^{-2}día^{-1}$)
ENE	Guerrero, Tam.	217
FEB	Camargo, Tam.	302
MAR	Tampico, Tam.	372
ABR	Ozulama, Ver.	412
MAY	Ozulama, Ver.	454
JUN	Tuxtla Gutiérrez, Chis.	422
JUL	Tequisistlán, Oax.	334
AGO	Tequisistlán, Oax.	328
SEP	Cosamaloapan, Ver.	253
OCT	Unión, Coah.	290
NOV	Cosamaloapan, Ver.	248
DIC	Cosamaloapan, Ver.	231

III Conclusiones

Como consecuencia fundamental de la notable irregularidad orográfica de nuestro país, existen gran variedad de climas que en muchos casos varían en distancias muy cortas, por consiguiente, una localidad específica podrá caracterizarse por un microclima particular o un conjunto de estos, es decir, un mesoclima. El microclima no excede por lo general a superficies mayores de 1 Km^2, mientras que el mesoclima o clima regional, comprende superficies más extensas.

Dado que en este trabajo, los datos de nubosidad empleados, no corresponden exactamente a localidades específicas, sino a regiones donde se ha designado una localidad de referencia, los resultados obtenidos deberán ser considerados en la misma forma, es decir, regionales.
No obstante que solamente se dispuso de tres años de datos de nubosidad, los resultados al ser comparados con los que aparecen en las publicaciones anteriormente citadas, permiten estimar una aproximación global del orden del 10% o mejor, sobretodo, en los resultados anuales.

Estatalmente, la radiación global anual resultó ser más intensa en: Baja California Sur, Sonora, Baja California Norte, el oeste de Chihuahua, casi todo Sinaloa, Nayarit, el oeste de Jalisco, Michoacán (excepto el noreste), casi todo Guerrero, el sureste de Oaxaca, el norte de Yucatán y el noreste de Quintana Roo. Los estados menos favorecidos durante el año fueron: Veracruz, el sureste de San Luis Potosí, el noreste de Querétaro e Hidalgo, el este y noreste de Puebla; el este, noreste y sureste de Oaxaca, el norte de Tabasco y casi todo Chiapas (excepto el sur).

Considerando que anualmente el 95% del territorio nacional recibe más de 400 $cal.cm^{-2}día^{-1}$, las perspectivas de aprovechamiento de la energía solar son magníficas. Las zonas áridas y semiáridas (ver último mapa) que ocupan casi el 41% del país, disfrutan de una esplendida insolación anual, por lo que la energía solar en estas zonas casi siempre alejadas de los centros distribuidores de combustible, puede servir como fuente energética primaria.

Concluyendo, puede decirse que dadas las características de insolación tan favorables en nuestro país, las aplicaciones que de la energía solar pretendan hacerse, fructificarán en el mejoramiento de la economía nacional, tanto en el plano agrícola como industrial, esperando que el presente estudio pueda contribuir en la selección de los sitios más favorables para desarrollar esta nueva tecnología, así como para un mejor conocimiento de la climatología solar de México.

Reconocimientos

Quiero hacer patente mi agradecimiento al Dr: Eric Mayer B., Investigador del C.I.M. - U.N.A.M., por sus comentarios, revisión del texto y el entusiasmo mostrado por la elaboración de este trabajo.

Agradezco al Dr. E. Mendoza y al Mat. Juan Luna, Investigadores del Instituto de Astronomía de la U.N.A.M., por la información concerniente a la fotointerpretación.

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Referencias

1. Précisions des Mesures Pyrhéliometriques, Technical Note No. 65, World Meteorological Organization No. 209, Geneve, 1967.

2. I.Galindo, A.Leyva, A.Muhlia, V.Valderrama, L.Galindo, A.Alvarez, I.Ramírez. Datos Geofísicos, Serie B.Meteorología 1, Instituto de Geofísica, U.N.A.M. México 1974.

3. Angstrom,A., "Solar and Terrestial Radiation", Quarterly Journal of the Royal Meteorological Society, Vol.50, 1924, p. 121-125.

4. Angstrom A., "On Computation of Global Radiation from the Records of Sunshine", Arkiv för Geofysica Stockholm, Vol. 2, No. 22, 1956.

5. Black,J.N., "Distribution of Solar Radiation over the Earth's Surface, Archiv Für Meteorologie, Geophysik und Bioklimatologie, Serie B, Band 7, 1956, p. 165.

6. Glover,J. and J.S.F. Mc Culloch "The Empirical Relation between Solar Radiation and Hours of Bright Sunshine in The High-Altitude Tropics", Quarterly Journal of the Royal Meteorological Society Vol. 84, 1958, p. 56-60.

7. Boer,H.J. DE, "A Calculation of Global Radiation in the Netherlands with the aid of Relative Duration of Sunshine, Archiv für Meteorologie, Geophysik und Bio-

klimatologie, Serie B, Band 10, 1961, p. 537.

8. Page, J.K., "The Estimation of Monthly Mean Values of Daily Total Short Wave Radiation on Vertical and Inclined Surfaces from Sunshine Records for Latitudes" 40°N-40°S." New Sources of Energy, Proceedings of the Conference of Rome, 21-31 August 1961, Vol. 4, Solar Energy, United Nations, New York 1964.

9. Angstrom,A., "The Parameters of Atmospheric Turbidity" The Eppley Foundation for Research, 1963.

10. E. Mendoza, J.Luna y T.Gómez. "Busqueda y Selección de Sitios Astronómicos mediante Satélites Meteorológicos" Bol. de Obs. de Tonantzintla y Tacubaya, N.38, V.6 1972

11. Solar Radiation and Radiation Balance Data (The World Net work), USSR Chief Administration of the Hydrometeorological Service, Leningrad 1969, 1970, 1971.

12. Bennett, I., "Monthly Maps of Mean Daily Insolation for the United States" Solar Energy Vol. 9, No. 3, 1965.

13. Hernández,H.E."Estudio Sobre el Modelo Termodinámico del Clima de Adem", Tesis Lic., Facultad de Ciencias U.N.A.M. 1974 p. 47-49.

14. Perrin de Brichambaut,Ch., "Rayonnement Solaire et Echanges Radiatifs Naturels", Gauthier Villard, Paris, 1963.

15. Fritz,S., "Solar Radiation During Cloudless Days", Heating and Ventilating, Vol. 46, January 1949.

16. Fritz,S., "Solar Energy on Clear and Cloudy Days", The Scientific Monthly, February 1957.

17. Klein W.H., "Calculation of Solar Radiation and the Solar Heat Load on Man", Journal of Meteorology, Vol. 5, No. 4, August 1948.

18. Perrin de Brichambaut, Ch., Lamboley,G., Cahiers de l'A.F.E.D.E.S., January 1968, Vol. I.

19. García E., "Modificaciones al Sistema de Clasificación Climática de Köppen", Instituto de Geografía, U.N.A.M., 1973.

20. García E., Falcón, Z., "Nuevo Atlas Porrúa de la República Mexicana", Ed. Porrúa, S.A., México,D.F., 1974.

Apéndice

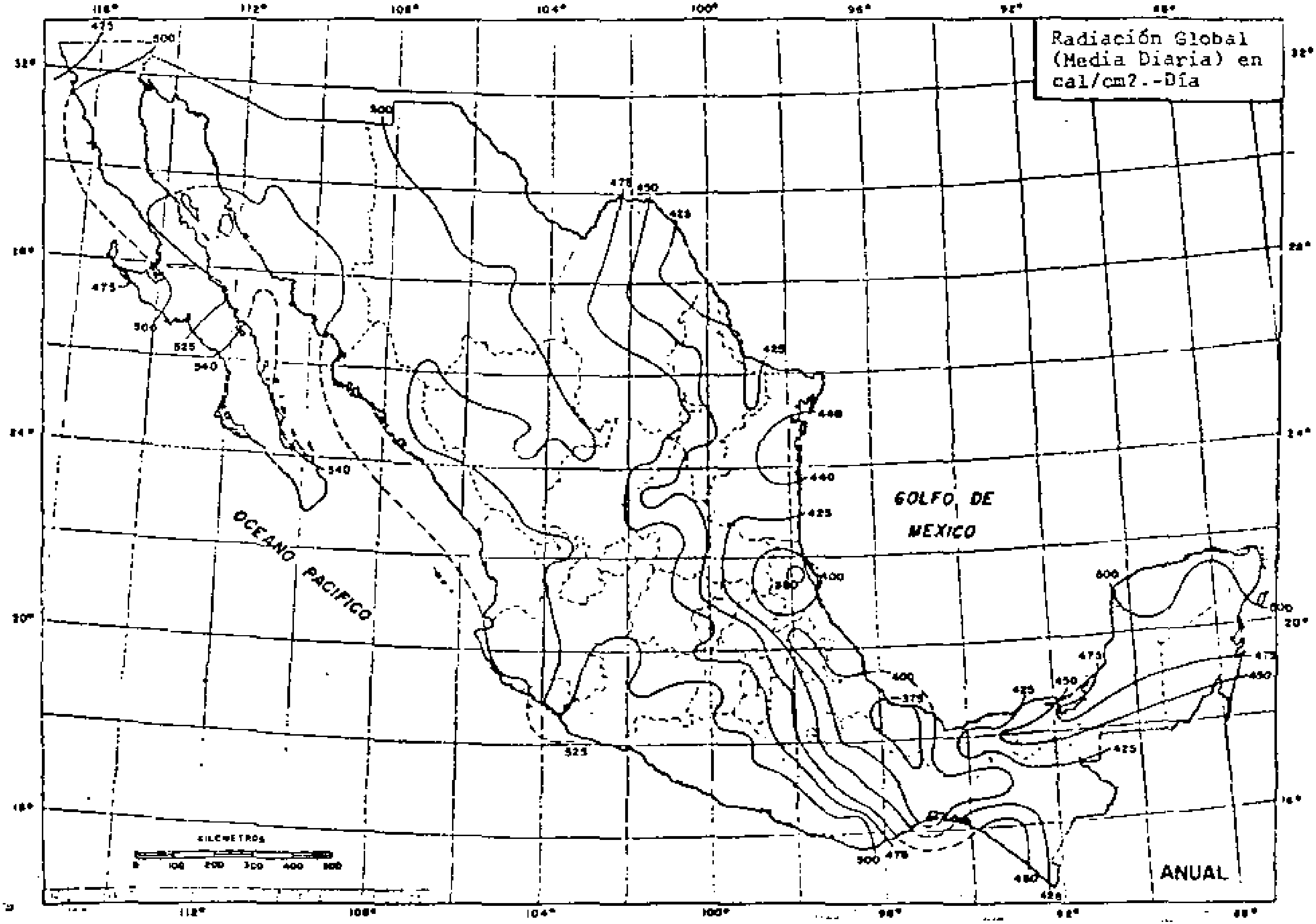
	LOCALIDADES DE REFERENCIA REGION	LATITUD		LONGITUD		ALTITUD
1	Aguascalientes,Ags.	21°	63'	102°	8'	1979 m
2	Mexicali, B.C.N.	32	39	115	30	4
3	San Borja, B.C.N.	28	47	113	57	400
4	San Fernando, B.C.N.	29	57	115	11	500
5	San Pedro Martir,B.C.N.	31	03	115	27	2850
6	Bahía Tortugas, B.C.S.	27	43	114	56	6
7	Cerro Giganta, B.C.S.	26	10	111	35	1767
8	La Paz, B.C.S.	24	09	110	20	19
9	Punta Sto.Domingo,B.C.S.	25	33	111	03	18
10	San Javier, B.C.S.	25	51	111	35	700
11	S.Luis Gonzaga,B.C.N.	29	45	114	25	0
12	Volcán Virgenes,B.C.S.	27	30	112	65	2054
13	Pustunich, Camp.	19	09	90	29	35
14	Tenabó, Camp.	20	02	90	15	0*
15	Las Animas, Coah.	28	28	103	15	1000*
16	Palo Verde, Coah.	26	20	101	30	1000*
17	Saltillo, Coah.	25	25	101	00	1589
18	Sierra Mojada, Coah.	27	17	103	42	1256*
19	Unión, Coah.	28	14	100	44	500*
20	Colima, Col.	19	15	103	43	494
21	Comitán, Chis.	16	15	92	08	1530
22	Ocosingo, Chis.	16	56	92	12	908
23	Tuxtla Gutiérrez,Chis.	16	45	93	07	536
24	Villa Flores, Chis.	16	14	93	16	610
25	Villa Ahumada, Chih.	30	39	106	31	1181

LOCALIDADES DE REFERENCIA REGION		LATITUD		LONGITUD		ALTITUD
26	Allende, Chih.	26°	55'	105°	25'	1000*
27	Cerro Mahinora, Chih.	25	58	107	3	3300*
28	Corrisal, Chih.	30	30	106	35	1000*
29	Chapo, Chih.	29	20	104	25	1000*
30	Chihuahua, Chih.	28	38	106	05	1423
31	Delicias, Chih.	28	11	105	29	1171
32	F.Magón, Chih.	29	55	106	55	1000*
33	Gómez Flores, Chih.	30	32	105	50	1000*
34	Guachochi, Chih.	26	49	107	04	2390
35	Maguarichic, Chih.	27	50	108	03	2000
36	Sierra Tasajera, Chih.	29	20	105	35	1000*
37	México, D.F.	19	26	99	08	2273
38	Ciudad Lerdo, Dgo.	25	32	103	32	1137
39	Cuencame, Dgo.	24	52	103	42	1665
40	Durango, Dgo.	24	01	104	40	1889
41	Nombre de Dios, Dgo.	23	50	104	14	1734
42	Sta. Ma. de Otaez, Dgo.	24	40	105	59	1889
43	Sta. Ma. del Oro, Dgo.	25	57	105	16	1765
44	Chilpancingo, Gro.	17	33	99	30	1360
45	S.Luis de la Loma,Gro.	17	10	100	54	0
46	Teloloapan, Gro.	18	22	99	53	1620
47	Tepecoacuilco, Gro.	18	17	99	28	1012
48	Guanajuato, Gto.	21	01	101	15	2037
49	S.Luis de la Paz, Gto.	21	18	100	31	1933
50	Ixmiquilpan, Hgo.	20	29	99	13	1745
51	Pisaflores, Hgo.	21	12	99	0	325
52	Cihuatlán, Jal.	19	15	104	35	145
53	Guadalajara, Jal.	20	41	103	20	1589
54	Talpa de Allende, Jal.	20	20	104	50	1039
55	Aguililla, Mich.	18	44	102	44	975
56	Huajambaro, Mich.	19	41	100	44	2390
57	Morelia, Mich.	19	42	101	11	1941

	LOCALIDADES DE REFERENCIA REGION	LATITUD		LONGITUD		ALTITUD
58	Tequicheo, Mich.	18°	54'	100°	45'	502m
59	Acaponeta, Nay.	22	36	105	22	64
60	Huajimic, Nay.	21	41	104	18	1170
61	Jesús María, Nay.	22	15	104	31	610
62	Ruiz, Nay.	21	58	105	09	55
63	Los Aldama, N.L.	26	04	99	12	188
64	Galeana, N.L.	24	49	100	4	1654
65	Monterrey, N.L.	25	40	100	18	538
66	Villaldama, N.L.	126	30	100	20	437
67	Juquila, Oax.	16	14	97	18	1500*
68	Juxtlahuaca, Oax.	17	20	98	01	1650
69	Oaxaca de Juárez, Oax.	17	04	96	43	1563
70	Tecomayaca, Oax.	17	58	97	31	660
71	Tequisistlán, Oax.	16	24	95	36	190
72	Chiautla de Tapia, Pue.	18	17	98	36	1060
73	Huauchinango, Pue.	20	11	98	3	1600
74	La Malinche, Pue.	19	14	98	02	4461
75	Querétaro, Qro.	20	36	100	23	1853
76	Cozumel, Q.R.	20	36	86	44	3
77	Polyuc, Q.R.	19	37	88	34	0*
78	Cerritos, S.L.P.	22	26	100	17	1153
79	Matehuala, S.L.P.	23	39	100	38	1581
80	Sto. Domingo, S.L.P.	23	20	101	34	1971
81	Vieja, S.L.P.	22	02	199	25	100
82	Cruz, Sin.	23	54	106	54	14
83	Culiacán, Sin.	24	48	107	24	53
84	La Laguna, Sin.	26	35	108	27	600*
85	Topolobampo, Sin.	25	37	109	05	3
86	Altar, Son.	30	43	111	51	397
87	Bacadehuachi, Son.	29	20	109	17	500*
88	Bacanora, Son.	28	59	109	23	446
89	Cerro Viejo, Son.	30	15	112	15	1625

LOCALIDADES DE REFERENCIA REGION		LATITUD		LONGITUD		ALTITUD
90	Hermosillo, Son.	29°	05'	110°	57'	237m
91	Libertad, Son.	29	54	112	45	0*
92	Onavas, Son.	20	28	109	35	251
93	Punta Peñasco, Son.	31	18	113	33	4
94	Quiriego, Son.	27	32	109	15	251
95	Comalcalco, Tab.	18	16	93	12	10
96	Villahermosa, Tab.	17	59	92	55	10
97	Abasolo, Tam.	24	04	98	23	84
98	Camargo, Tam.	26	19	98	50	68
99	Casas, Tam.	23	44	98	44	34
100	Guerrero, Tam.	26	47	99	21	94
101	Jaumave, Tam.	23	25	99	23	735
102	Jiménez, Tam.	24	13	98	29	101
103	Matamoros, Tam.	25	52	97	31	12
104	Tampico, Tam.	22	14	97	51	12
105	Coatzacoalcos, Ver.	18	19	94	25	14
106	Coatzintla, Ver.	20	29	97	26	144
107	Cosamaloapan, Ver.	18	22	95	48	65
108	Ozuluama, Ver.	21	40	97	51	229
109	Pico de Orizaba, Ver.	19	02	97	16	5700
110	San Felipe, Yuc.	21	34	88	30	0*
111	Sisal, Yuc.	21	10	90	2	0
112	Valladolid, Yuc.	20	41	88	12	18
113	Concepción del Oro, Zac.	24	37	101	25	2543
114	Ojo Caliente, Zac.	22	35	102	15	2114
115	Pinos, Zac.	22	18	101	35	2538
116	Valparaiso, Zac.	22	47	103	39	1950
117	Villa de Cos, Zac.	23	18	102	21	2050

*Altitud aproximada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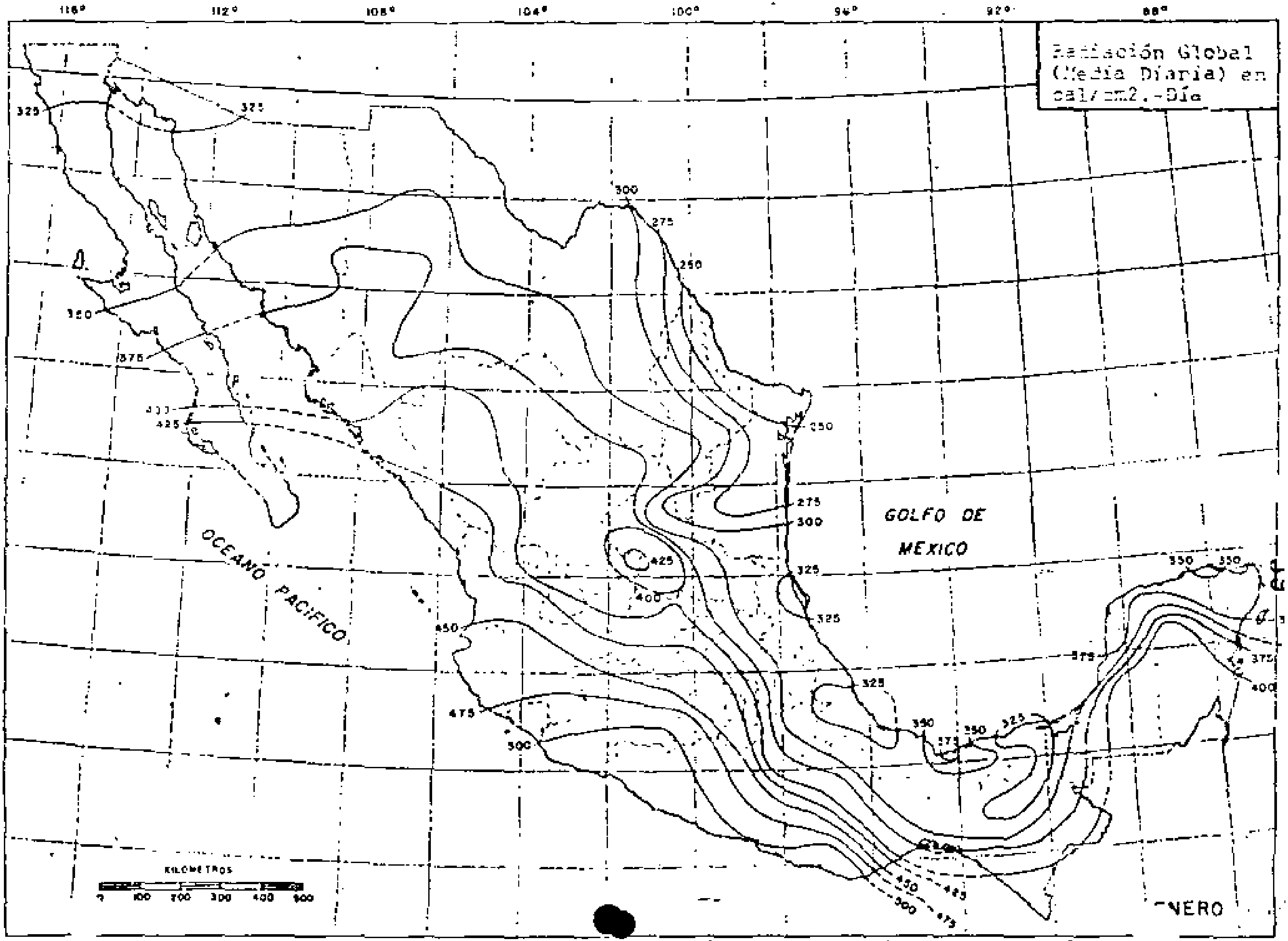

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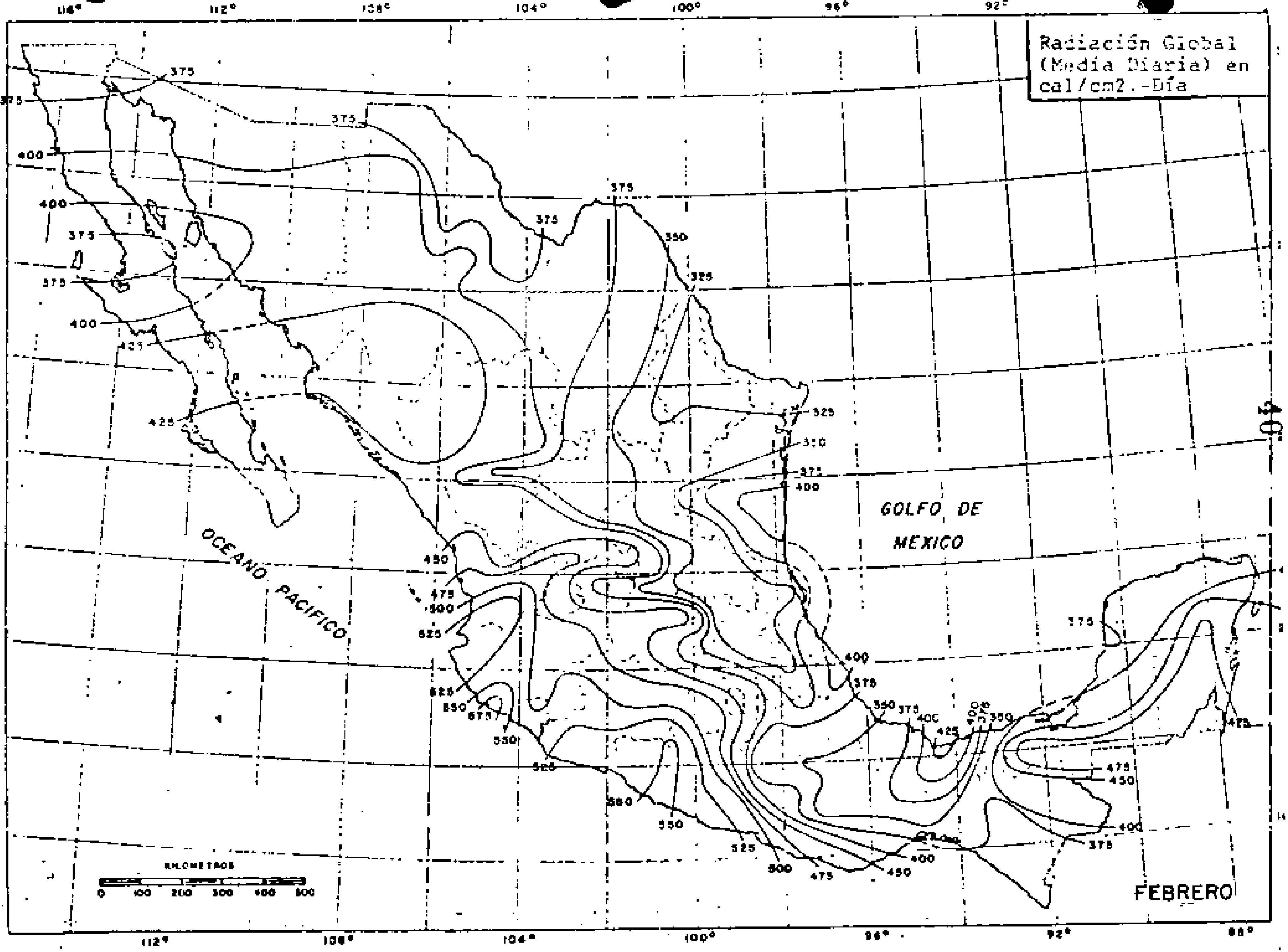
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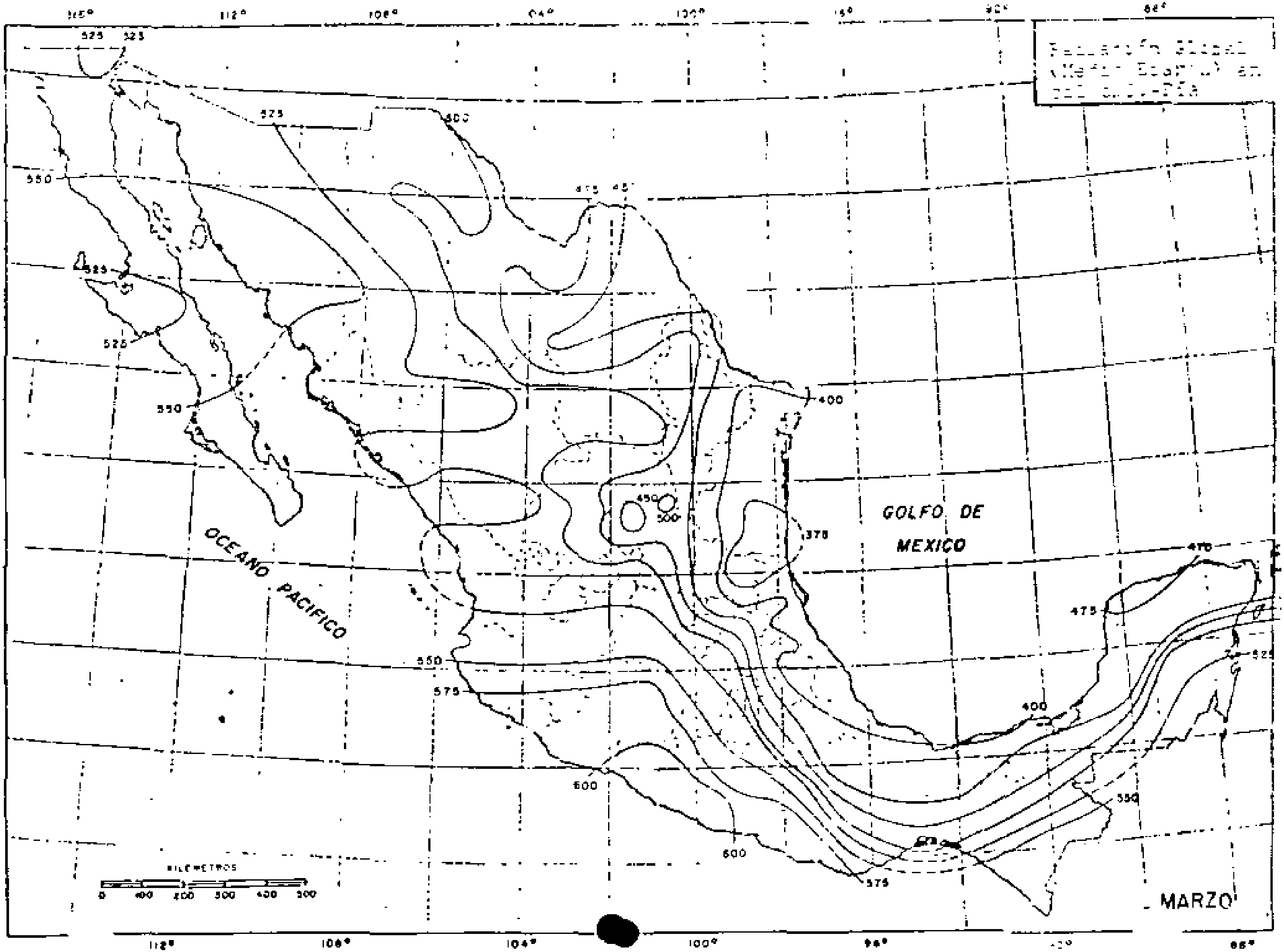

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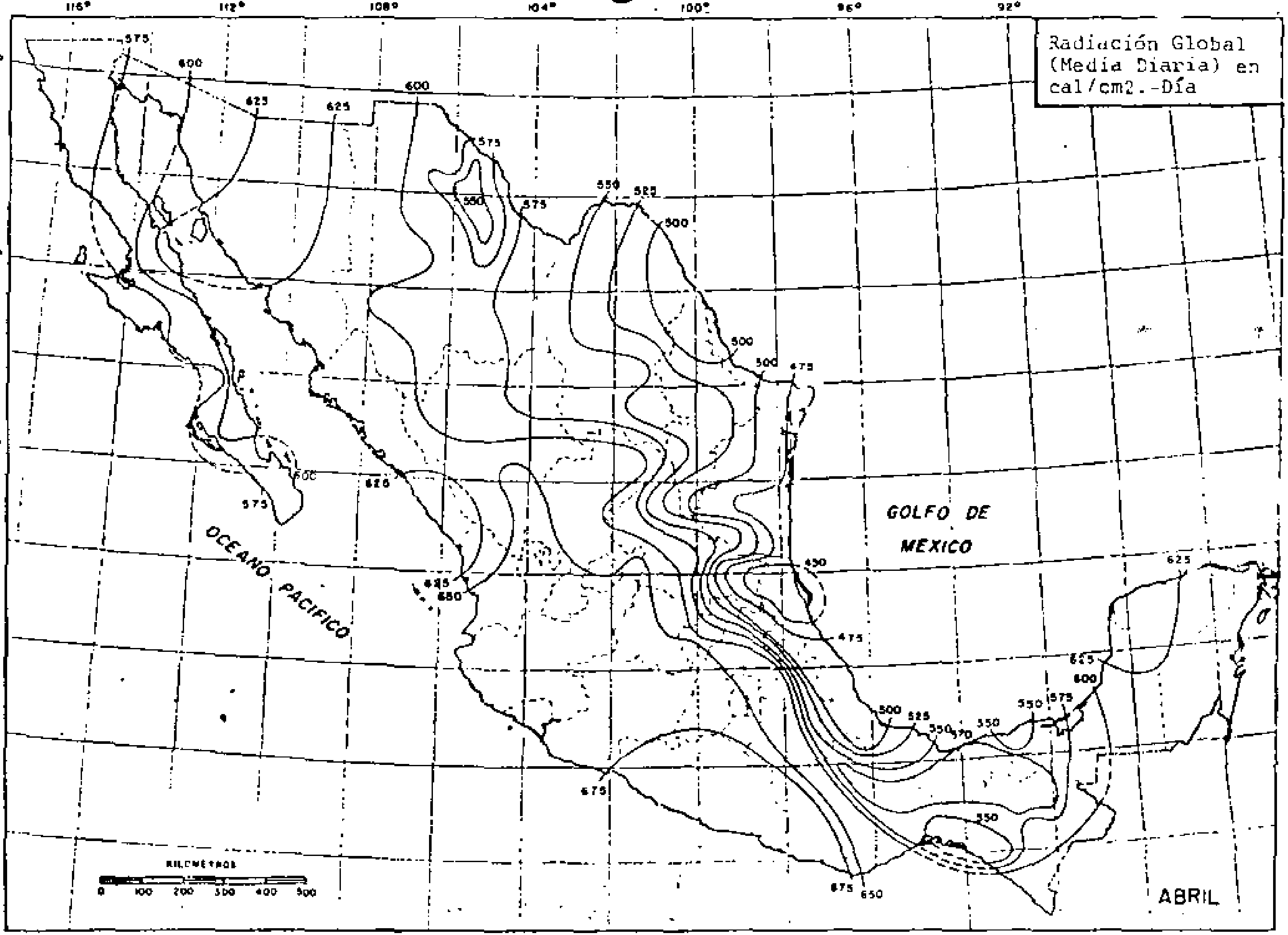

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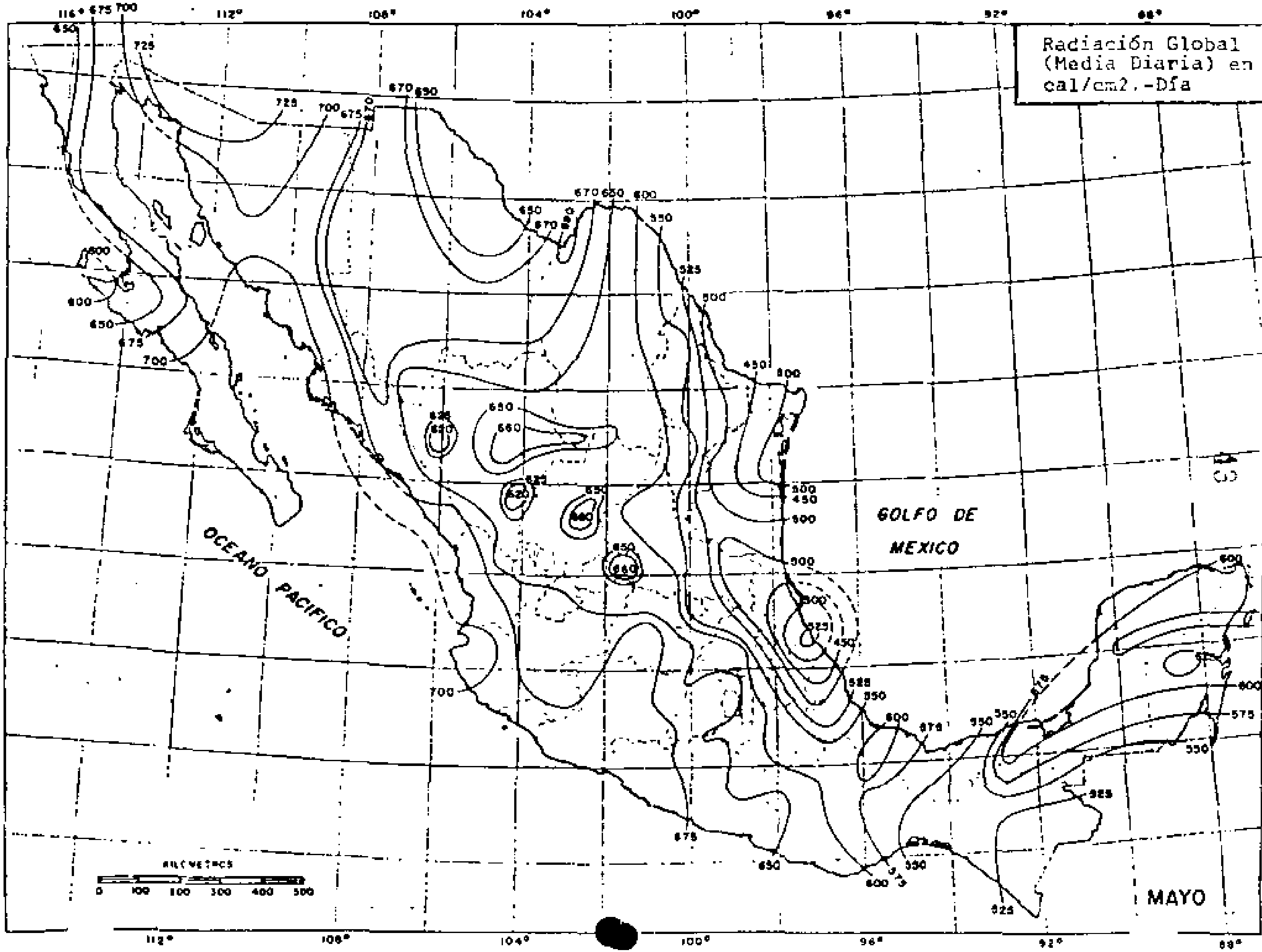

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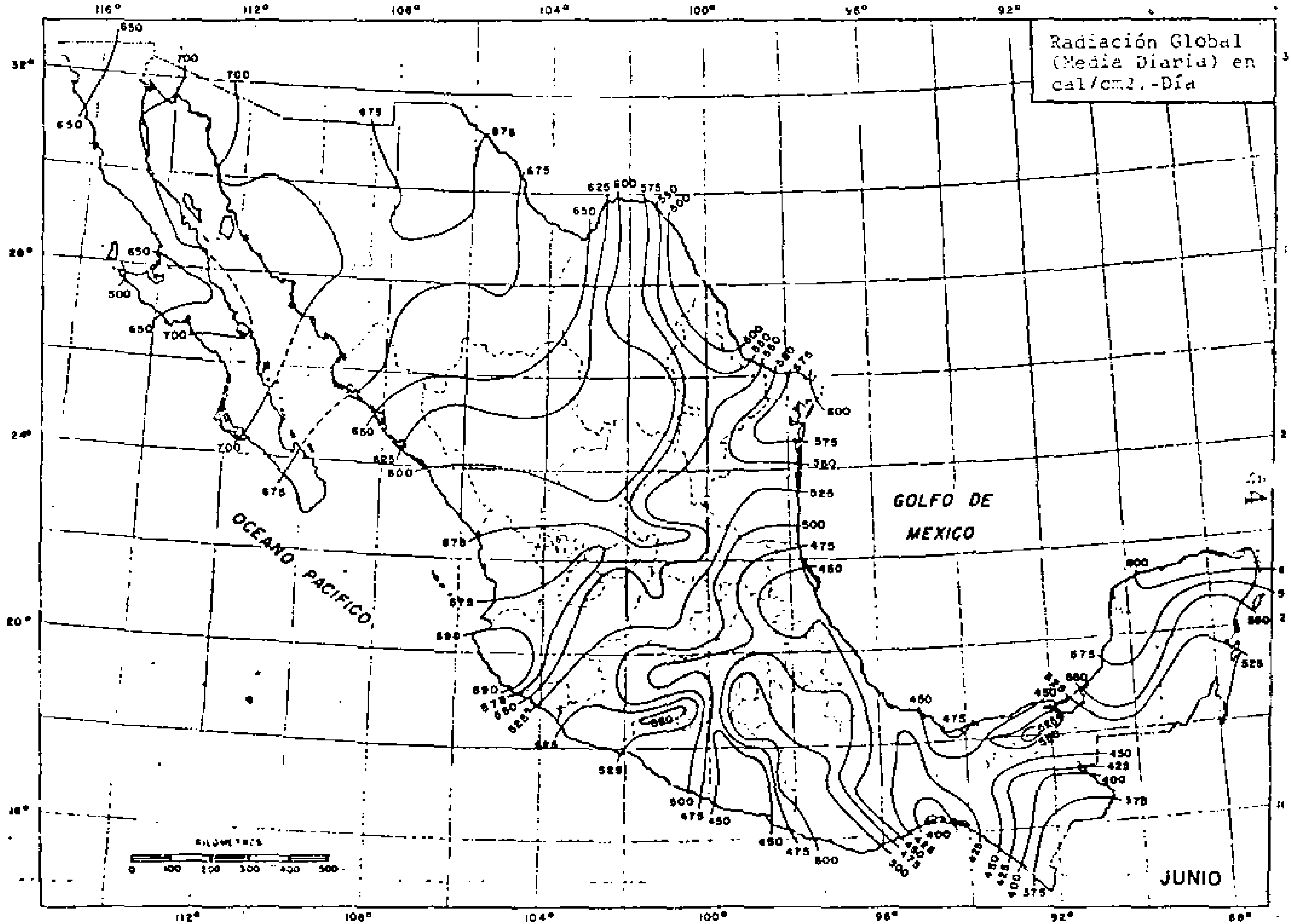

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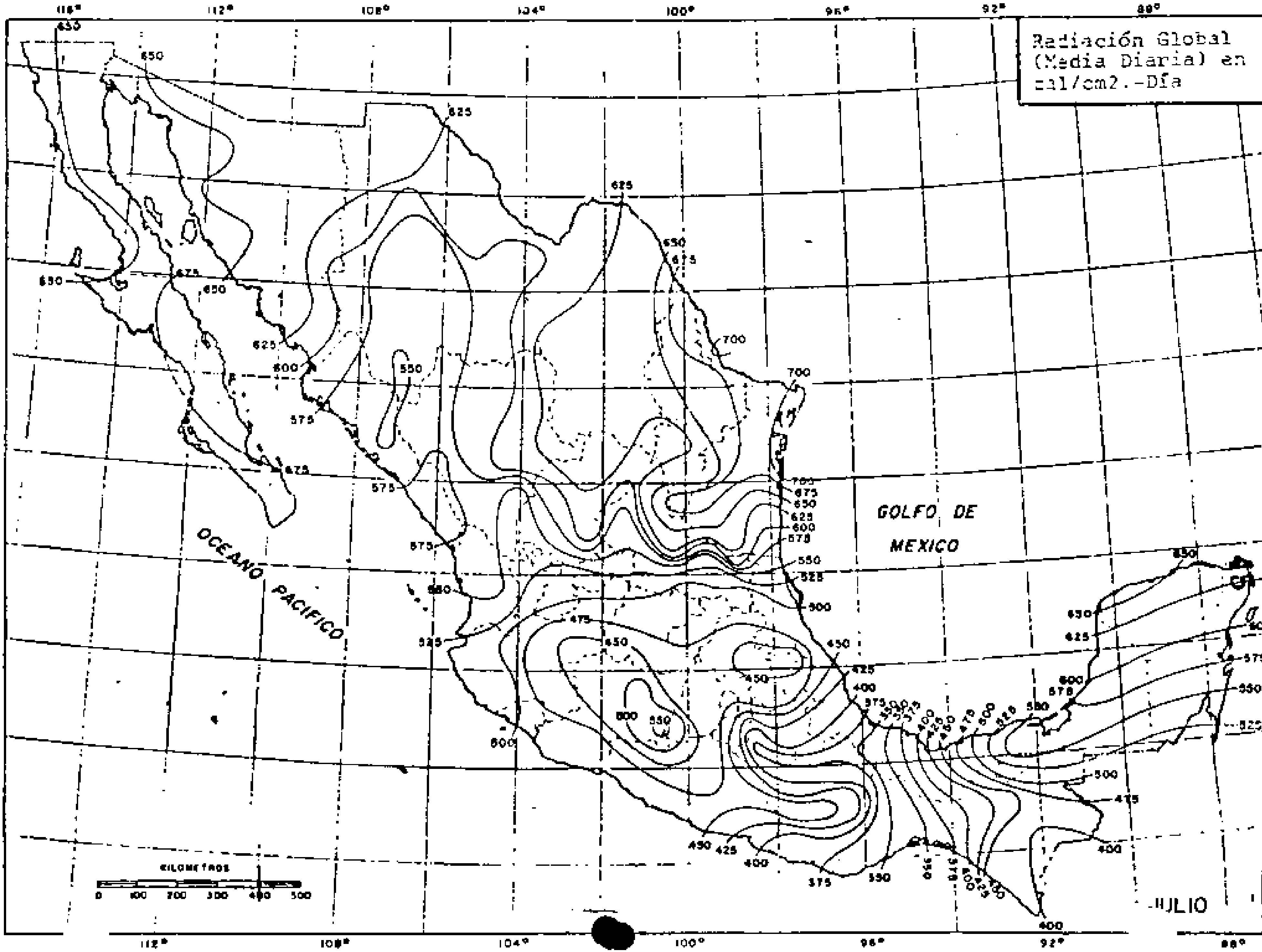
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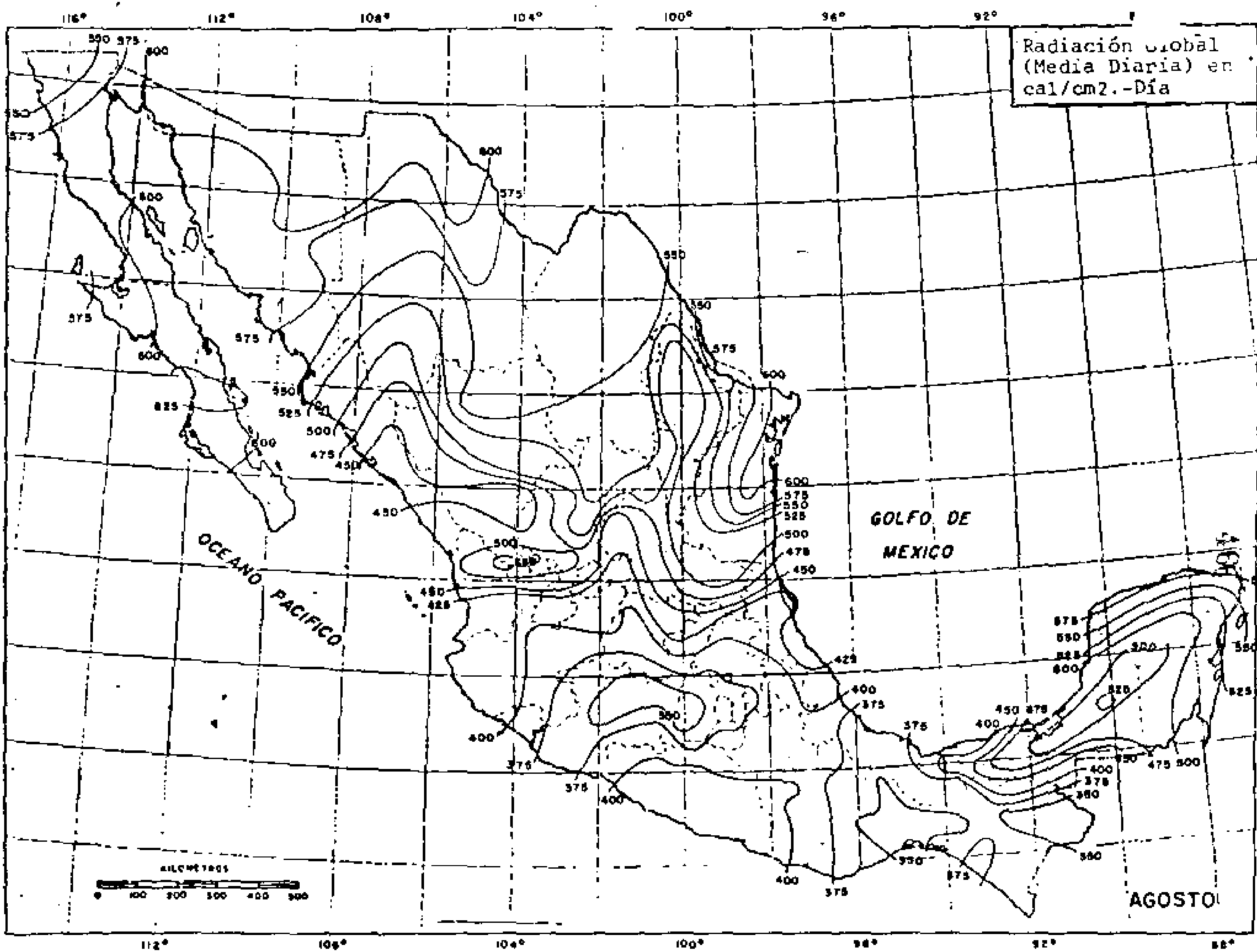
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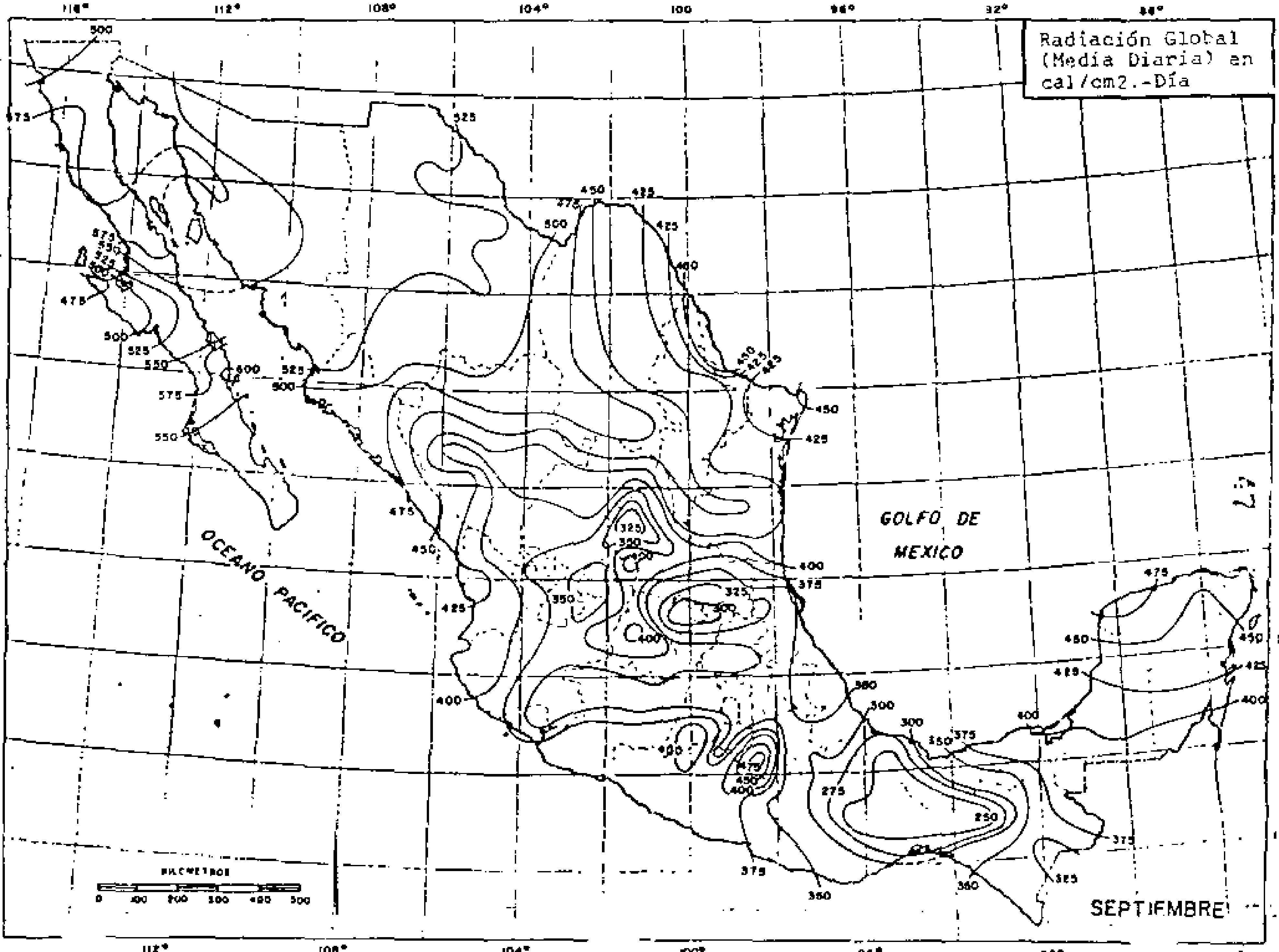

Radiación Global
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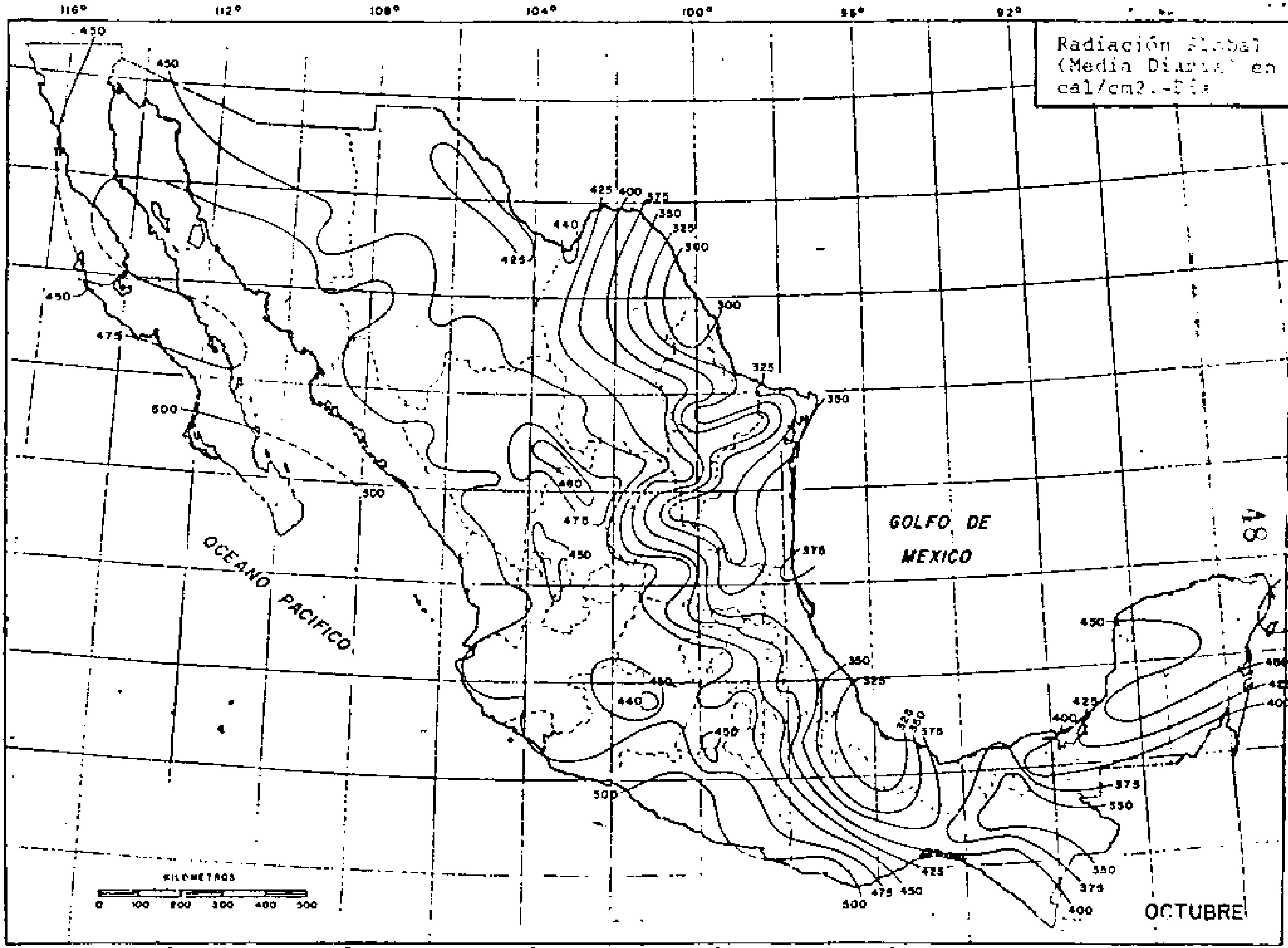
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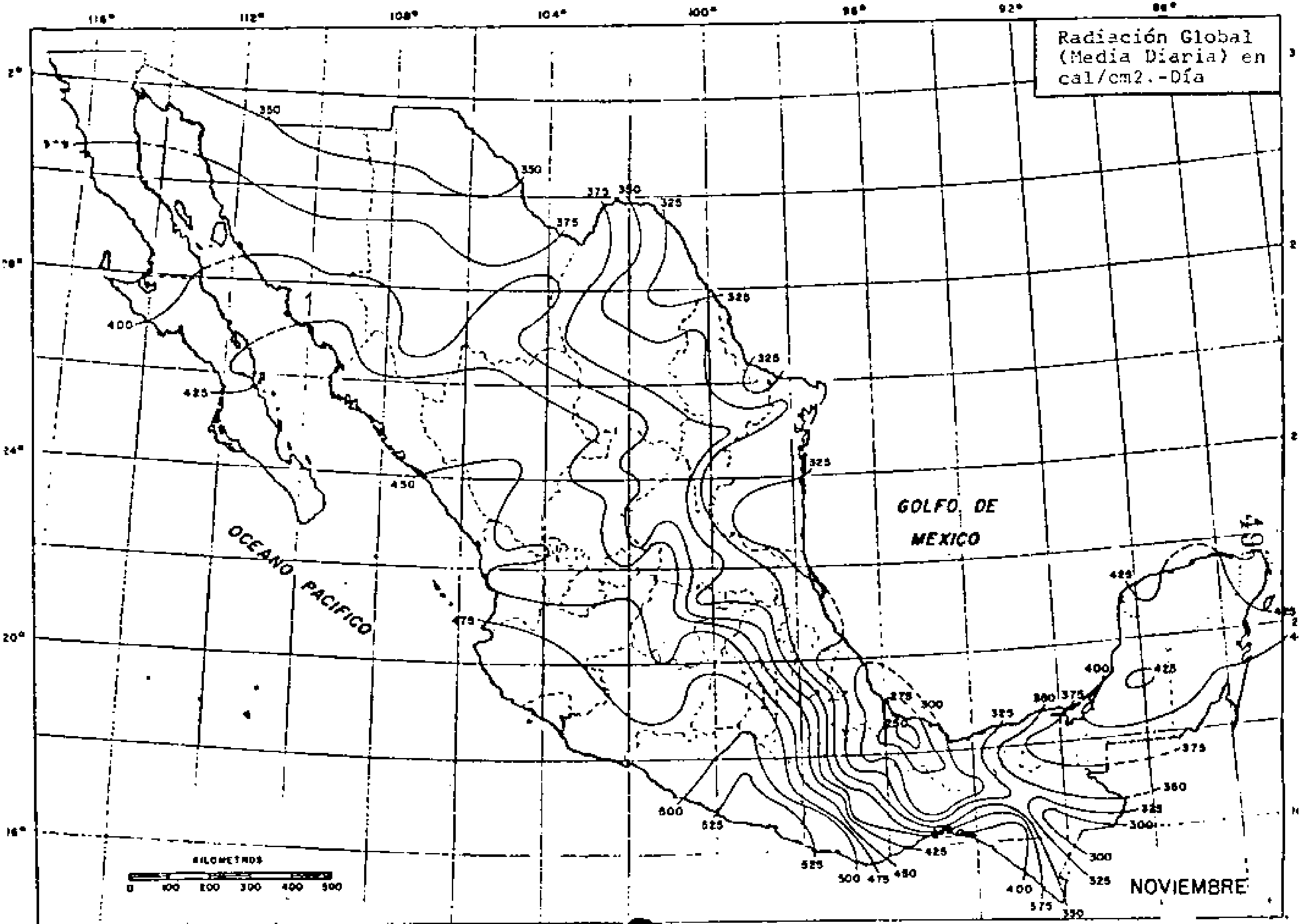
32° 28° 24° 20° 16°
88°



Radiación Global
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MEXICO
OCEANO PACIFICO
KILOMETROS
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NOVIEMBRE
350
375
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PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

DISTRIBUCION REGIONAL DE LA NUBOSIDAD EN MEXICO

AGOSTO, 1979

Palacio de Minería Calle de Tacuba 5, primer piso. México 1, D. F. Tel: 521-40-20

1. INTRODUCCION

Ante las características de cuerpo negro que presentan las nubes a la radiación infrarroja y su variable reflectividad a la radiación comprendida en la región del visible, resulta importante el estudio de la distribución de la cubierta de nubes no sólo desde el punto de vista del intercambio radiativo solar y terrestre, sino también por aquellos aspectos de índole meteorológico, hidrológico, biológico y muy especialmente los que están relacionados con el aprovechamiento de la energía solar.

Aunque existen varios estudios sobre la distribución de la nubosidad a escala nacional, éstos sin embargo no han incluído el trazo de las isolíneas que conectan puntos con el mismo índice de nubosidad, comunmente llamadas isonefas. Por esta razón, y haciendo uso de las ventajas que presenta la fotointerpretación de datos observacionales de satélite meteorológicos (1), en este estudio se presentan las isonefas obtenidas sobre todo el territorio nacional.

Las variaciones latitudinales y longitudinales de la nubosidad pueden ser fácilmente observadas a partir de los mapas que contienen los valores medios anuales, estacionales y mensuales.

La ubicación de las isonefas obtenidas reflejan una influencia notable y determinante del sistema orográfico nacional, así como del transporte de las masas de aire húmedo características de los vientos predominantes en cada época del año.

2. ANTECEDENTES

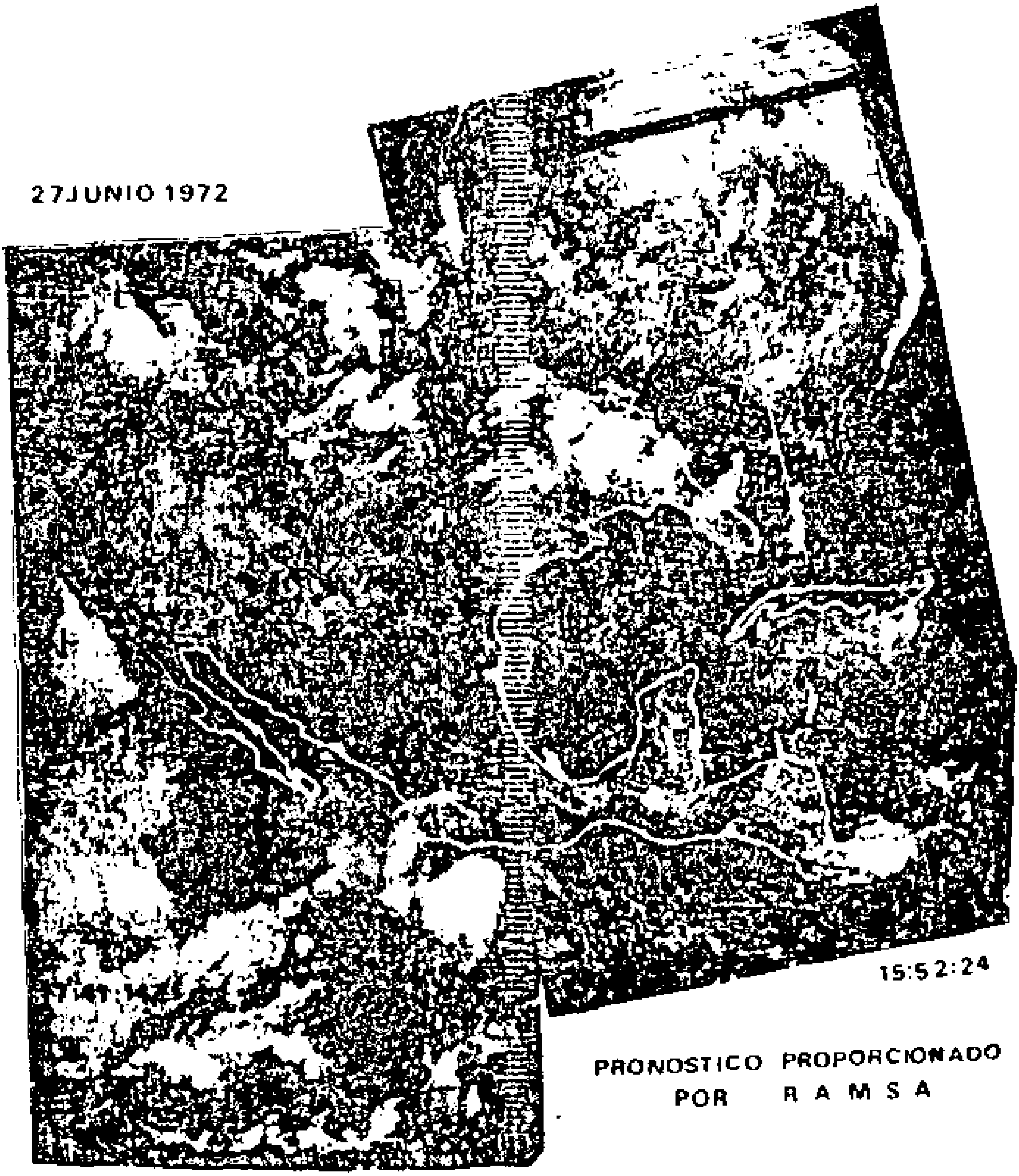
Una serie de fotografías tomadas por los satélites meteorológicos NIMBUS III y ESSA-8 durante un período de 3 años (1969-1971), como la que se muestra en la fotografía, fueron analizadas por E. Mendoza, J. Luna y T. Gómez (1), quienes reportan importante información en histogramas referentes a la distribución longitudinal y latitudinal del número de días despejados en el país e incluyen también un mapa mostrando los porcentajes estatales correspondientes.

COMISION NACIONAL DEL ESPACIO EXTERIOR

DE LA

SECRETARIA DE COMUNICACIONES Y TRANSPORTES

27JUNIO 1972



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PRONOSTICO PROPORCIONADO POR RAMSA

3. OBJETIVOS

En base a los antecedentes antes mencionados, se ha creído conveniente complementar los trabajos anteriores con la obtención de las isonefas correspondientes, las cuales resultan más adecuadas en estudios climatológicos e hidrológicos, pues permiten una correlación más rápida y directa con otros parámetros meteorológicos cuya distribución regional se acostumbra representar por medio de isolíneas, como por ejemplo: las isoyetas (lluvia), las isotermas (temperatura), las isobaras (presión), las isohipsas (altitud), etc.

Vale la pena también remarcar la importancia que existe entre las isonefas y las isolíneas de radiación solar, ya sea esta global, difusa o directa y sobre todo, en la selección de lugares adecuados para el aprovechamiento de este tipo de energía que presenta un futuro prometedor en nuestro país.

Un conocimiento más completo de la distribución de la cubierta de nubes permite la evaluación de los coeficientes de transmisión, reflexión y absorción de la radiación solar en su trayecto atmosférico desde la estratósfera hasta la superficie terrestre; con lo cual, se puede avanzar un poco más en el conocimiento del balance de radiación solar y terrestre. Este balance, es importante ya que es el que finalmente determina las características climáticas de cada región.

Este estudio es parte de una serie que se tiene programada en el Centro de Investigación de Materiales, fundamentalmente enfocados al aprovechamiento de la energía solar y sólo abarcará -preliminarmente- el conjunto de datos observacionales correspondientes al período de tres años antes mencionados, aunque en la actualidad ya se está trabajando sobre un período más largo, que permitirá complementar la información aquí presentada.

4. DISTRIBUCION DE LA NUBOSIDAD EN EL HEMISFERIO NORTE

De acuerdo con un estudio publicado por J. London (2) sobre la distribución de la nubosidad en el hemisferio Norte, los valores estacionales y anuales de la cubierta de nubes, son los que aparecen en la Tabla 1.

Lat. °N	Invierno	Abril	Verano	Octubre	Anual
0-10	47	51	54	53	51.2
10-20	36	42	49	48	43.8
20-30	38	42	42	41	40.8
30-40	50	52	41	46	47.2
40-50	59	59	55	56	57.2
50-60	63	62	63	66	63.5
60-70	58	60	66	70	63.5
70-80	47	59	69	70	61.2
80-90	40	55	64	60	54.8
Promedio Hemisferio Norte	47.9	51.3	52.0	53.0	51.1

Tabla 1. DISTRIBUCION ESTACIONAL DE LA NUBOSIDAD TOTAL (porcentaje de cielo cubierto)

En esta Tabla puede apreciarse que la posición geográfica del territorio nacional (entre los 14°30' N y 32°42' N) y que abarca zonas de las regiones: tropical (10°- 25) y subtropical (25°- 35) coincide con la zona del hemisferio norte de menor índice de nubosidad anual; que en promedio es de alrededor de 41%. El porcentaje más bajo (36%) ocurre durante el invierno, precisamente entre los 10°N y 20°N. Entre los 20°N y 30°N ocurre el valor inmediato superior (38%) durante la misma estación.

Concretando, es entre estas dos franjas latitudinales, donde el promedio anual de nubosidad es mínimo (Figura 1) y en consecuencia son zonas de escasa precipitación pluvial (Figura 2), mínima humedad atmosférica (Figura 3); e intensa insolación (Figuras 4 y 5)

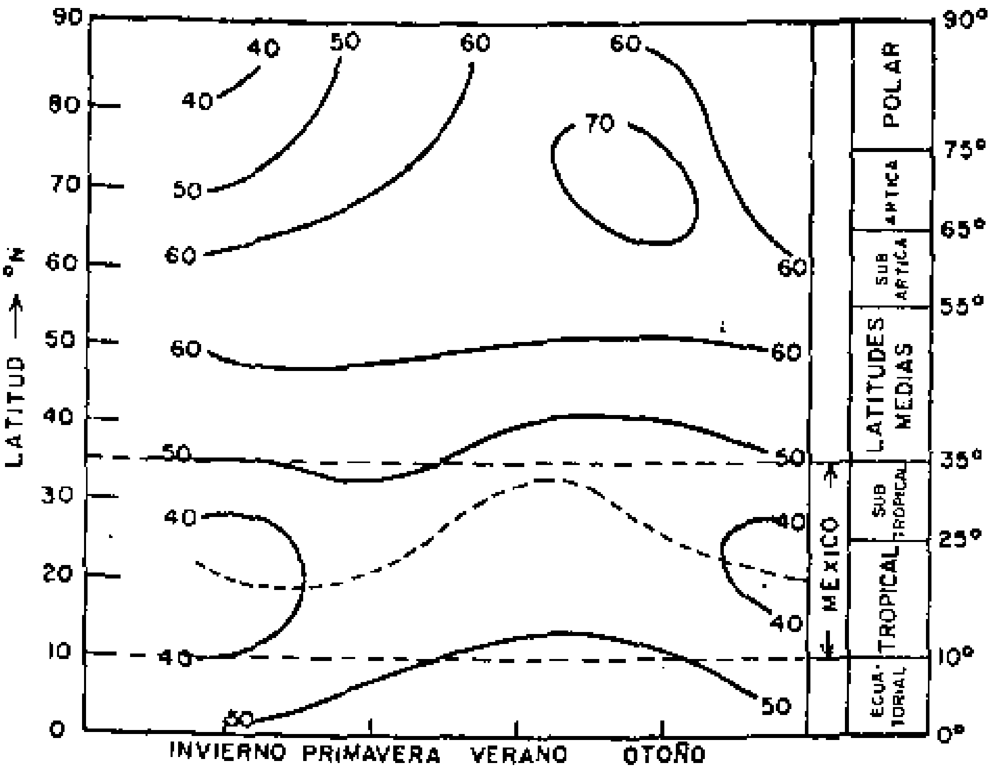


FIG. 1 DISTRIBUCION ESTACIONAL DE LA NUBOSIDAD (%)

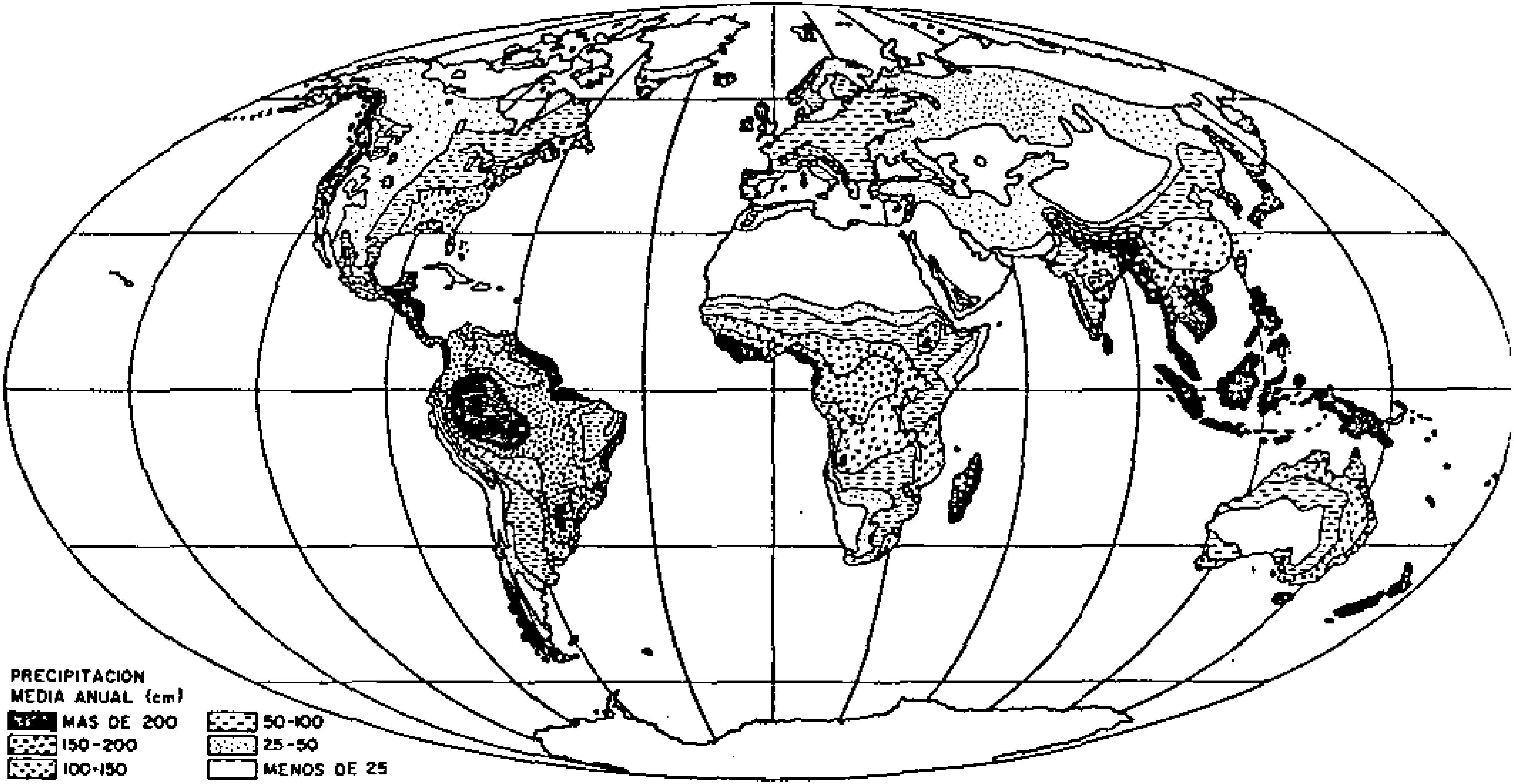


Fig. 2 DISTRIBUCION MUNDIAL DE LA PRECIPITACION MEDIA ANUAL (2)

80

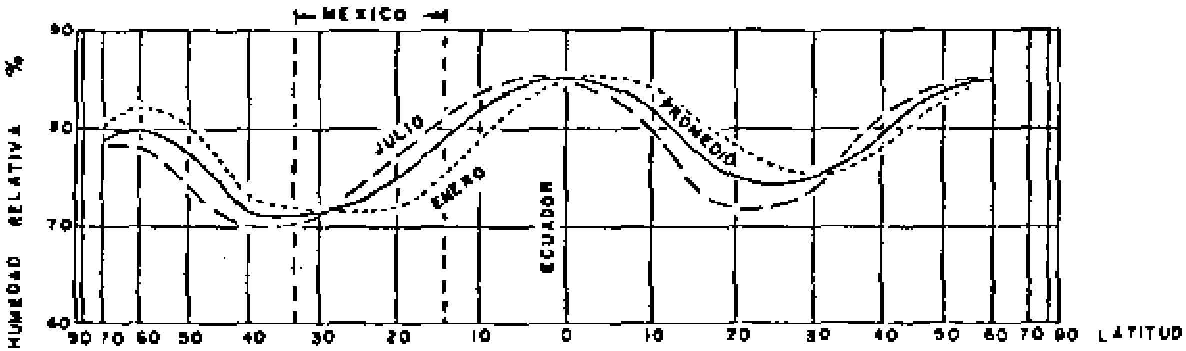


Fig. 3 DISTRIBUCION LATITUDINAL DE LA HUMEDAD RELATIVA (3)

Fig. 4 INSOLACION EN VARIAS LATITUDES Y EPOCAS DEL AÑO

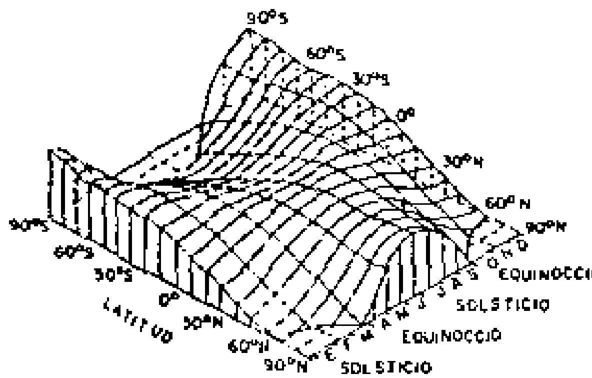
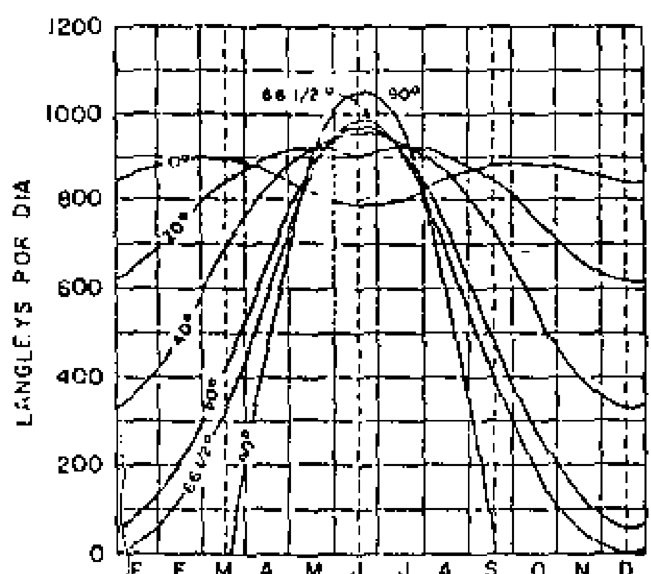


Fig. 5 INSOLACION EN VARIAS LATITUDES DEL HEMISFERIO NORTE.



La circulación general de la atmósfera en estas zonas es tal, que entre los 25° y 35° de latitud (cinturones subtropicales de vientos variables y calmas), grandes masas de aire seco descienden de los niveles atmosféricos superiores, esparciéndose sobre la superficie terrestre en direcciones ecuatorial (celda de Hadley y celda polar) tal como puede verse en las figuras 6 y 7.

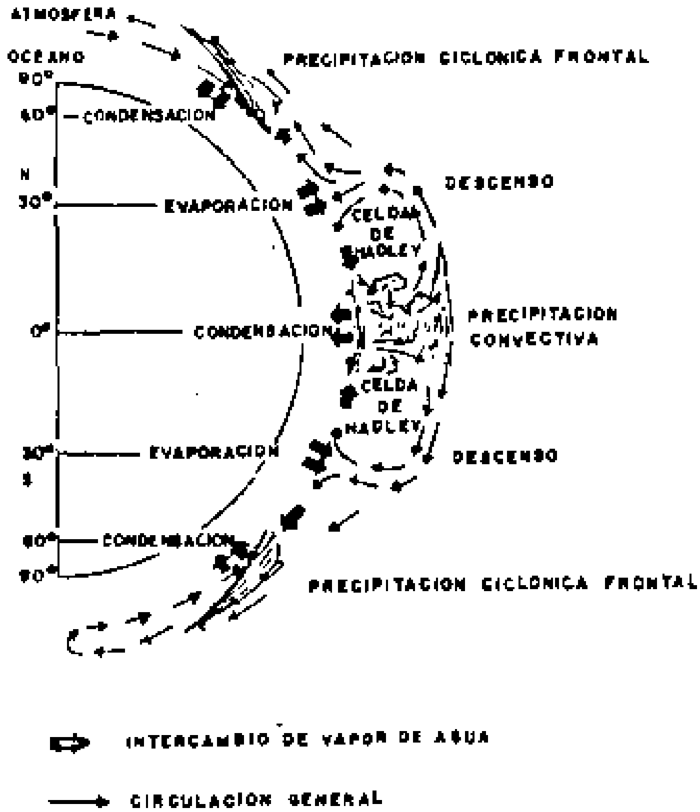
Estas masas descendentes de aire seco producen, únicamente, nublados muy escasos y lluvias demasiado leves, en consecuencia, la humedad en estas regiones es mínima por lo que las grandes zonas desérticas del planeta se encuentran localizadas también en estas latitudes.

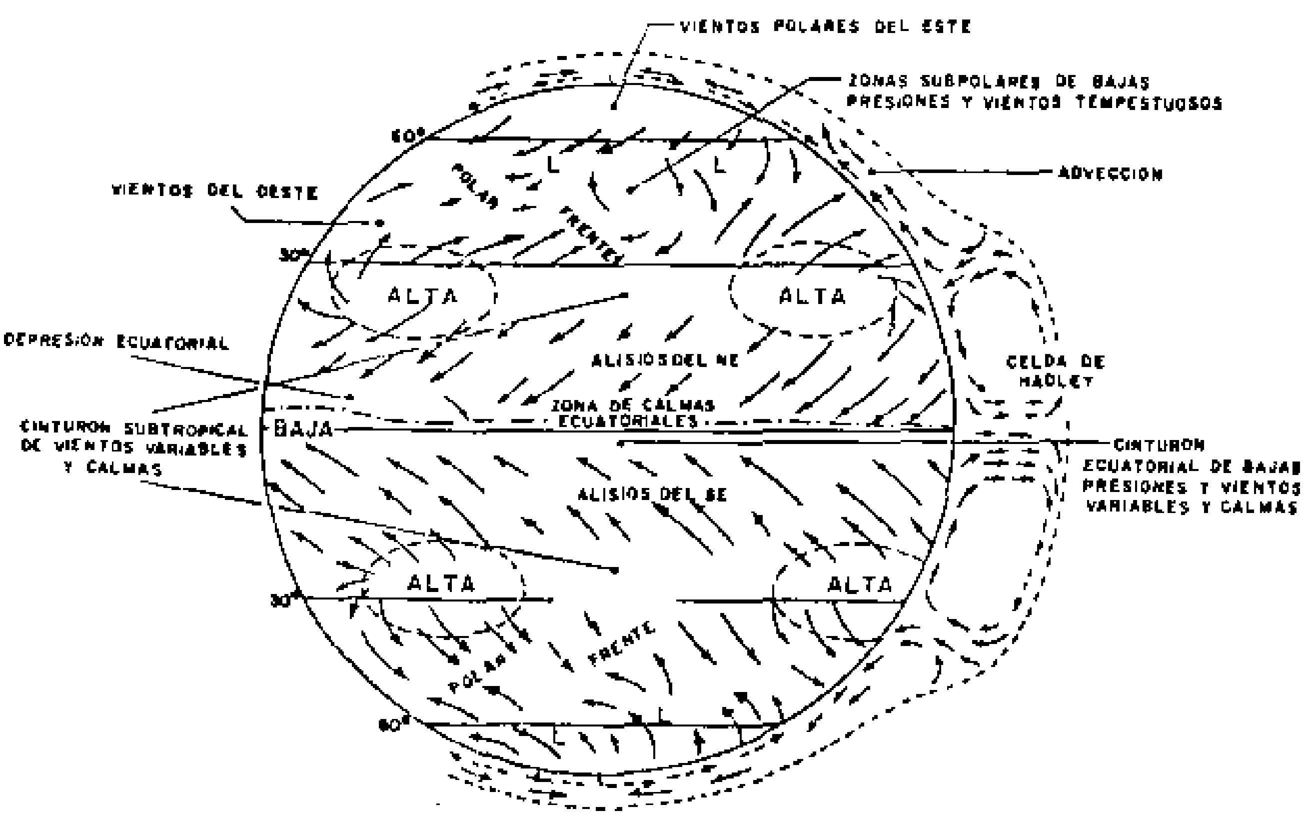
Las figuras 8 y 9 muestran las proporciones continentales de las zonas áridas y su distribución latitudinal respectiva.

Del primero se observa que las zonas áridas son más escasas en el Continente Americano, aunque desafortunadamente, nuestro país abarca más de la mitad del total continental de zonas áridas en América del Norte (aproximadamente el 52%).

Las zonas áridas y semi-áridas de México (Figura 10) se encuentran localizadas precisamente a partir de los 20°N de latitud.

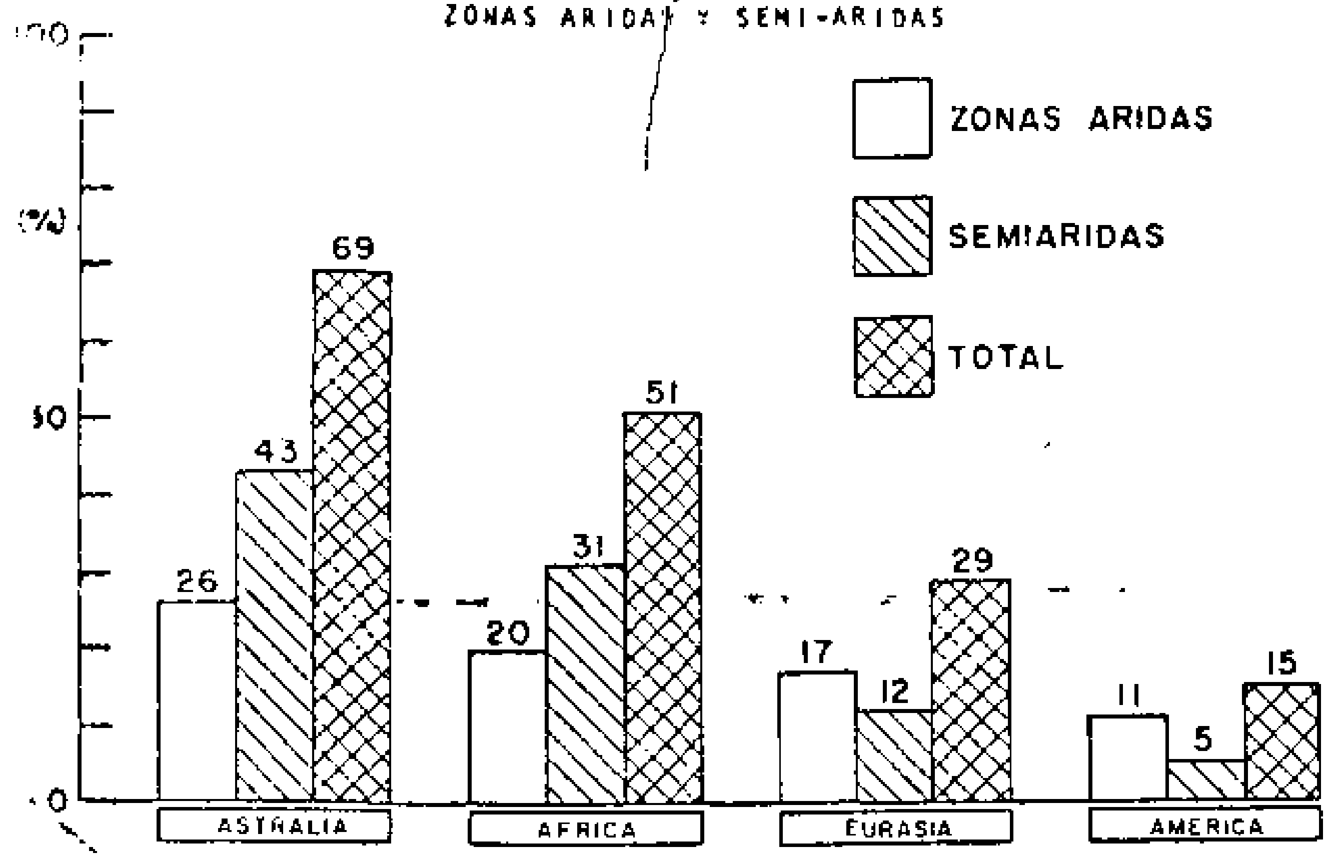
En general, la nubosidad alcanza valores anuales máximos en las zonas ecuatoriales y subpolares donde la condensación del vapor de agua es máxima (Figura 7)



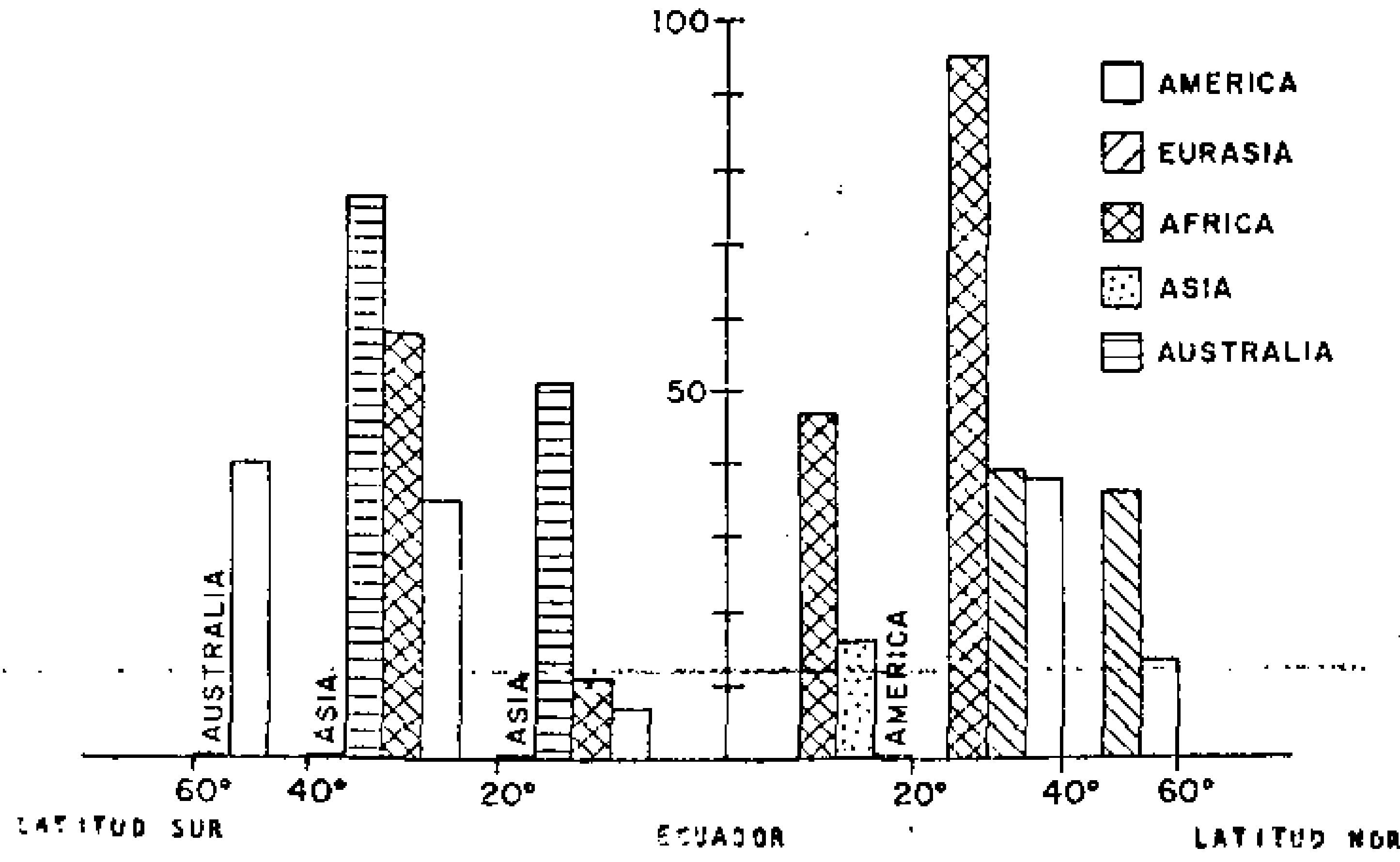


Figs. 6 y 7 CIRCULACION GENERAL DE LA ATMOSFERA

Fig. II HISTOGRAMAS DE LA DISTRIBUCION MUNDIAL DE ZONAS ARIDAS Y SEMI-ARIDAS



ZONAS ARIDAS Y SEMIARIDAS



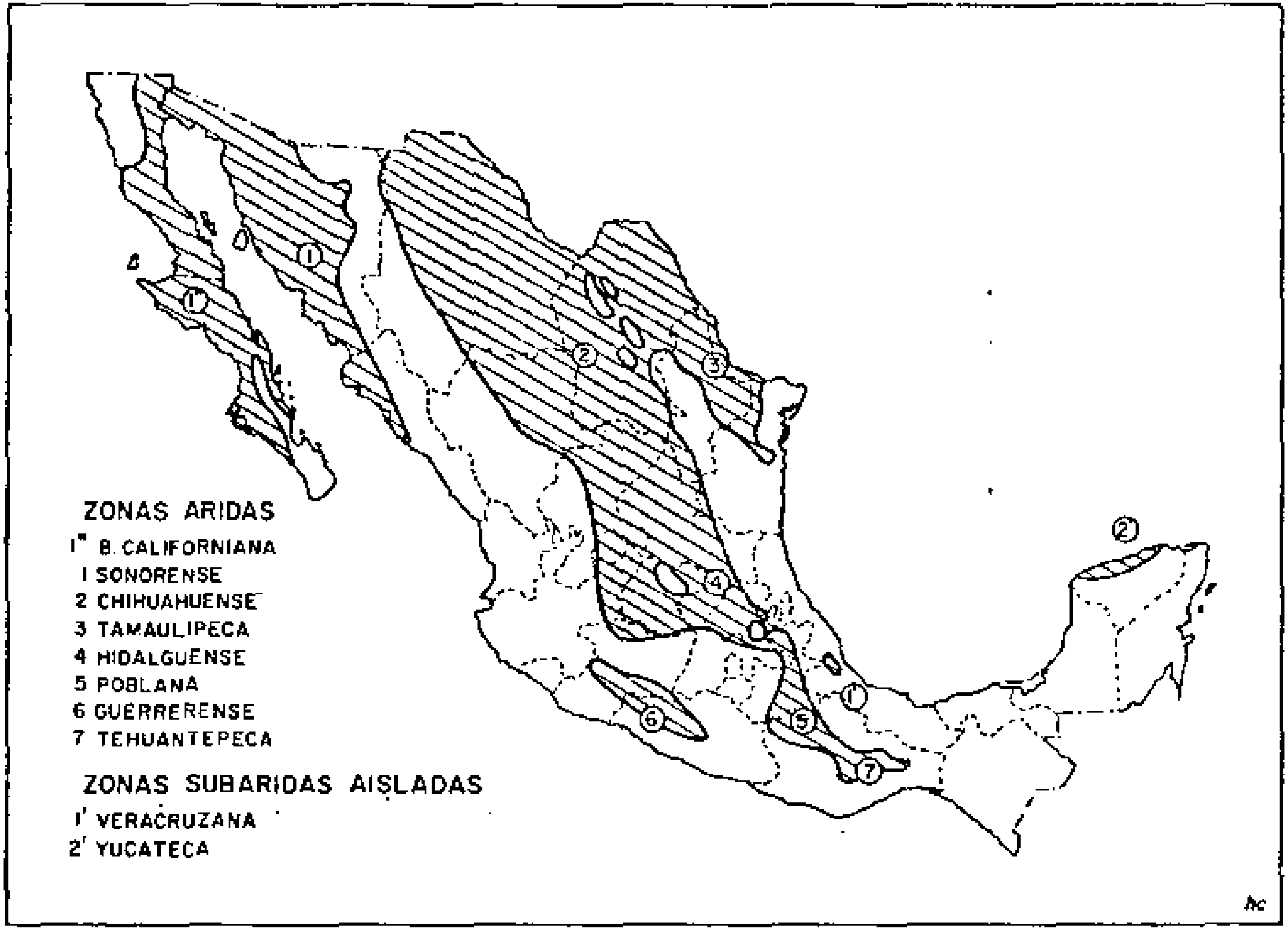


Fig. 9 ZONAS ARIDAS Y SEMI-ARIDAS DE MEXICO

OBTENCION DE LA DISTRIBUCION DE LA NUBOSIDAD EN MEXICO

La distribución estacional y anual de la cubierta de nubes en México, está regulada principalmente por las características de la circulación general de la atmósfera en nuestras latitudes así como por las grandes diferencias en extensión y altitud del relieve continental.

Tomando como referencia el mapa altimétrico, podemos darnos cuenta de estas diferencias (Fig. 10)

Si consideramos que un enfriamiento del aire húmedo por encima del punto de rocío da lugar a la formación de nubes, es de esperarse una distribución regional de la nubosidad notablemente dependiente del relieve orográfico.

CARTA ALTIMETRICA

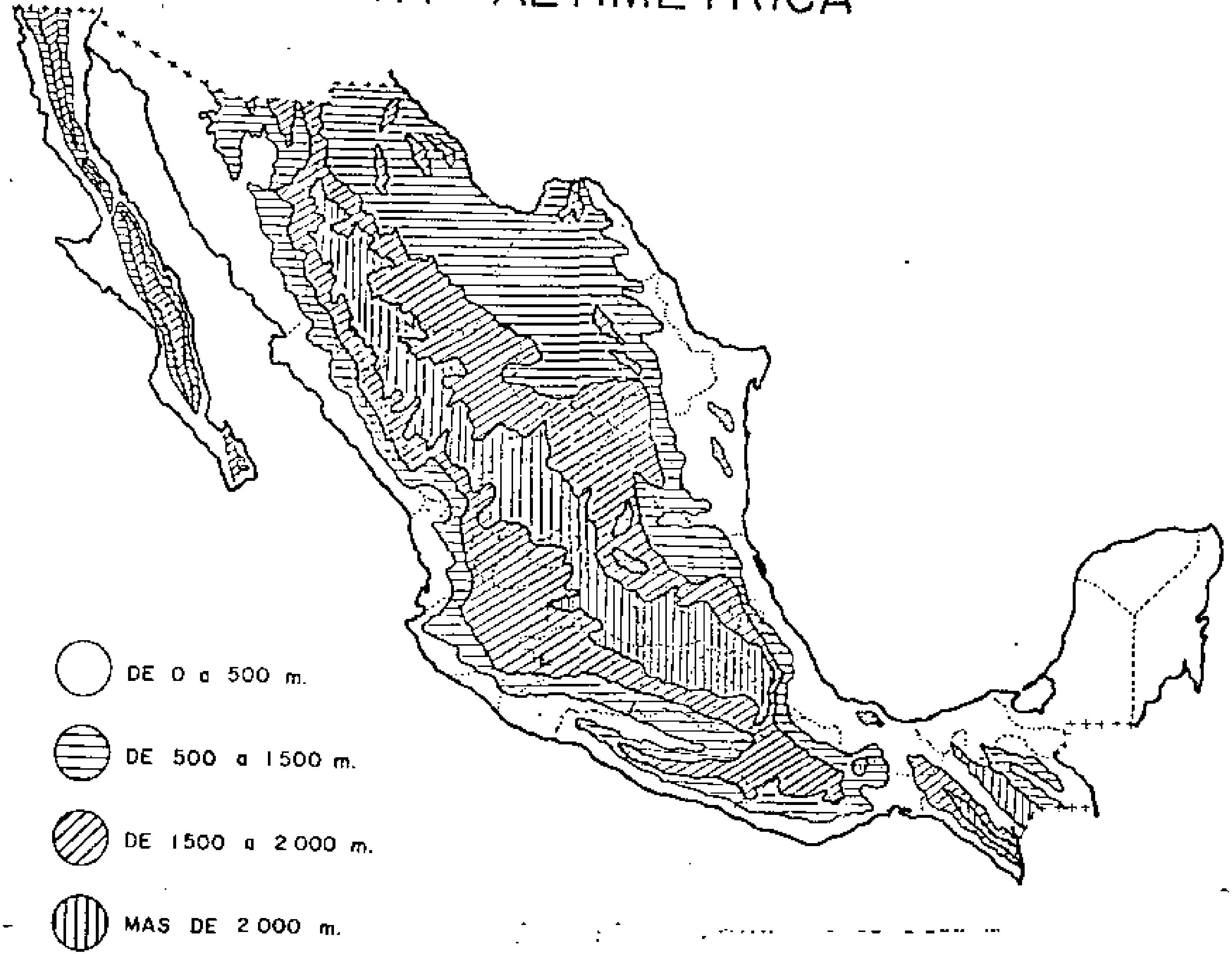


FIGURA 10

El índice de nubosidad fraccional ε varía desde cero (completamente despejado) hasta 1 (completamente nublado), por lo que ε puede ser relacionado con la duración real de la insolación directa S (cielo despejado) por medio de la relación:

$$\varepsilon = \frac{Smax - S}{Smax}$$

donde Smax representa la duración máxima posible de la insolación en el lugar en cuestión.

En estudios previos (6) se han obtenido valores de la duración relativa de la insolación (Sr), es decir, del intervalo de tiempo respecto al máximo posible durante el cual hay iluminación directa (Sr = S/Smax). Los valores promedio de ε fueron calculados a partir de la expresión:

$$\bar{\varepsilon} = 1 - \bar{S}_r$$

Los resultados anuales, estacionales y mensuales obtenidos, fueron a su vez interpolados y extrapolados en función de las regiones altimétricas semejantes, con lo cual, pudieron representarse los contornos de las isonefas resultantes de manera precisa. La distribución regional obtenida de la cubierta fraccional de nubes se muestra en los diecisiete mapas que comprenden este estudio (Figuras 11 a 27).

CONCLUSIONES

Al examinar los mapas obtenidos puede apreciarse que la distribución global de la nubosidad en nuestro país se caracteriza por una mayor nubosidad en la parte oriental que en la occidental, disminuyendo gradualmente en la dirección noreste-suroeste, gradiente que se puede observar en los mapas estacionales.

Este gradiente tiene su origen en la dirección de las grandes masas de aire húmedo, que en diferentes épocas del año invaden extensas regiones del territorio nacional. Estas masas provienen principalmente del Golfo de México (alisios del Noreste) así como también de la zona tropical del Atlántico, de la zona del Caribe y de la zona tropical del Oceano Pacífico.

La estación del año con mayor índice de nubosidad resulta ser el verano, coincidiendo así con la estación de máxima precipitación pluvial.

El desplazamiento de estas masas, sin embargo, se ve obstaculizado por las principales cadenas montañosas que atraviesan el país y que forman grandes barreras, especialmente la Sierra Madre Oriental. El efecto de estos obstáculos puede comprobarse al examinar los valores tan elevados de los índices de nubosidad encontrados a lo largo de la vertiente oriental de esta cordillera, afectando a los estados de Tamaulipas, Veracruz, Tabasco, Campeche, Yucatán (excepto el Norte del estado). En esta región se producen varios efectos importantes sobre las masas de aire marítimo tropical provenientes del Golfo de México, que según Mosiño, y E. García (4), pueden ser clasificados como sigue:

a) Represamiento o embalse de las corrientes aéreas
b) Desviación o encañonamiento de los vientos

c) Levantamiento forzado del aire
d) Calentamiento adiabático por ascenso del aire (a sotavento)

Los tres primeros efectos modelan notablemente la distribución de la cubierta de nubes de esta región y en consecuencia afectan sensiblemente la distribución anual de la precipitación (Figura 28).

Los valores más elevados de la nubosidad se encuentran precisamente a lo largo de esta región oriental durante el verano, así podemos notar que existe una zona en el estado de Veracruz cuyo promedio anual de nubosidad sobrepasa el 60%.

Cabe mencionar además, que esta región también es afectada por los Nortes (vientos polares), que se presentan desde fines de Otoño hasta el principio de la Primavera. Estas perturbaciones atmosféricas se producen debido a las masas boreales de aire, que el cruzar por las tibias aguas del Golfo de México absorben grandes cantidades de vapor de agua originando así extensos nublados y fuertes precipitaciones sobre la porción Este de la Sierra Madre Oriental.

El ascenso forzado del aire húmedo sobre un declive orográfico, contribuye a la formación de grandes cadenas de nuebes sobre las vertientes de las barreras montañosas. Este fenómeno tiende a incrementarse en función de la variación de temperatura que produce una inestabilidad termodinámica en la masa de aire húmedo ascendente; es decir, este fenómeno depende de la cantidad de calor latente liberado en la condensación del vapor de agua atmosférico, lo que contribuye al calentamiento y por consiguiente el ascenso de las masas de aire húmedo adyacentes a niveles más fríos.

FIG. 28 CARTA DE ISOYETAS

Estas masas al condensarse nuevamente, liberan energía calorífica favoreciendo la evolución de este fenómeno, a través del cual, es posible que se lleguen a formar verdaderas barreras de nubes sobre los flancos de barlovento.

Debido a la notable altitud de la porción oriental del Altiplano, las masas de aire incidentes no alcanzan a rebasar este nivel más que en determinadas ocasiones. Lo mismo puede decirse del obstáculo que presenta la Sierra de Chiapas al desplazamiento de las masas de aire polar modificado que llegan a invadir la región ístmica de Tehuantepec y regiones colindantes con Guatemala. Estos obstáculos orográficos, favorecen la formación de extensas cubiertas de nubes, tal como se aprecia en los mapas a lo largo de todo el año.

En la península de Yucatán, el Altiplano y el Suroeste de México, se presentan elevados índices de nubosidad de origen convectivo debidos al intenso calentamiento de la superficie continental, notoriamente durante el Verano y el Otoño.

Este sobrecalentamiento de la superficie continental favorece la formación de grandes nubes que aprovechan el efecto evolutivo antes descrito en el cual se liberan grandes cantidades de calor latente generado por la condensación del vapor de agua.

En las regiones desérticas y semidesérticas del país, existen como es de esperarse, bajos índices de nubosidad. Esto se debe fundamentalmente al cuarto de los factores antes mencionados. El calentamiento adiabático en sí, producido en el descenso de las masas de aire que han cruzado las cordilleras donde han desprendido casi todo el vapor de agua, es de gran relevancia sobre todo en regiones sometidas sistemáticamente a regímenes de vientos con una dirección preferente, como lo son en nuestro país los alisios del Noreste.

La disminución de la humedad relativa que se deriva de este calentamiento adiabático a sotavento, ya sea sobre un declive o un valle, ocasiona el resecamiento de las masas de aire y por consiguiente, disminuye notablemente la formación de nubes, razón por la cual, las regiones afectadas por este fenómeno son casi siempre áridas. Esta situación se presenta principalmente al Norte del paralelo de los 24° N, en especial en las porciones Oeste y Central que comprenden las mayores extensiones desérticas del territorio nacional; aunque cabe indicar que en la parte central y la zona montañosa del Sur, existen también algunas regiones, no tan extensas, que se ven afectadas por este fenómeno.

Existen, por último, otras regiones de nuestro país, que desde el punto de vista geográfico quedarían fuera de la clasificación de las zonas desérticas, sin embargo, por el hecho de estar situadas a sotavento de grandes sistemas montañosos, largas cadenas de nubes cruzan estas regiones sin que llegue a producirse lluvia alguna, motivo por el cual presentan características climáticas similares a las desérticas. Este fenómeno se observa, por ejemplo, en las regiones de los Llanos de Apam, Valle del Mezquital, Tehuacán, y la Cuenca Alta del Balsas.

Se ha creído conveniente complementar este estudio con una tabla de distribución regional de la nubosidad en la que se han asignado características de cielo despejado y nublado de las 19 regiones que se muestran en la Tabla No. II

TABLA No. 11 DISTRIBUCION REGIONAL DE LA NUBOSIDAD

PERIODOS \ REGIONES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ENERO	○	○	○	○	○	○		○		○	○	○	○		⊜	⊜	⊜	⊜	
FEBRERO	○	○	○									○	○	⊜	⊜	⊜	⊜	⊜	
MARZO	○	○	○				⊜					○	○	○	⊜	⊜	⊜	⊜	
ABRIL	○	○	○			○	○	○		○	○	○	○	○	⊜	⊜			○
MAYO	○	○	○	○	○	○	○	○	○	○	○	○	○		⊜	⊜		⊜	○
JUNIO	○	○	○	○			⊜	⊜	⊜	⊜	⊜	⊜	⊜	⊜	⊜	⊜	⊜	⊜	
JULIO	○	○						⊜	⊜	⊜	⊜	⊜	⊜	⊜	○	○	⊜	⊜	○
AGOSTO	○	○	○					⊜	⊜	⊜	⊜	⊜	⊜	⊜	○		⊜	⊜	
SEPTIEMBRE	○	○	○				⊜	⊜	⊜	⊜	⊜		⊜		⊜		⊜	⊜	
OCTUBRE	○	○	○	○	○	○	○			⊜	⊜		○	⊜	⊜	⊜	⊜	⊜	
NOVIEMBRE	○	○	○	○	○	○		○		○	○	○	○		⊜		⊜	⊜	○
DICIEMBRE	○	○	○	○	○	○	○	○	○	○	○	○	○	○	⊜	⊜		○	○
PRIMAVERA	○	○	○	○	○	○		○		○	○	○	○	○	⊜	⊜			○
VERANO	○	○	○	○						⊜	⊜	⊜	⊜	⊜		⊜	⊜	⊜	○
OTOÑO	○	○	○	○	○	○		⊜	⊜	⊜			○	⊜	⊜	⊜	⊜	⊜	○
INVIERNO	○	○	○	○	○	○		○		○	○		○		⊜	⊜	⊜	⊜	○
ANUAL	○	○	○	○	○	○					○	○	○		⊜	⊜	⊜	⊜	○

○ DESPEJADO ⊜ NUBLADO

LISTA DE LAS REGIONES FISIOGRAFICAS ESTUDIADAS EN LA TABLA ANTERIOR

1. Península de Baja California
2. Llanura del Golfo de California y del Pacífico
3. Sierra Madre Occidental
4. Mesa del Norte
5. Sierra de la Breña
6. Sierra de Zacatecas
7. Sierra de San Luis
8. Sierra de Guanajuato
9. Sierra Gorda
10. Mesa Central (Anáhuac)
11. Eje Volcánico
12. Sierra Madre del Sur
13. Cuenca del Balsas
14. Región de los Valles
15. Sierra Madre Oriental
16. Llanura Costera del Golfo
17. Istmo de Tehuantepec
18. Región del Sureste
19. Península de Yucatán

REFERENCIAS

1. E. Mendoza, J. Luna y T. Gómez, 1972, "Búsqueda y Selección de Sitios Astronómicos Mediante Satélites Meteorológicos", Bol. de Obs. Tonantzintla y Tacubaya, No. 38, V.6.

2. Penman H.L. "The Water Cycle".-Scientific American. September 1970.

3. Strahler, A., 1963, Earth Sciences, Harper & Row.

4. Millan Kovitch, A., 1947, "Canon of Insolation and the Ice-Age Problem", Israel Prog. for Scientific Translations, Jerusalem. U.S. Dep. Commerce, Scientific Technical Inf.

5. Hernández E., 1976, "La Distribución de la Radiación Global en México evaluada mediante la Foto-interpretación de la Nubosidad observada por Satélites Meteorológicos", Tesis de Maestría en Ciencias, pub. CIM-UNAM.

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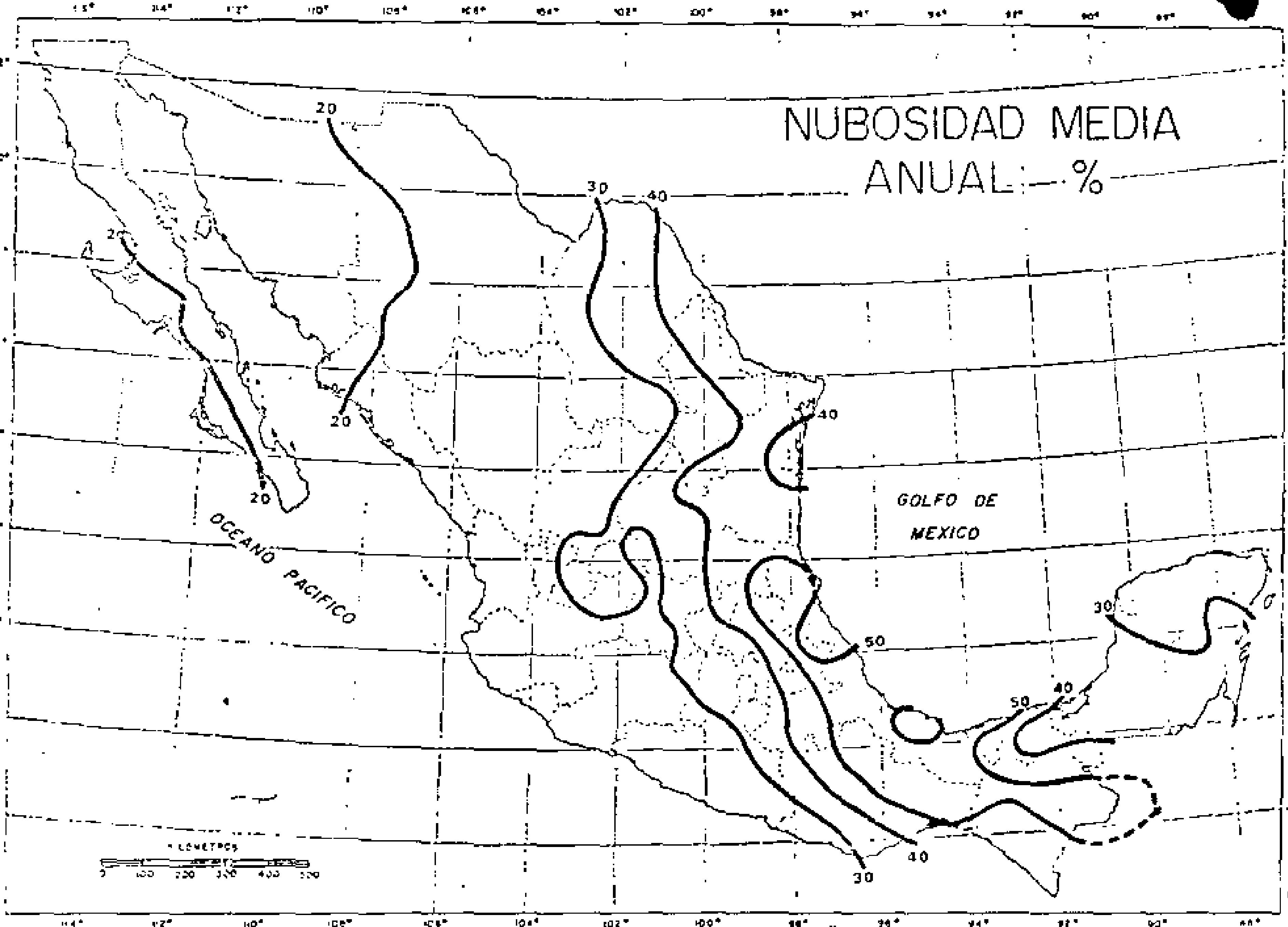
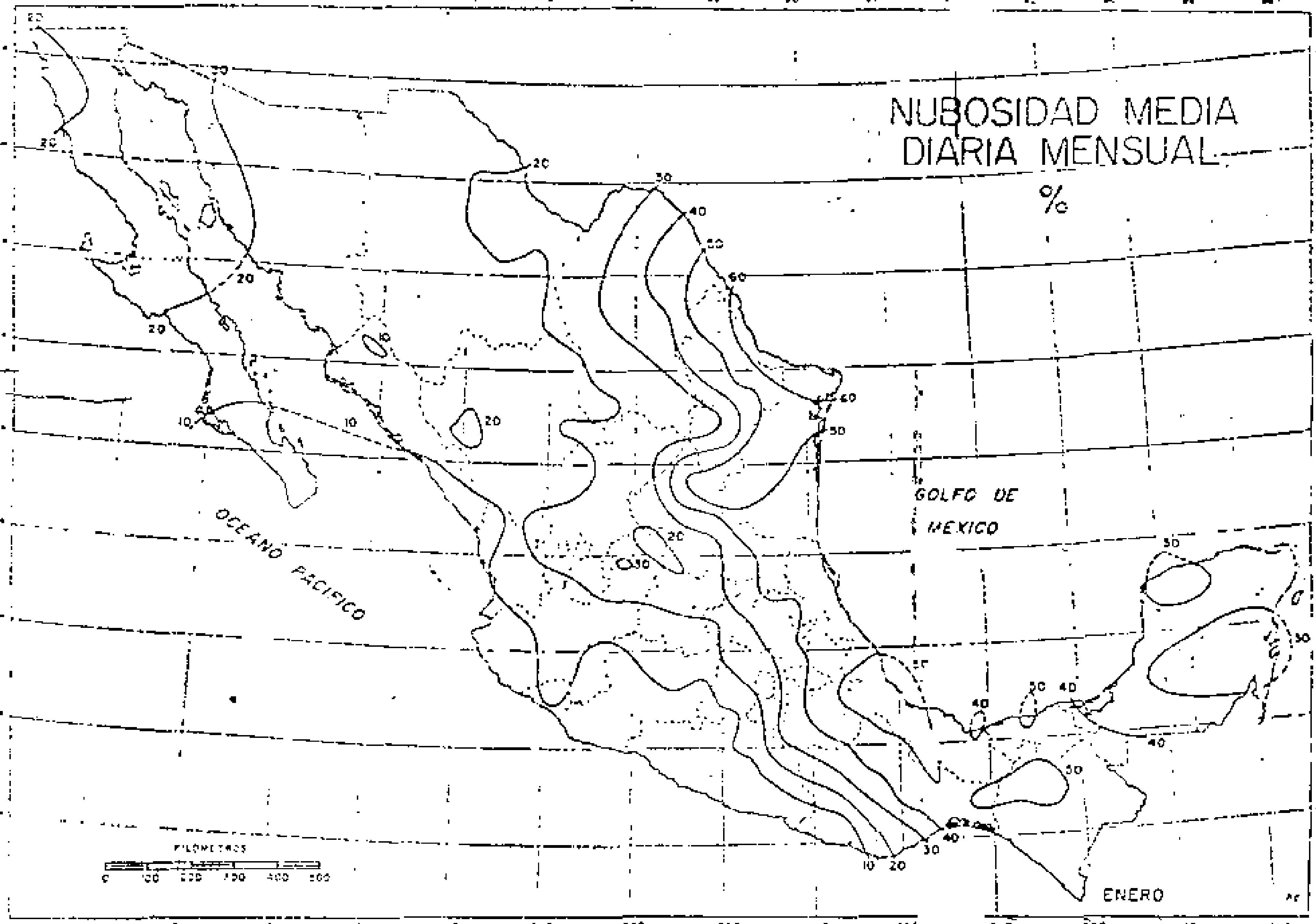
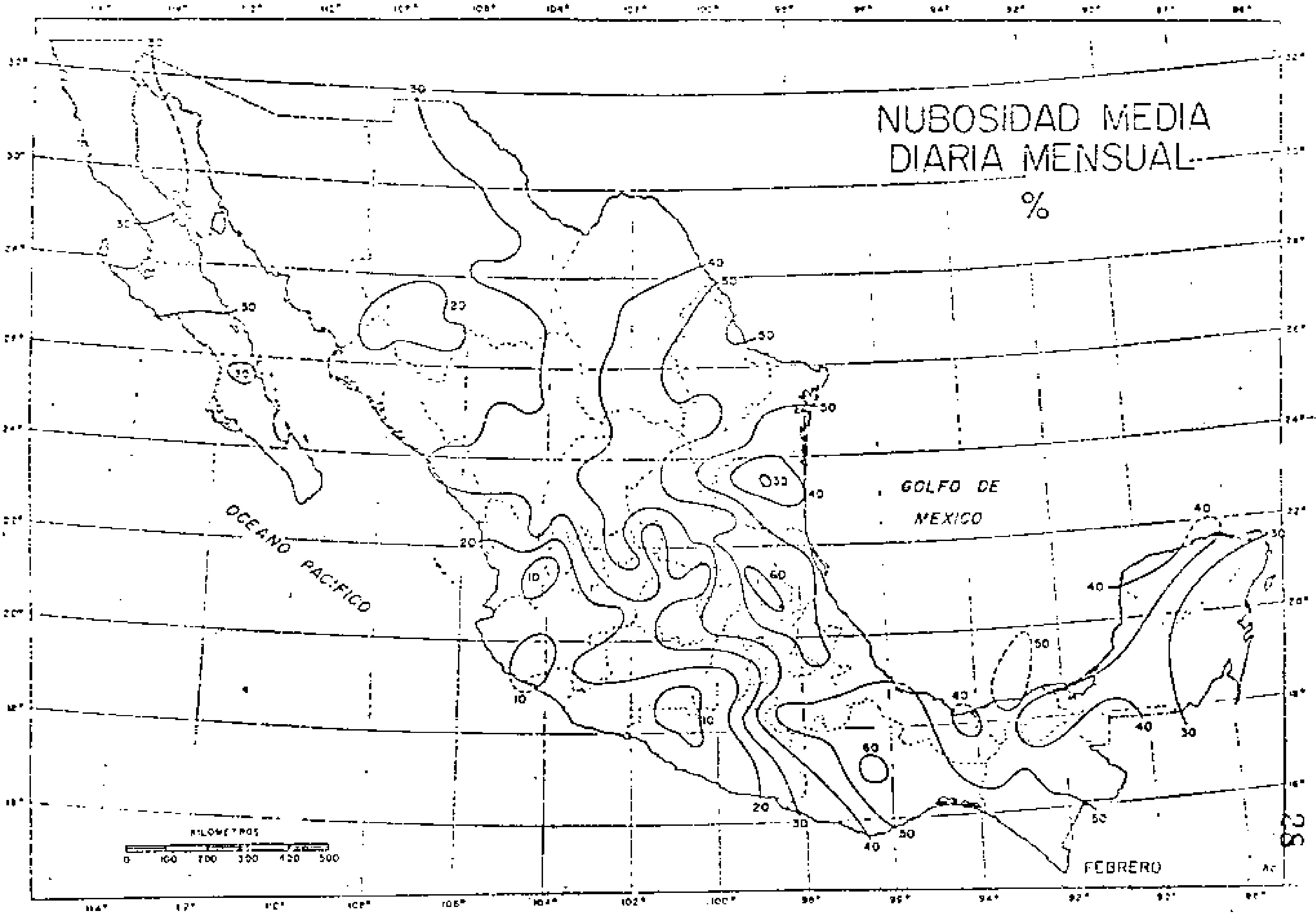
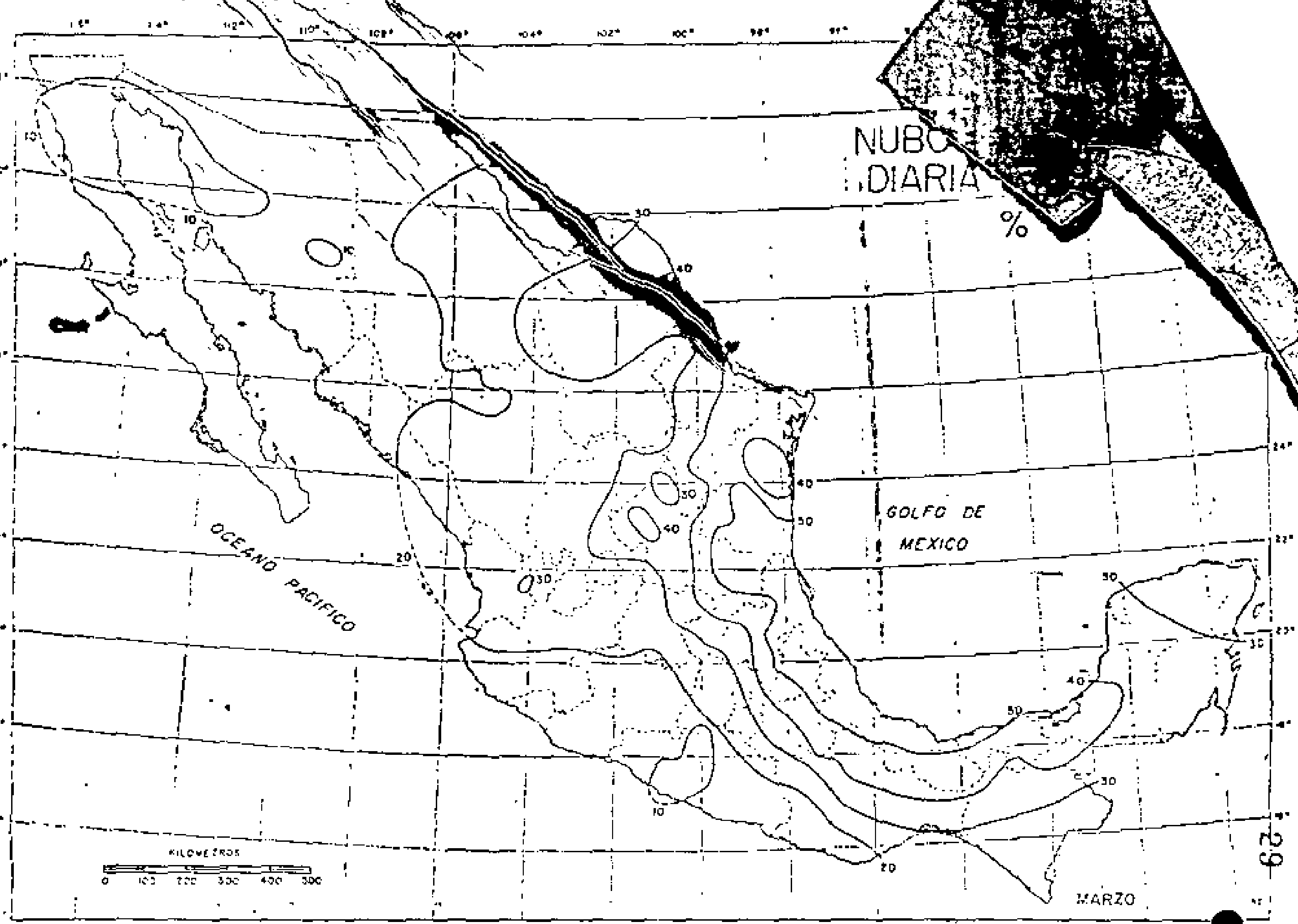
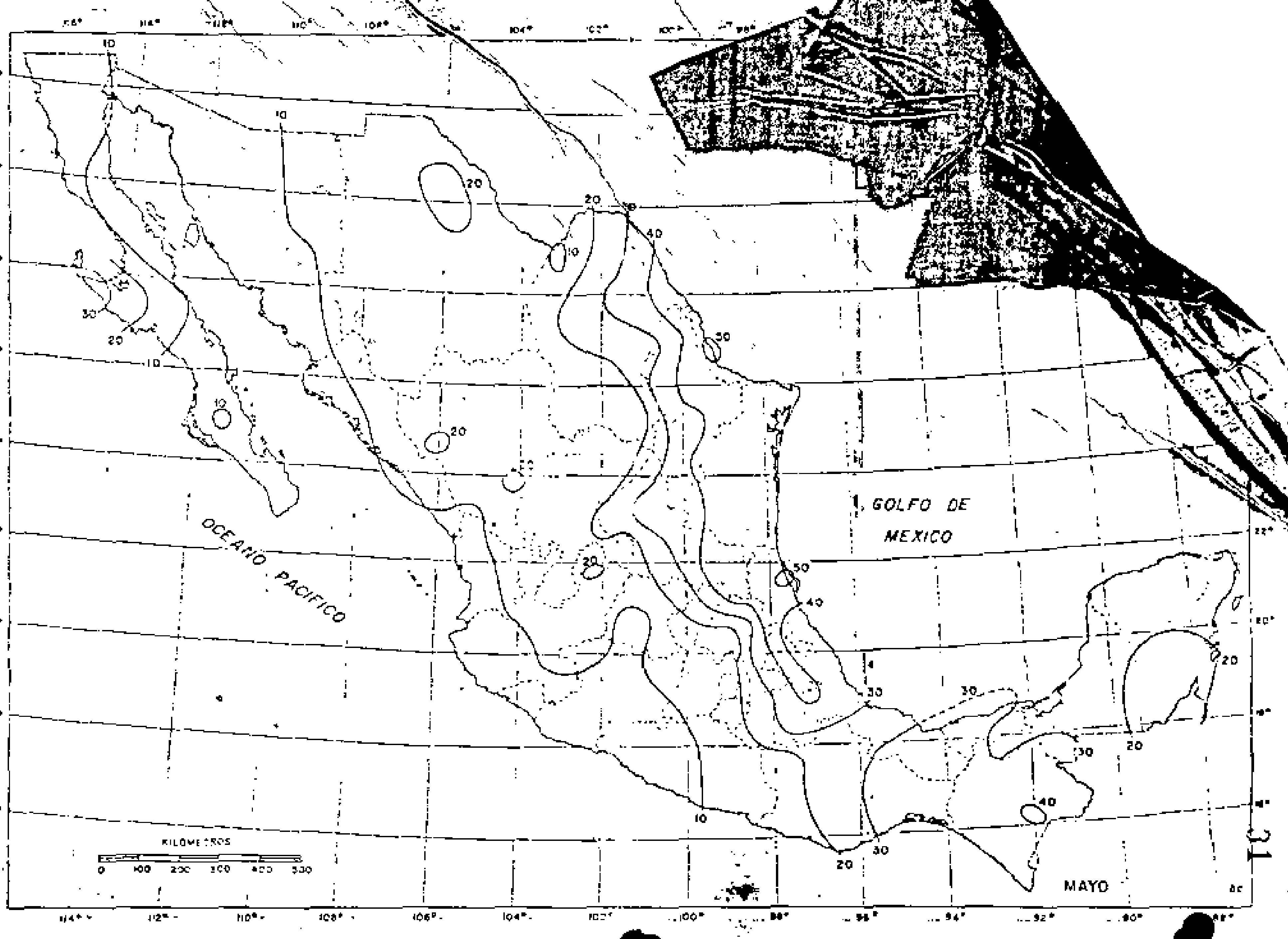

NUBOSIDAD MEDIA
ANUAL - %
GOLFO DE
MEXICO
OCEANO PACIFICO
20
30
40
50
KILOMETROS


NUBOSIDAD MEDIA
DIARIA MENSUAL
%
GOLFO DE
MEXICO
OCEANO PACIFICO
KILOMETROS
0 100 200 300 400 500
ENERO

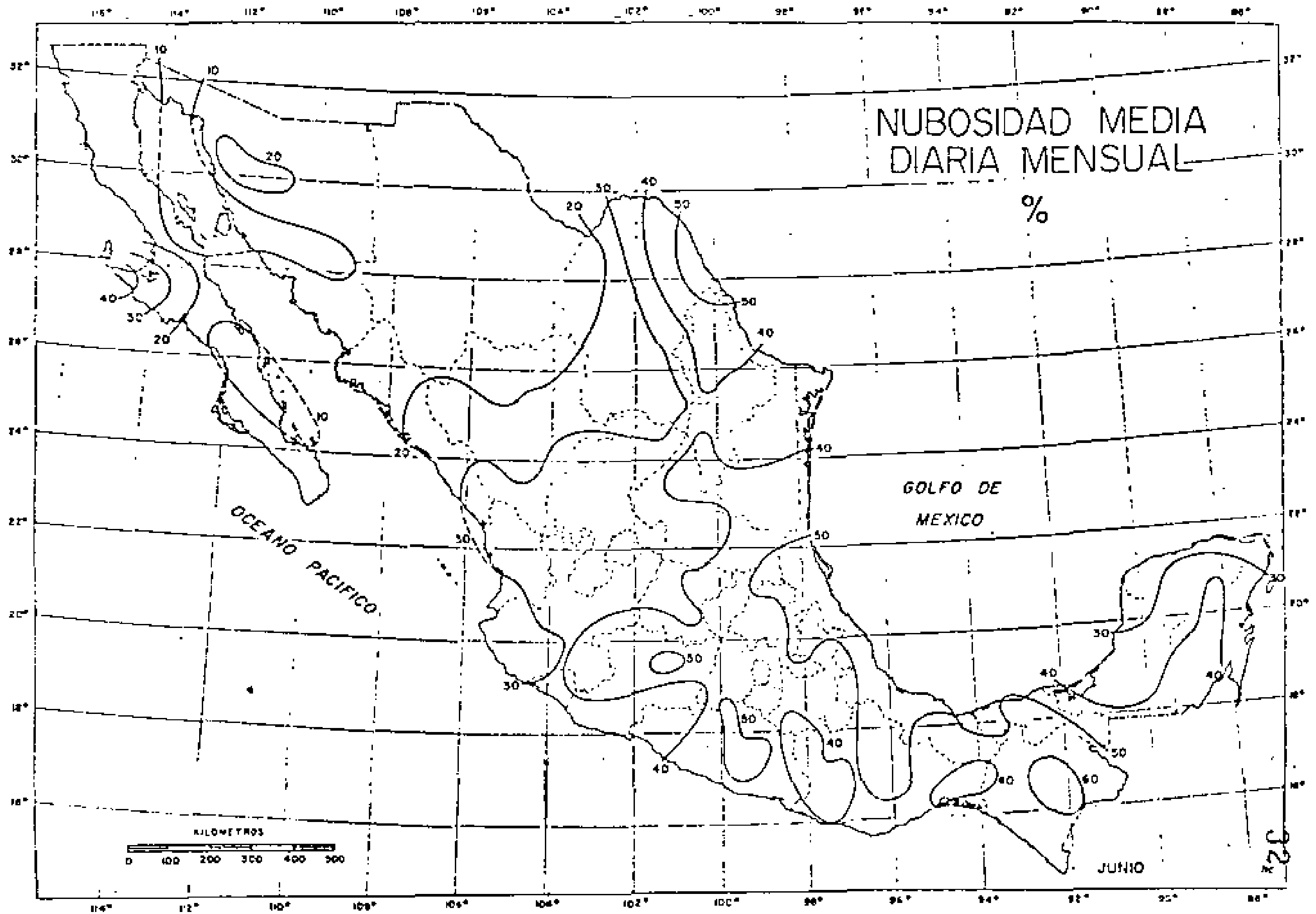

NUBOSIDAD MEDIA
DIARIA MENSUAL
%
GOLFO DE
MEXICO
OCEANO PACIFICO
KILOMETROS
0 100 200 300 400 500
FEBRERO

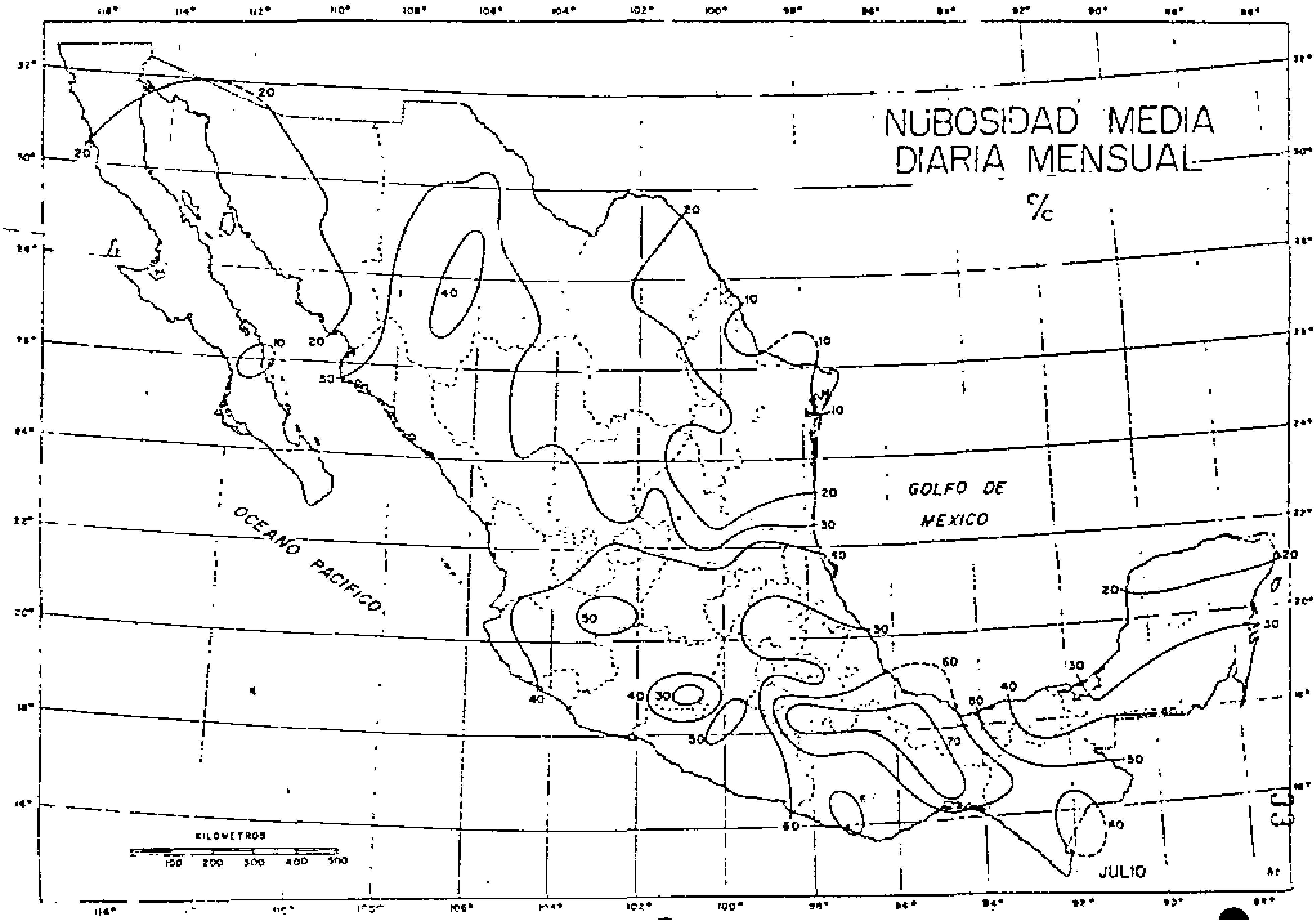

NUBO
DIARIA
%
GOLFO DE MEXICO
OCEANO PACIFICO
MARZO
KILOMETROS
0 100 200 300 400 500
10
20
30
40
50


NUBOSIDAD MEDIA
DIARIA MENSUAL
%
GOLFO DE
MEXICO
OCEANO PACIFICO
ABRIL
KILOMETROS
0 100 200 300 400 500
10
20
30
40
50
30

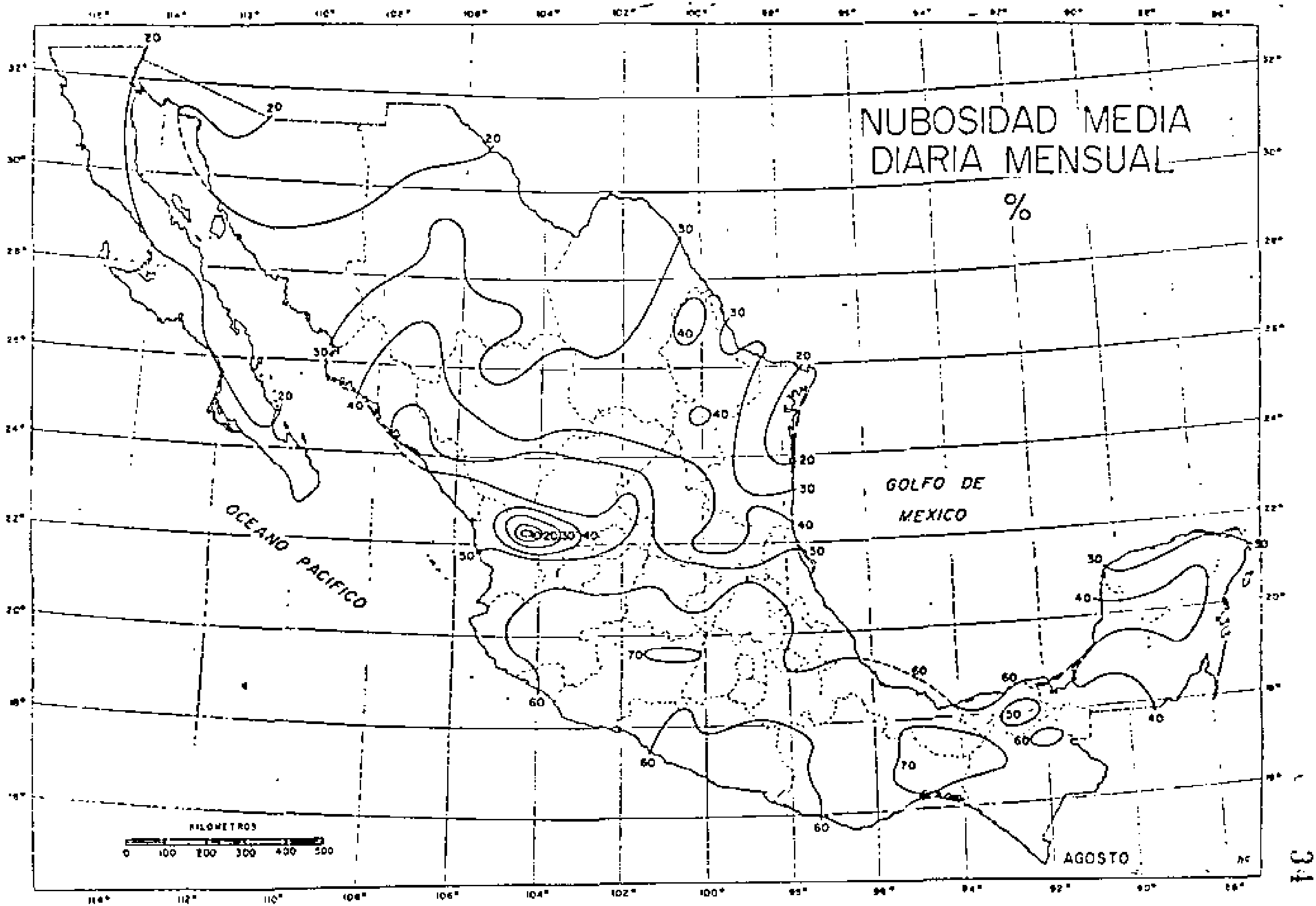


GOLFO DE
MEXICO
OCEANO PACIFICO
KILOMETROS
0 100 200 300 400 500
MAYO
10
20
30
40
50


NUBOSIDAD MEDIA
DIARIA MENSUAL
%
GOLFO DE
MEXICO
OCEANO PACIFICO
KILOMETROS
0 100 200 300 400 500
JUNIO
32



NUBOSIDAD MEDIA
DIARIA MENSUAL
%
GOLFO DE
MEXICO
OCEANO PACIFICO
KILOMETROS
100 200 300 400 500
JULIO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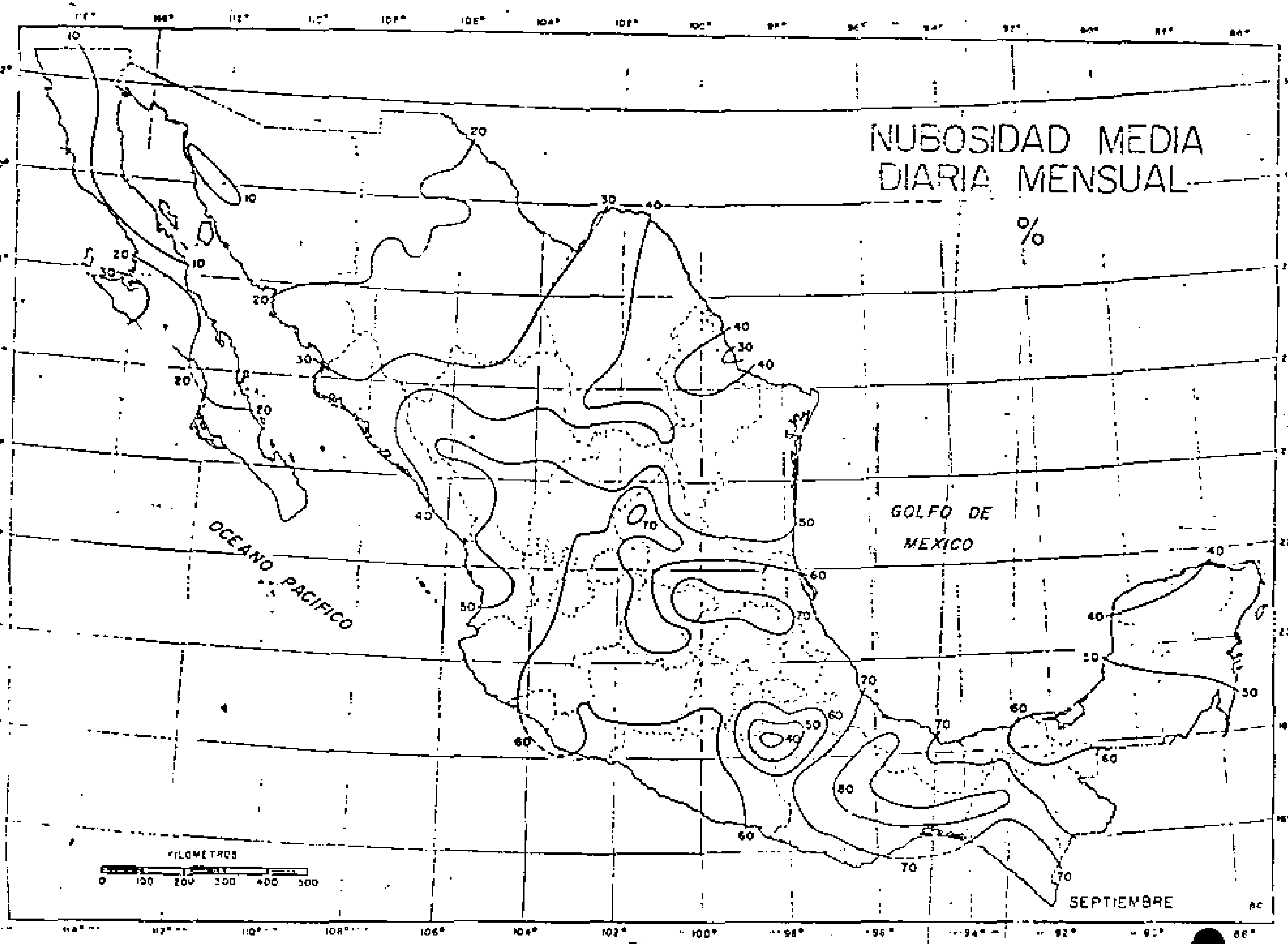
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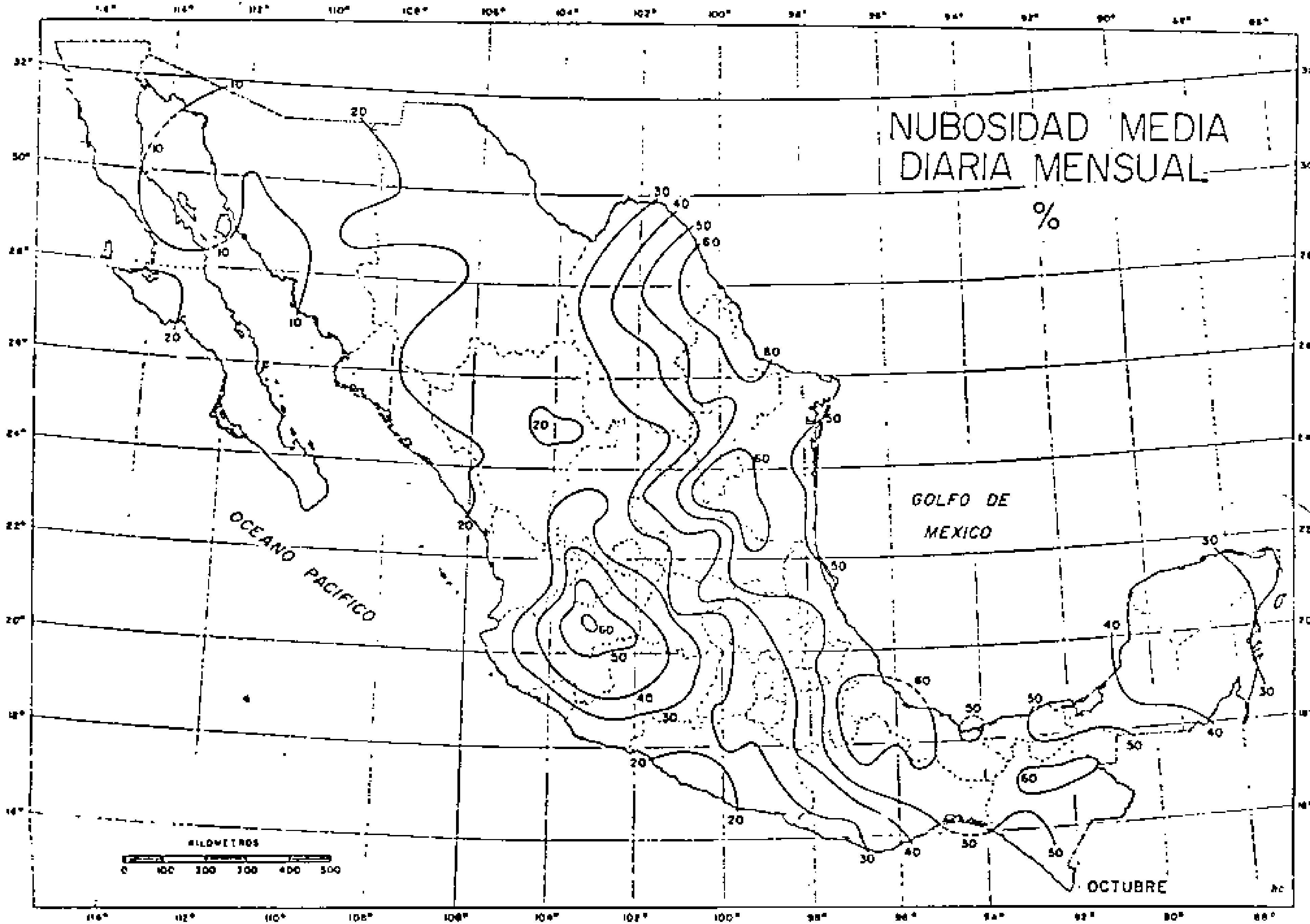
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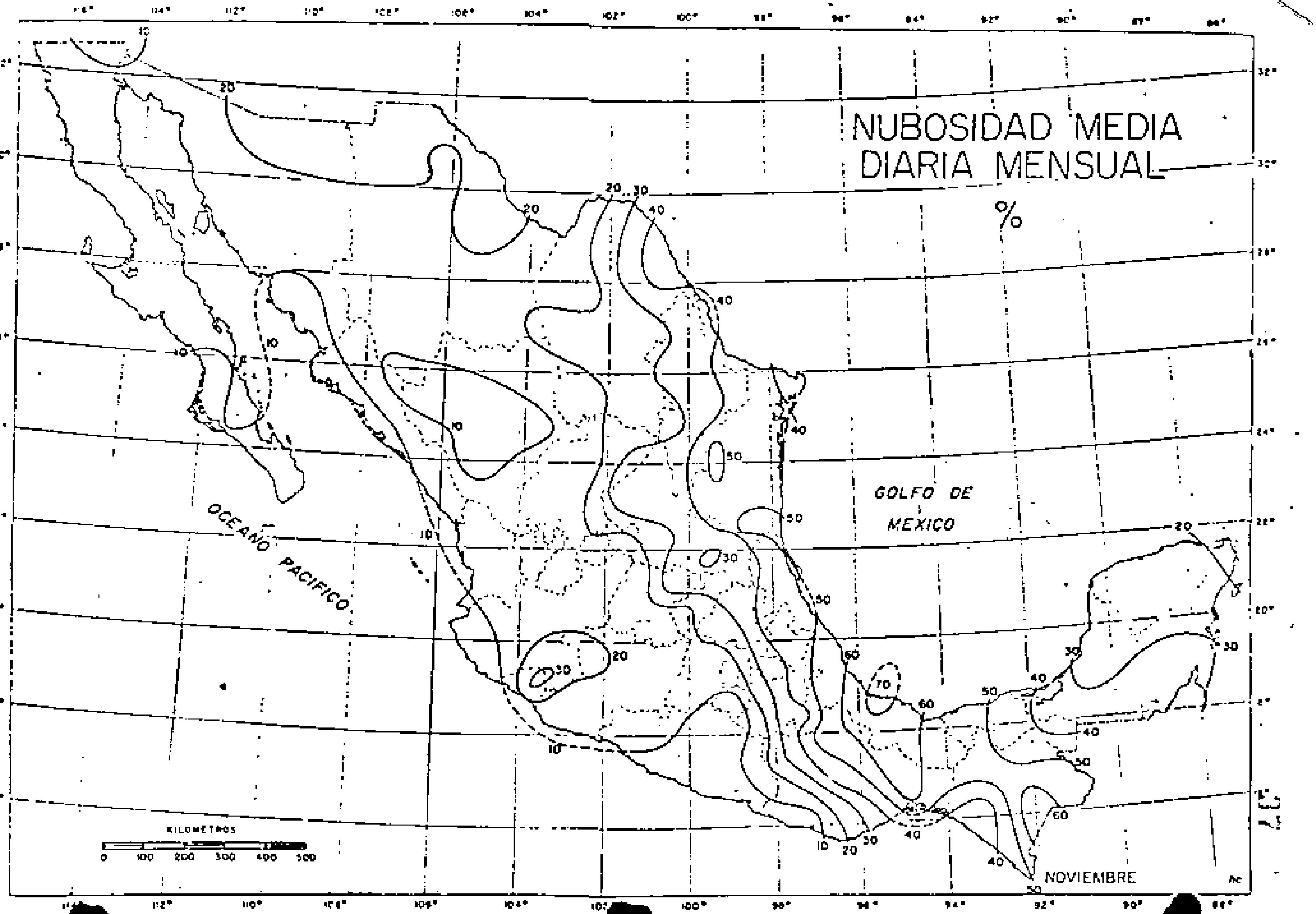

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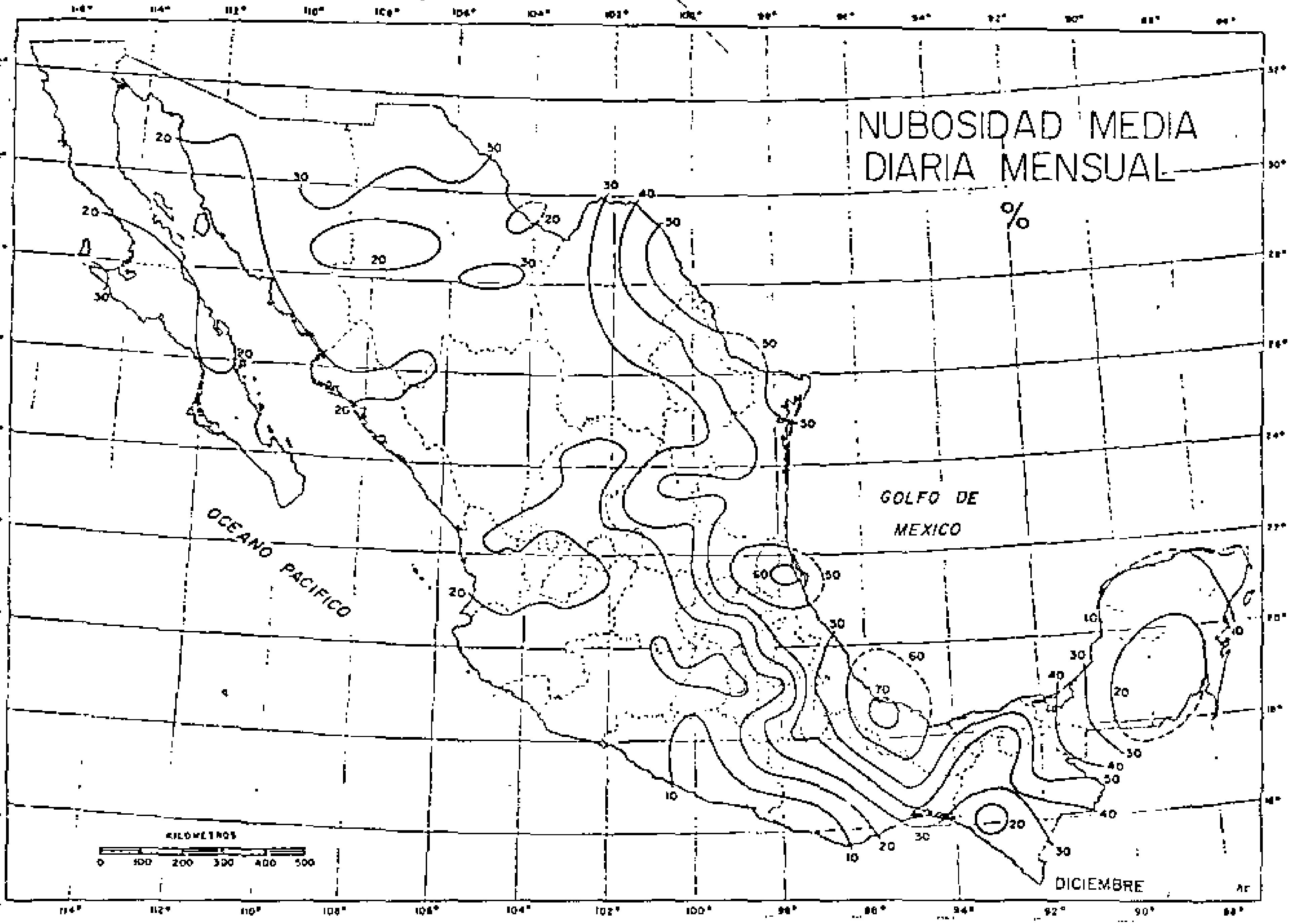
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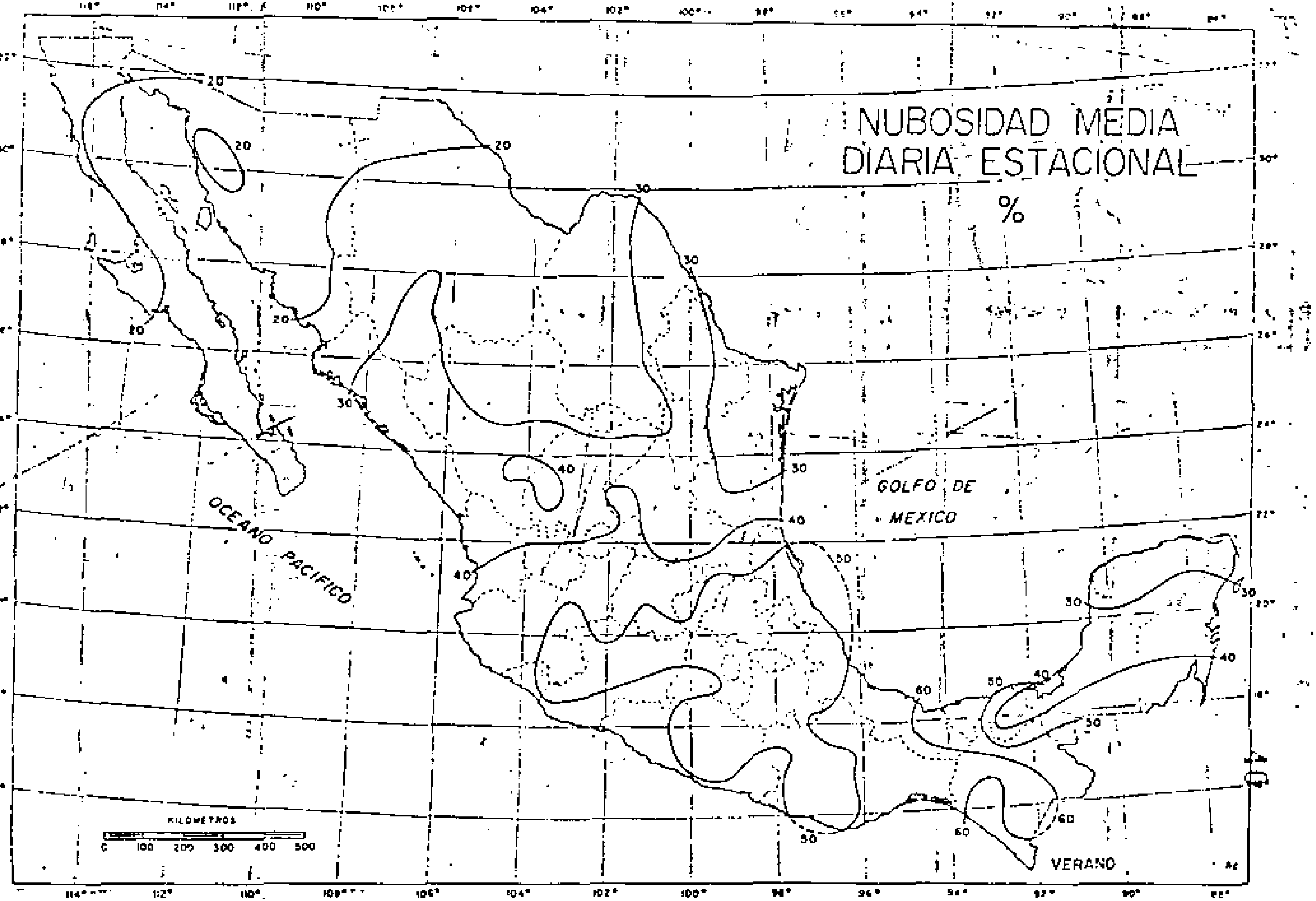
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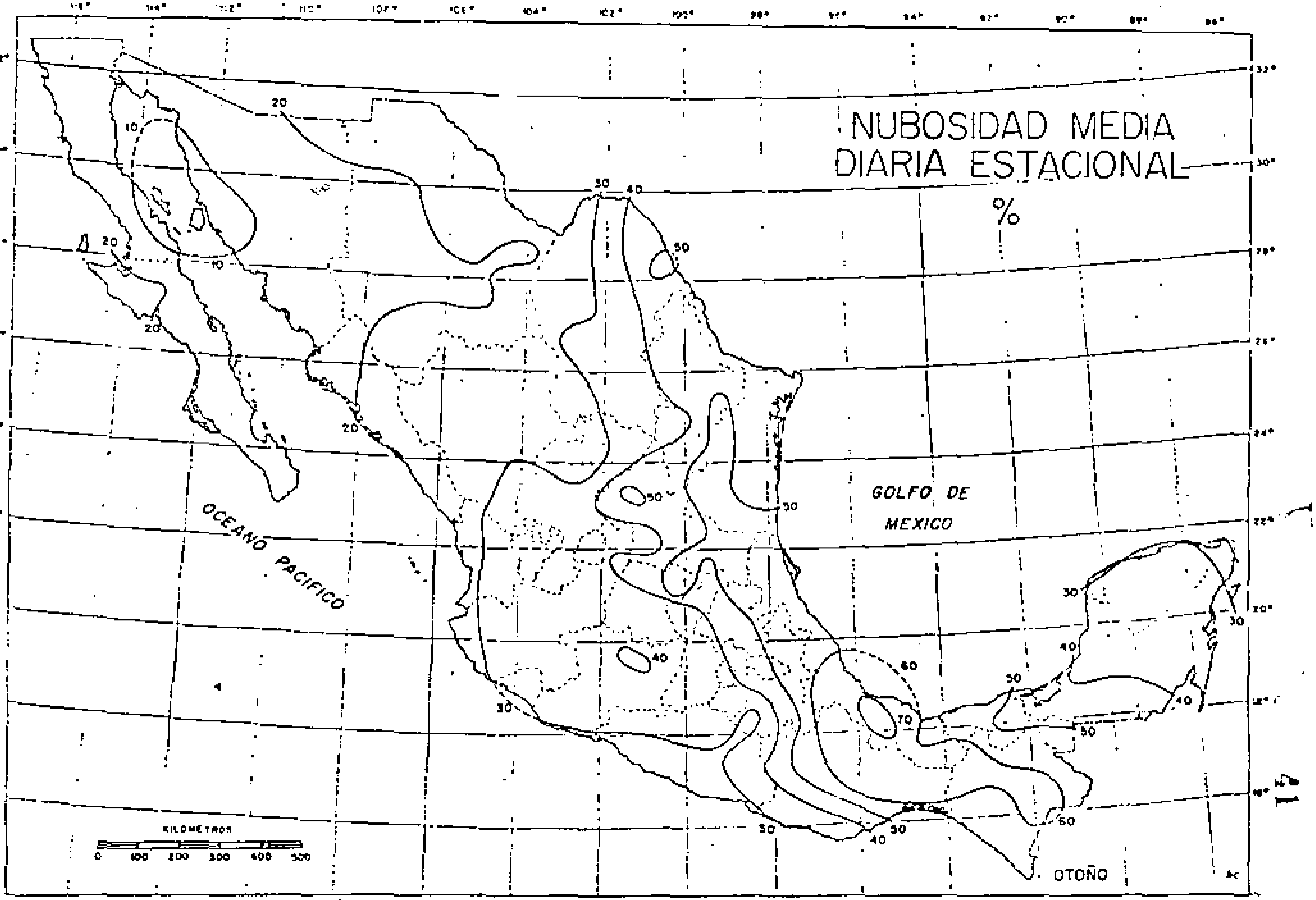
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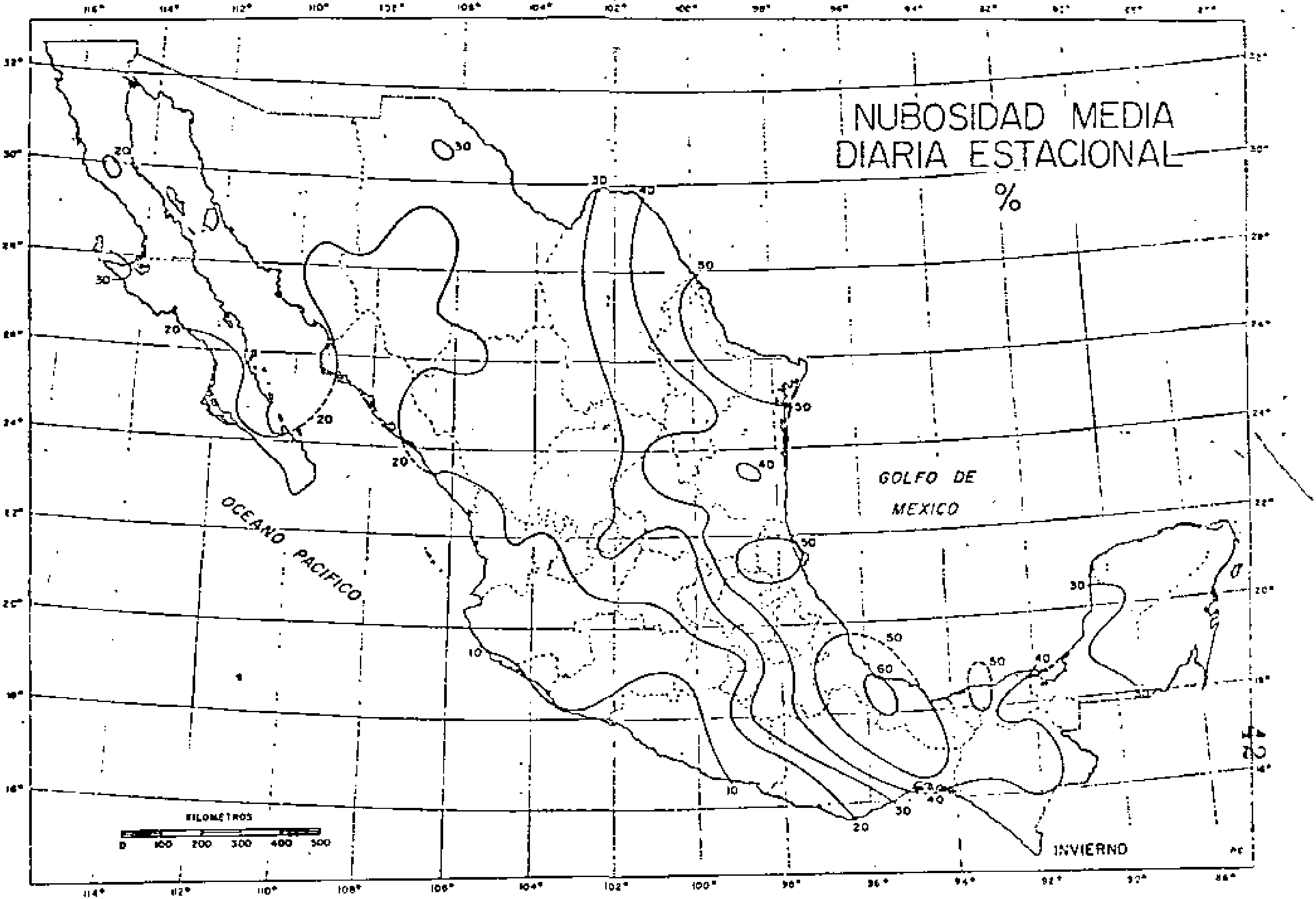

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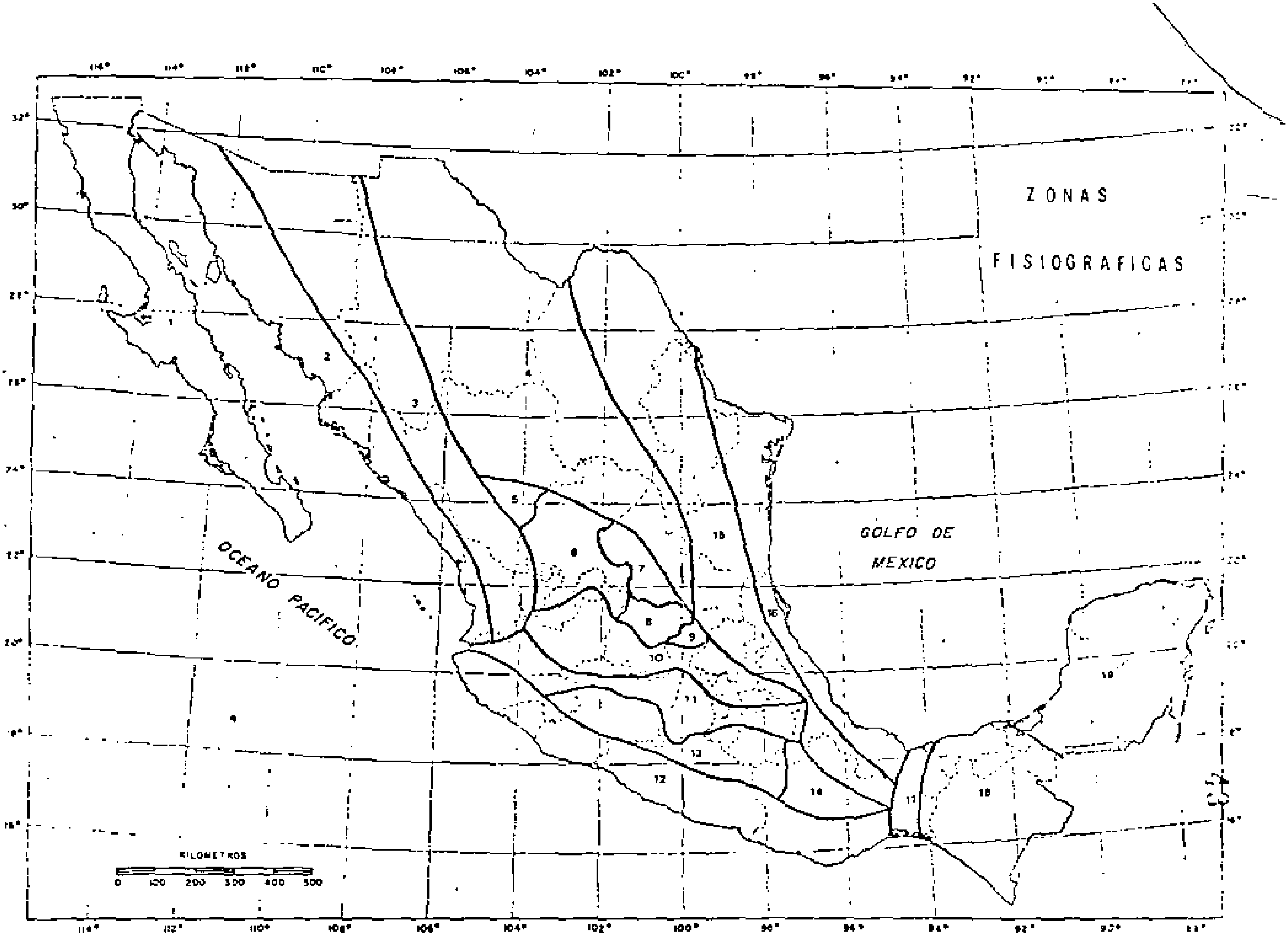
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facultad de ingeniería, unam

PRINCIPIOS Y APLICACIONES DE LA ENERGIA SOLAR

G E N E R A L I D A D E S

AGOSTO, 1979

Palacio de Minería Calle de Tacuba 5, primer piso. México 1, D. F. Tel: 521-40-20

GENERALIDADES

Colectores Solares

La energía solar recibida instantáneamente sobre la superficie terrestre en nuestras latitudes durante días despejados y claros puede alcanzar el valor de 1000 watts/m^2. Esta es una cantidad apreciable que puede ser captada mediante colectores planos o concentradores.

El proceso de captación se logra mediante la transformación de la radiación solar incidente en energía calorífica absorbida por el fluido circulante. Un dispositivo de captación de energía solar difiere de un intercambiador de calor, en el sentido de que la transferencia de energía radiante hacia el colector se realiza desde una fuente energética distante (sol) a un fluído de trabajo (agua). En tales condiciones se tienen bajos coeficientes de transferencia de calor y el transporte de energía por radiación viene a ser el fenómeno de transferencia predominante.

Colectores Planos

Los colectores planos son aquellos sobre los cuales se intercepta y absorbe la energía solar usando una superficie plana revestida por un película ennegrecida u otra altamente absorbente de la radiación solar (superficie selectiva).

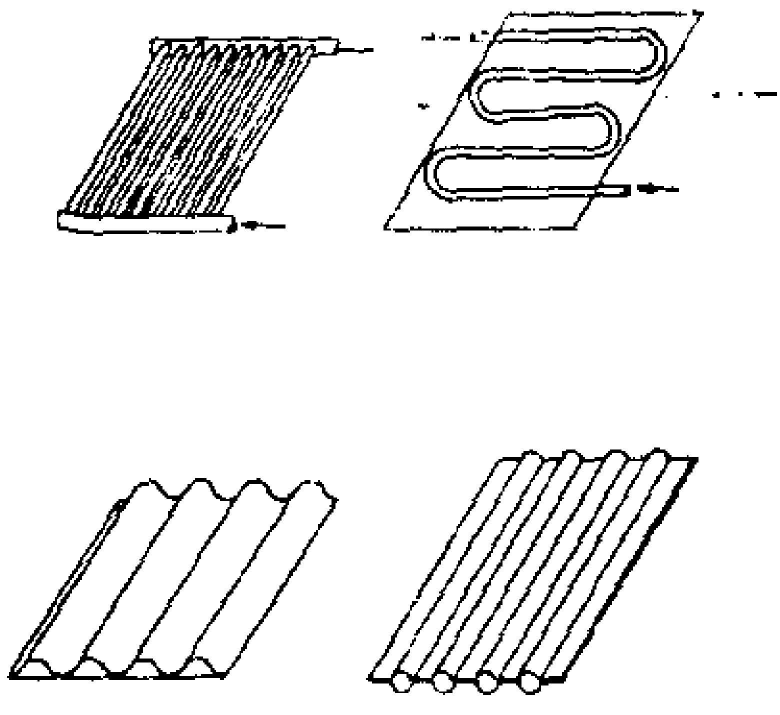

FIG. 1 TIPOS DE COLECTORES SOLARES

Los tipos más comunes son: tubos soldados a una placa; tubos paralelos soldados en sus extremos a dos cabezales y láminas metálicas unidas , una de ellas acanalada (Figura 1).

La placa colectora se aísla térmicamente en el fondo y en los lados para disminuir las pérdidas por conducción calorífica. La parte superior de la placa se cubre a cierta distancia, de una o varias cubiertas transparentes (de vidrio o de plástico), cuya finalidad es la de producir el efecto de invernadero y a su vez eliminar pérdidas por convección con el aire ambiente y por radiación, al atrapar la radiación infrarroja, emitida por la placa colectora.

Esta placa se construye de cobre, aluminio o hierro, materiales que poseen buenas conductividades térmicas y muy variadas dimensiones. Su revestimiento ennegrecido favorece la absorción de radiación solar incidente. Si es selectivo disminuye la emisión de radiación infrarroja.

Como los colectores planos están comúnmente fijos, estos aprovechan la radiación solar global, es decir, la proveniente directamente del sol (radiación directa) y la que ha sido reflejada y dispersada por la atmósfera y nubes (radiación difusa).

Su inclinación y orientación se fijan en base a los factores astronómicos de posición (latitud geográfica,declinación solar) y climatológicos regionales (nubosidad).

La aplicación de estas unidades está dirigida esencialmente a los sistemas de calentamiento de agua, aire acondicionado, refrigeración, destilación y secado de granos.

Concentradores

Los concentradores o captadores focales mediante superficies reflectoras dirigen la radiación solar sobre una superficie cuya área es menor que aquella que intercepta a la energía incidente.

Este tipo de colectores aprovecha únicamente la radiación solar directa y por tal razón deben seguir el movimiento del sol. Para tal fin, se requiere de un mecanismo apropiado (heliotropo) que eleva el costo del dispositivo, sin embargo las temperaturas que se alcanzen son hasta de 3500°C (dependiendo de la perfección óptica del diseño).

Estos se clasifican en función del tipo de sus superficies reflectoras, en : cónicos, cilíndricos y parabólicas.

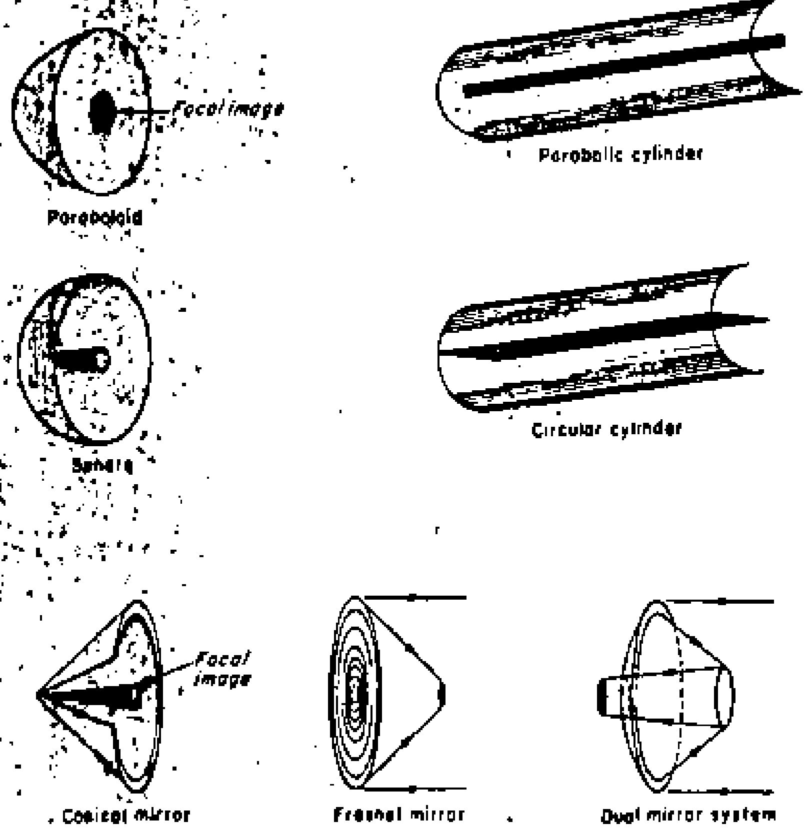

Fig. 2 Basic mirror shapes.

ANALISIS TERMICO DE UN CALENTADOR SOLAR

El funcionamiento de un colector operando bajo condiciones estacionarias? se puede describir mediante un balance energético que incluya a los siguientes componentes: energía solar incidente, energía útil aprovechada por el fluído, pérdidas de calor y energía almacenada. El balance energético total se expresa mediante la siguiente ecuación :

$$A \left[(HR\,(\tau\alpha))_b + (HR\,(\tau\alpha))_d \right] = Q_u + Q_p + Q_a \; . \; . \; . \; . \; . \; . \; (1)$$

donde :

A = área del colector (m^2)

H = radiación solar incidente directa (b) ó difusa (d) recibida sobre un plano horizontal, sobre la unidad de superficie por unidad de tiempo (watts/m^2)

R = factor de conversión, para la radiación directa y difusa recibida sobre un plano horizontal y la captada sobre un plano colector con cierta inclinación

$(\tau\alpha)$ = producto transmisividad-absortividad de las cubiertas transparentes a la radiación directa (b) ó difusa (d) (adimensional)

Q_u = calor útil absorbido por el fluído de trabajo(watts)

Q_p = pérdidas de calor del colector por unidad de tiempo hacia el medio ambiente por convección, radiación y conducción (watts)

Q_a = energía almacenada por el colector por unidad de tiempo (watts)

La eficiencia del colector se define como el cociente de la energía útil aprovechada por el colector -en cualquier período de tiempo-y la energía global incidente en ese mismo período:

$$\eta = \frac{\int \frac{Q_u}{A}\, dt}{\int HR\, dt} \quad \ldots\ldots (2)$$

donde :

η = eficiencia

t = período estudiado

HR = la suma de la radiación directa ($H_b R_b$) más la difusa ($H_d R_d$), captada por la unidad de superficie por unidad de tiempo, corregida a la inclinación del colector.

El calor útil del colector Q_u, se determina mediante la siguiente expresión :

$$Q_u = m\, c_p\, (t_s - t_e) \quad \ldots .(3)$$

donde :

m = gasto másico del fluído, (g/seg)

c_p = capacidad calorífica del agua a la temperatura media del agua en el colector (Joule/g °C)

t_s = temperatura de salida del agua del colector (°C)

t_e = temperatura de entrada del agua al colector (°C)

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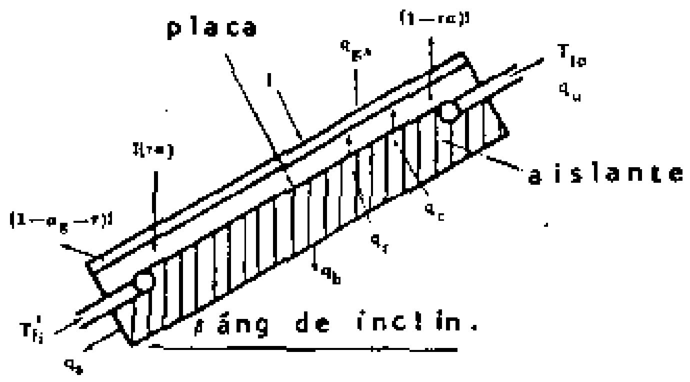

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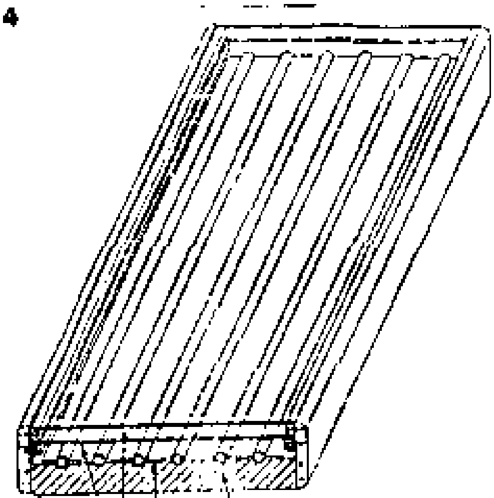


Las pérdidas de calor ocurren en la parte superior y posterior del colector. Para la mayoría de colectores solares la evaluación de las pérdidas laterales es muy compleja, aunque en general son demasiado pequeñas cuando se utiliza un espesor semejante al de la parte posterior del colector y en ese caso pueden ser despreciadas.

En la figura 5 están representadas las resistencias al flujo de calor en un colector solar con una cubierta transparente.

Las pérdidas por la parte inferior del colector son principalmente por conducción a través del aislante (suponiéndose un flujo unidireccional). El coeficiente de pérdidas por la parte inferior U_p, se expresa como :

$$U_p = \frac{1}{R_1} = \frac{k}{1} \quad . . . . (14)$$

donde : R_1 = resistencia por conducción , $\frac{m^2 \ °C}{watts}$

k = conductividad térmica del aislante $\frac{watts}{m \ °C}$

l = espesor del aislante , m

El coeficiente de pérdidas de la parte superior del colector, se ex-

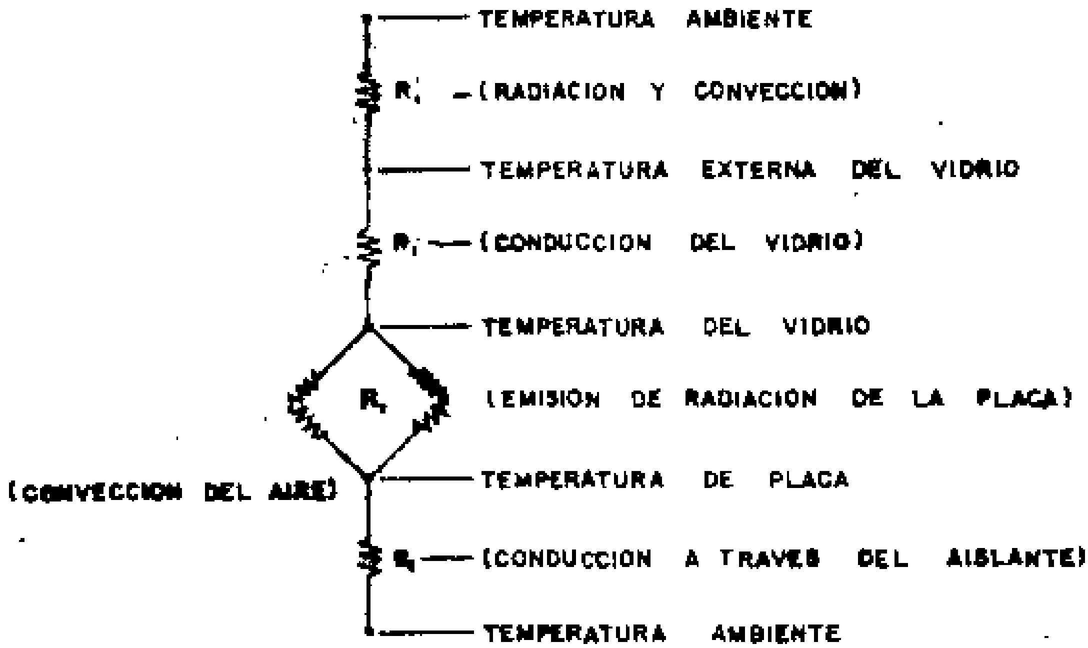


FIGURA 5

DIAGRAMA DE LAS RESISTENCIAS TERMICAS EN EL COLECTOR SOLAR presa así :

$$U_s = \frac{1}{R_2 + R_3 + R_4} \quad \ldots\ldots\ldots(15)$$

La resistencia a la transferencia de calor entre la placa metálica y la cubierta transparente R_2 esta dada como:

$$R_2 = \frac{1}{h_c + h_r} \quad \ldots\ldots\ldots(16)$$

donde :

h_c = coeficiente de transferencia de calor por convección watts/ m^2 °C

Mediante consideraciones de análisis dimensional, la transferencia de calor entre placas paralelas se correlaciona en la forma siguiente :

$$Nu = C\ (Gr\ .\ Pr\ )^n \quad \ldots\ldots\ldots(17)$$

donde :

Nu = número de Nusselt, $\frac{h_c\ l}{k}$, adimensional

l = distancia entre placas, m

k = conductividad térmica del aire, watts/ m °C

Gr = número de Grashof = $\frac{g\ v\ \Delta T\ l^3\ \rho^2}{\mu}$

Pr = número de Prandtl = $\frac{c_p\ \mu}{k}$

g = aceleración de la gravedad, m/seg^2

v = coeficiente de expansión térmica del aire, °C $^{-1}$

ρ = densidad del aire, kg/m^3

ΔT = diferencia de temperatura entre las placas, °C

c_p = capacidad calorífica del aire, joule / kg °C

μ = viscocidad del aire, kg/seg m

C,n = constantes determinadas experimentalmente

Todas las propiedades del aire son consideradas para una temratura media entre las dos placas.

La ecuación 17 puede ser reescrita de la siguiente manera:

$$Nu = \frac{h_c\, l}{k} = C\ (\,a\ l^3\ \Delta T\,)^n \ldots\ldots\ldots\ (17a)$$

donde :

$$a = \frac{g\ \gamma\ \rho^2\ c_p}{\mu\ k}\ ,\ m^{-3}\ \ {}^{\circ}C^{-1} \ldots\ldots\ldots\ldots\ (17b)$$

La cual es una propiedad del aire.

H. Tabor[2] recomienda para aire con un Pr de 0.7, las siguientes correlaciones:

a) placas horizontales, flujo de calor ascendente, un rango de $10^4 < Gr < 10^7$

$$Nu = 0.168\ (\,Gr\ Pr\,)^{0.281} = 0.152\ (\,Gr\,)^{0.281} \ldots\ldots\ldots\ (18)$$

b) placas a 45°, flujo de calor ascendente y un rango de $10^4 < Gr < 10^7$

$$Nu = 0.102\ (\,Gr\ Pr\,)^{0.310} = 0.093\ (\,Gr\,)^{0.310} \ldots\ldots\ldots\ (19)$$

c) placas verticales, $1.5 \times 10^5 < Gr < 10^7$

$$Nu = 0.0685\ (\,Gr\ Pr\,)^{0.327} = 0.062\ (\,Gr\,)^{0.327} \ldots\ldots\ldots\ (20)$$

d) placas verticales, $1.5 \times 10^4 < Gr < 10^5$

$$Nu = 0.0369\ (\,Gr\ Pr\,)^{0.381} = [illegible]\ (\,Gr\,)^{0.381} \ldots\ldots\ldots\ (21)$$

Despejando de la ecuación 17 a queda como:

$$h_c = C\,(ka^n)\,\frac{\Delta T^n}{l^{1-3n}} \quad \ldots\ldots\ldots\ldots (17b)$$

Para una temperatura media del aire de 10 °C, el coeficiente de convección para las correlaciones anteriores se expresa como :

a') $$h_c = \frac{1.61\,\Delta T^{0.281}}{l^{0.157}} \quad \ldots\ldots\ldots\ldots (18a)$$

b') $$h_c = \frac{1.14\,\Delta T^{0.310}}{l^{0.070}} \quad \ldots\ldots\ldots\ldots (19a)$$

c') $$h_c = \frac{0.82\,\Delta T^{0.327}}{l^{0.019}} \quad \ldots\ldots\ldots\ldots (20a)$$

d') $$h_c = \frac{0.57\,\Delta T^{0.381}}{l^{-0.140}} \quad \ldots\ldots\ldots\ldots (21a)$$

donde l está expresada en cm y ΔT en °C.

Para placas paralelas inclinadas 19° (latitud de México D.F.) se obtuvo la siguiente ecuación :

$$h_c = \frac{1.61\,\Delta T^{0.293}}{l^{0.121}} \quad \ldots\ldots\ldots (22)$$

Para diferentes temperaturas medias del aire en °C, h_c puede evaluarse así:

$$h_{\bar{T}} = h\,(1 - 0.0018\,(\bar{T} - 10)) \quad \ldots\ldots\ldots (23)$$

donde $\bar{T}$ es la temperatura media del aire entre las placas diferente de 10 °C.

De la figura 6, referida a una $\bar{T}$ de 10 °C se obtiene el coeficiente de convección, el número de Nusselt y el número de Grashof a diferentes distancias entre placa y cubierta transparente inclinadas a 19 ° con respecto a la horizontal.

Para corregir las propiedades del aire a temperaturas mayores de 10°C se introducen dos factores de corrección F_1 y F_2, que varían con la temperatura como lo muestra la figura 6 .

El efecto de la variación de la distancia entre la placa metálica del colector y la cubierta transparente (vidrio) se determina mediante la ecuación 17b, siendo h_c directamente proporcional a $l^{(3n-1)}$. Para los casos de placas horizontales e inclinadas a 19°, 45 y 90° el valor de h_c es proporcional a $l^{-0.157}$, $l^{-0.121}$, $l^{-0.07}$ y $l^{-0.019}$ respectivamente. Duplicando la distancia entre las placas l, el valor del coeficiente de convección h_c se reduce en un 10, 8, 5 y 1.3 % respectivamente. Cabe indicar que no es conveniente utilizar una l demasiado grande debido a las sombras que se proyectarían al tener que aumentar las paredes laterales del armazón que contiene al colector.

La evaluación del coeficiente de transferencia de calor por radiación entre la placa y la cubierta transparente h_r, suponiendo que las pérdidas por radiación son lineales , se determina así:

$$h_r = \frac{\sigma \left(T_p^2 + T_v^2 \right) \left(T_p + T_v \right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_v} - 1} \quad \ldots\ldots (24)$$

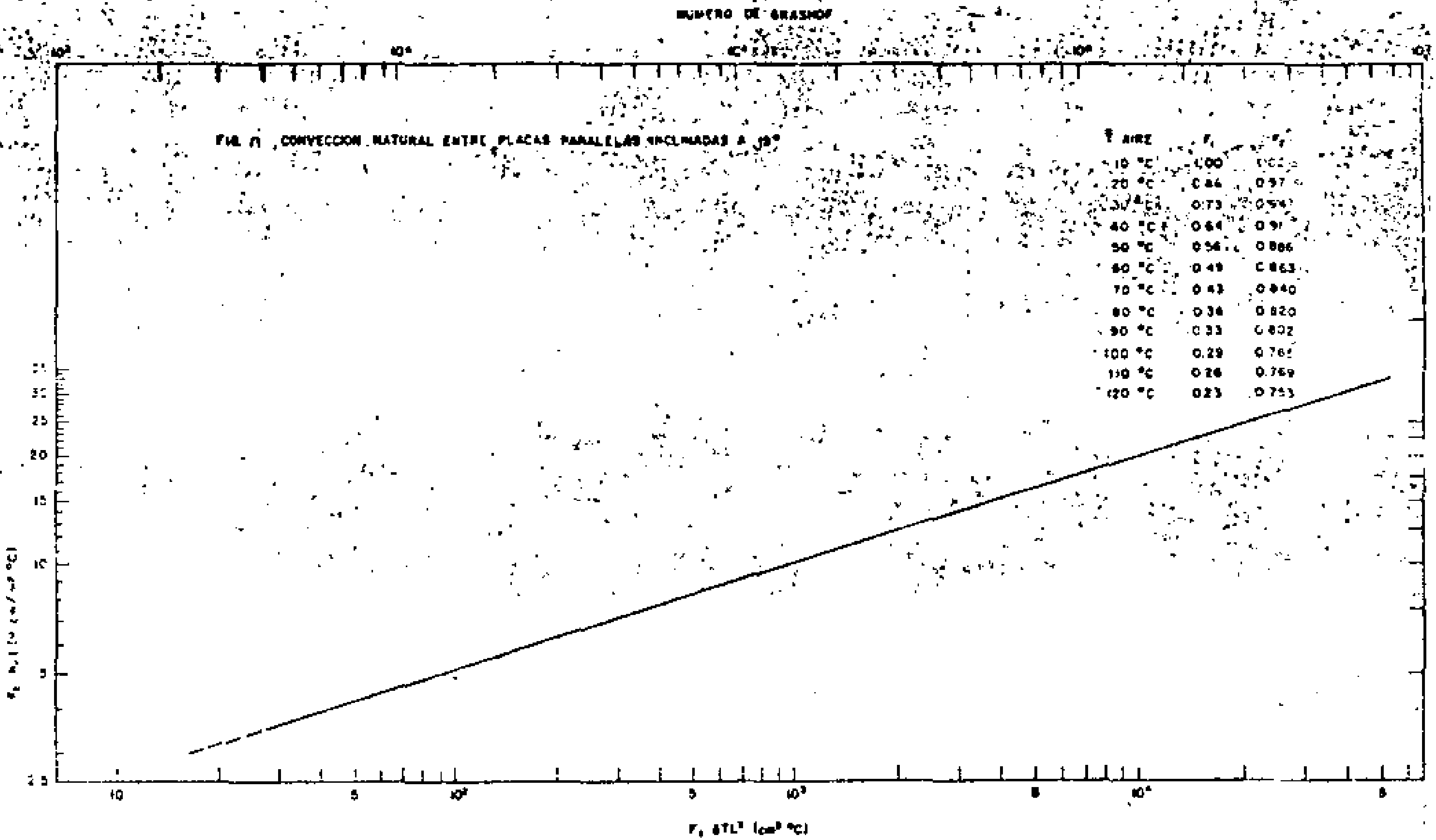
donde:

h_r = coeficiente de radiación entre placa y cubierta transparente , $\frac{watt}{m^2\ °C}$

σ = constante de Stefan-Boltzmann ($5.67 \times 10^{-8}\ \frac{watt}{m^2\ °K^4}$)

T_p, T_v = temperaturas de placa y vidrio °K

$\varepsilon_p, \varepsilon_v$ = emisividades de placa y vidrio


NUMERO DE GRASHOF
CONVECCION NATURAL ENTRE PLACAS PARALELAS INCLINADAS
T AIRE / F_1 / F_2
10 °C / 1.00
20 °C / 0.86 / 0.97
30 °C / 0.73
40 °C / 0.64 / 0.91
50 °C / 0.56 / 0.886
60 °C / 0.49 / 0.863
70 °C / 0.43 / 0.840
80 °C / 0.38 / 0.820
90 °C / 0.33 / 0.802
100 °C / 0.29
110 °C / 0.26 / 0.769
120 °C / 0.23 / 0.753
$F_1\ \Delta T L^3$ (cm³ °C)

Las pérdidas de calor por unidad de area entre la placa y la cubierta transparente están dadas como:

$$Q_{p-v}/A = (h_c + h_r)(T_p - T_v) \quad \ldots\ldots (25)$$

en donde $\frac{Q_{p-v}}{A}$ está expresada en watt/ m^2.

La resistencia a la transferencia de calor en el vidrio R_3 es:

$$R_3 = \frac{1}{k} \quad \ldots\ldots (26)$$

donde:

l = espesor del vidrio, m

k = conductividad térmica del vidrio, watt/ m °C

El flujo de calor de la cubierta al medio ambiente, es tanto por convección como por radiación, por lo que:

$$R_4 = \frac{1}{h_{r'} + h_v} \quad \text{en } m^2\ °C / \text{watt} \ldots (27)$$

Mc Adams obtuvo una relación en la cual el coeficiente de convección h_v está en función de la velocidad del viento en m/ seg y esta dada como:

$$h_v = 5.7 + 3.8\,V \quad \text{en watt/ } m^2 \text{ seg} \quad \ldots\ldots (28)$$

En la figura 7, se puede apreciar graficado h_v en función de V.

El coeficiente por radiación entre la cubierta transparente y el cielo se calcula así:

$$h_{r'} = e_v\,\sigma\,(T_v + T_a)(T_v^2 + T_a^2) \quad \ldots (29)$$

donde T_a es la temperatura ambiente en °K.

Las pérdidas de calor entre el vidrio y el cielo están dadas por:

$$Q_{v-c}/A = (h_v + h_{r'})(T_v - T_a) \text{ en watt/ } m^2 \quad \ldots (30)$$

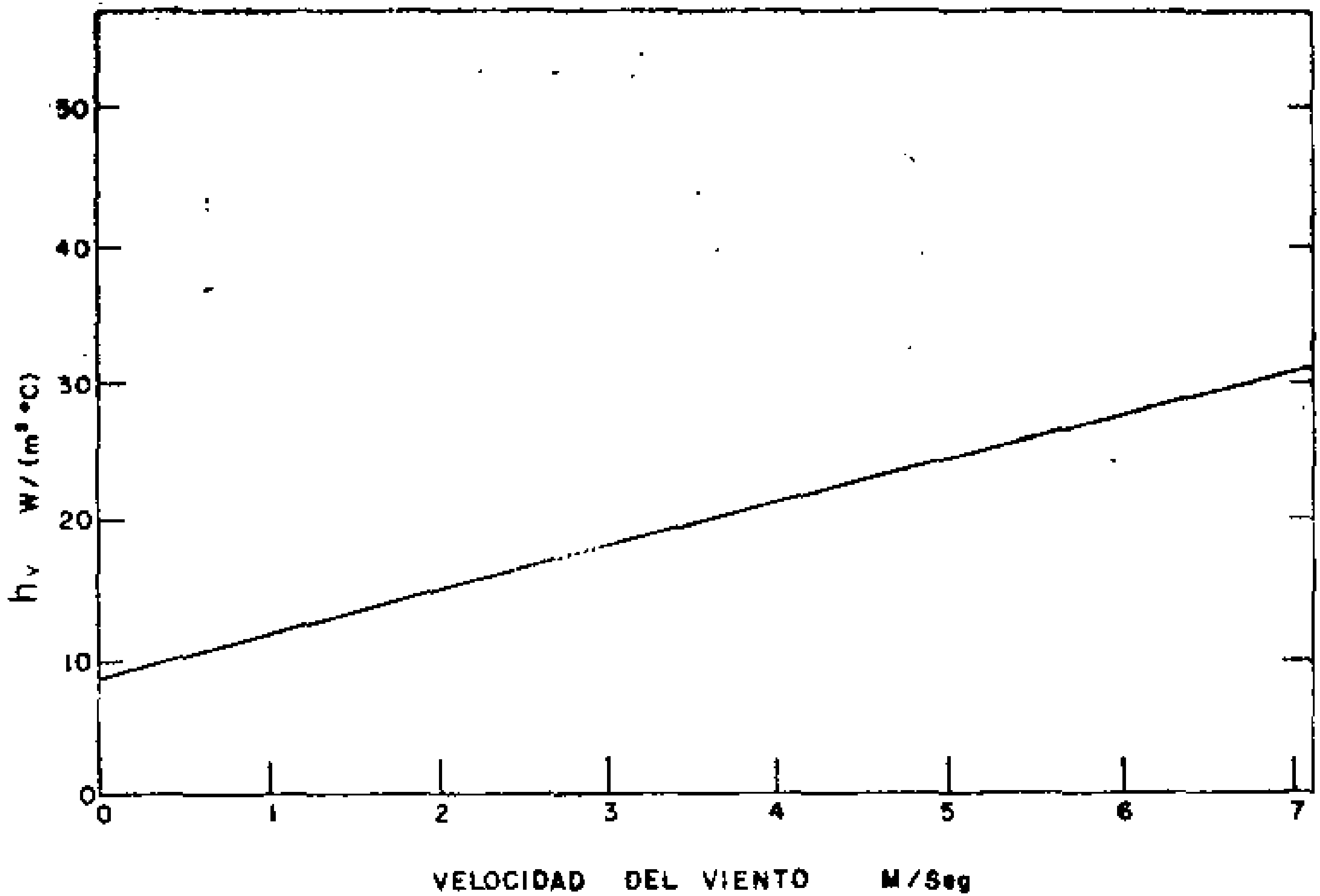


FIG. 7 COEFICIENTE DE TRANSFERENCIA DE CALOR POR CONVECCION PARA UN COLECTOR SOLAR EN FUNCION DE LA VELOCIDAD DEL VIENTO.

El coeficiente global de pérdidas de calor en el colector se expresa como :

$$U_T = U_p + U_b \text{ en watt/m}^2 \text{ seg} \quad \ldots\ldots (31)$$

Por lo tanto las pérdidas totales de calor en el colector vienen a ser:

$$Q_p = U_T \; A \; (T_p - T_a) \text{ en watts} \quad \ldots\ldots (32)$$

Klein[2] desarrolló una ecuación empírica para calcular U_p a temperaturas de placa entre 40 y 130 °C con una exactitud del orden de $\pm$ 0.2 watt/ m^2 °C y está dada como:

$$U_p = \left(\frac{N}{(344/T_p)((T_p - T_a)/(N+f))^{0.31}} + \frac{1}{h_v} \right)^{-1} + \frac{\sigma (T_p + T_a)(T_p^2 + T_a^2)}{(e_p + 0.0425N(1-e_p))^{-1} + ((2N + f - 1)/e_v) - N} \quad \ldots (33)$$

en donde N número de cubiertas transparentes

$f = (1 - 0.04\ h_v + 5.0 \times 10^{-4}\ h_v^2)(1 + 0.058\ N)$

T_a temperatura ambiente en °K

T_p temperatura de placa en °K

Todos los parámetros que influyen en el diseño de un colector solar se relacionan por un factor que depende principalmente de las variables de diseño, de la masa velocidad G, de la capacidad calorífica del fluído y del coeficiente total de pérdidas de calor U_T. Por lo tanto las condiciones de operación como temperaturas, radiación solar, velocidad de viento, etc. tienen una influencia mínima. A este factor se le denomina factor de calor removido F_R, que se define como energía útil ganada por el colector entre la energía útil aprovechada si toda la superficie del colector estuviera a la temperatura de entrada del fluído y se expresa como :

$$F_R = G\,C_p / U_T \left(1 - e^{-(U_T F' / GC_p)} \right) \quad . . . \quad (34)$$

en donde G gasto másico por unidad de área del colector en g/m^2 seg

C_p capacidad calorífica del fluído en joule/g °C

F' es el factor de eficiencia del colector y se define como el cociente de la energía útil ganada entre la energía útil ganada si el colector se encontrara a la temperatura media del fluído y para el colector analizado en el presente estudio se expresa como:

$$F' = \cfrac{1}{1 + \cfrac{U_T}{h_f + \cfrac{1}{\cfrac{1}{\bar{h}_f} + \cfrac{1}{\bar{h}_{r''}}}}} \quad . . . \quad (35)$$

El coeficiente de convección entre el fluído y el tubo h_f está dado por la expresión :

$$h_f = Nu\, k / D \quad \text{en watt/m}^2\ °C \quad . . \quad (36)$$

en donde k es la conductividad térmica del fluído en watt/m^2 °C y D es el diámetro interno de los tubos . En el caso de tubos de sección rectangular se debe emplear el diámetro hidraúlico D_h que se calcula así : $D_h = 2\,ab/(a + b)$, en donde a y b son los lados del tubo rectangular.

Para colectores solares funcionando a circulación natural el fluído circula en régimen laminar. Considerando que los tubos son relativamente cortos, de diámetro pequeño y diferencia de temperatura moderada entonces la siguiente ecuación es una buena aproximación para el cálculo del número de Nusselt:

$$Nu = 1.86 \; (Re \; Pr \; D_h/L)^{1/3} \qquad \ldots \quad (37)$$

en donde Re es el número de Reynolds expresado como:

$$Re = D_h \, v \, \rho / \mu$$

y v es la velocidad del fluído en los tubos del colector en m/seg, ρ es la densidad del fluído en kg/m^3 y μ es la viscosidad del fluído en kg/ m seg. Pr es el número de Prandtl para el fluído y L la longitud de los tubos en m.

El coeficiente de radiación $h_{r''}$ entre el interior del tubo y el fluído esta dado en watt/m^2 °C y se calcula utilizando la temperatura media $\bar{T}$ entre ambos, quedando como:

$$h_{r''} = 4 \, \sigma \, \bar{T}^3 \, / \, (2/e_t - 1) \qquad \ldots \quad (38)$$

en donde e_t es la emisividad del tubo.

El calor útil considerando F_R se expresa como:

$$Q_u = A \, F_R \, (H \, (\tau\alpha)_e - U_T \, (T_e - T_a)) \text{ en watts} \quad \ldots \quad (39)$$

Y para obtener Q_u en función de F' , viene a ser:

$$Q_u = A \, F' \, (H \, (\tau\alpha)_e - U_T \, ((T_e + T_s/2) - T_a)) \text{ en watts.} \quad . \; (40)$$

Al sustituir Q_u/A en la ecuación 2 se obtiene que:

$$\eta = F_R \, (\tau\alpha)_e - F_R \, U_T \, (T_e - T_a)/ H \quad \ldots \quad (40)$$

$$\eta = F' \, (\tau\alpha)_e - F' \, U_T \, (T_e + T_s /2 - T_a)/H \quad \ldots \quad (41)$$

Si se grafica η contra(Te-Ta)/ H o contra $\frac{(T_e + T_s/2 - T_a)}{H}$ se obtienen rectas en donde la intersección con el eje de las ordenadas está en función de $(\tau\alpha)_e$; así como la pendiente de la recta, de U_T.

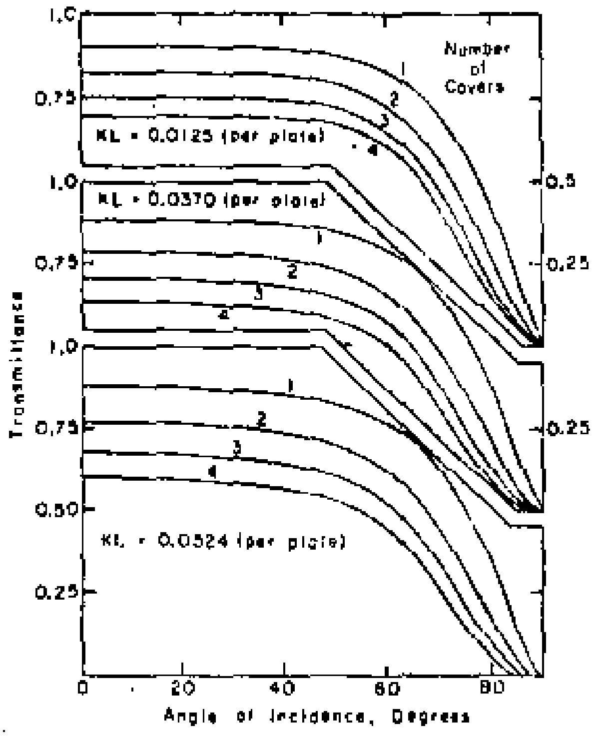


FIG. Transmittance of cover systems taking account of both absorption and reflection.

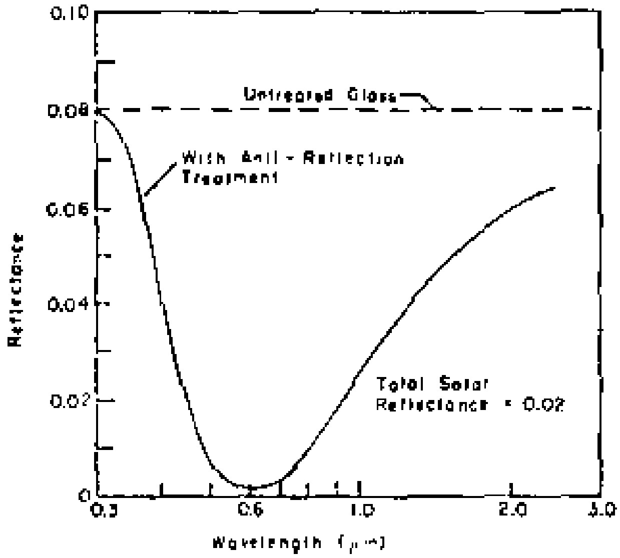


FIG. Reflectance of antireflection treated glass.

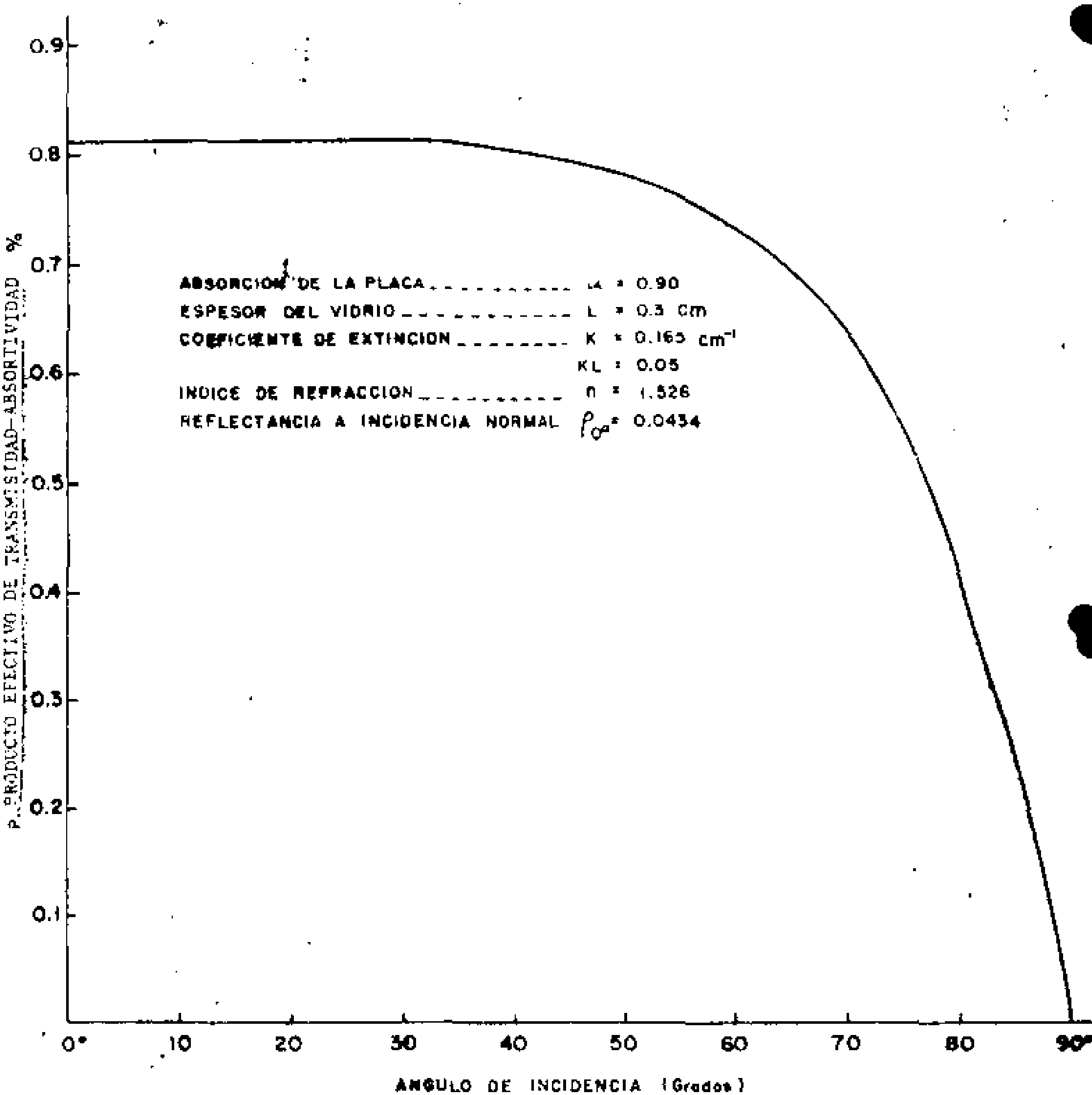


FIG. PRODUCTO EFECTIVO DE TRANSMISIVIDAD-ABSORTIVIDAD PARA VIDRIO COMUN

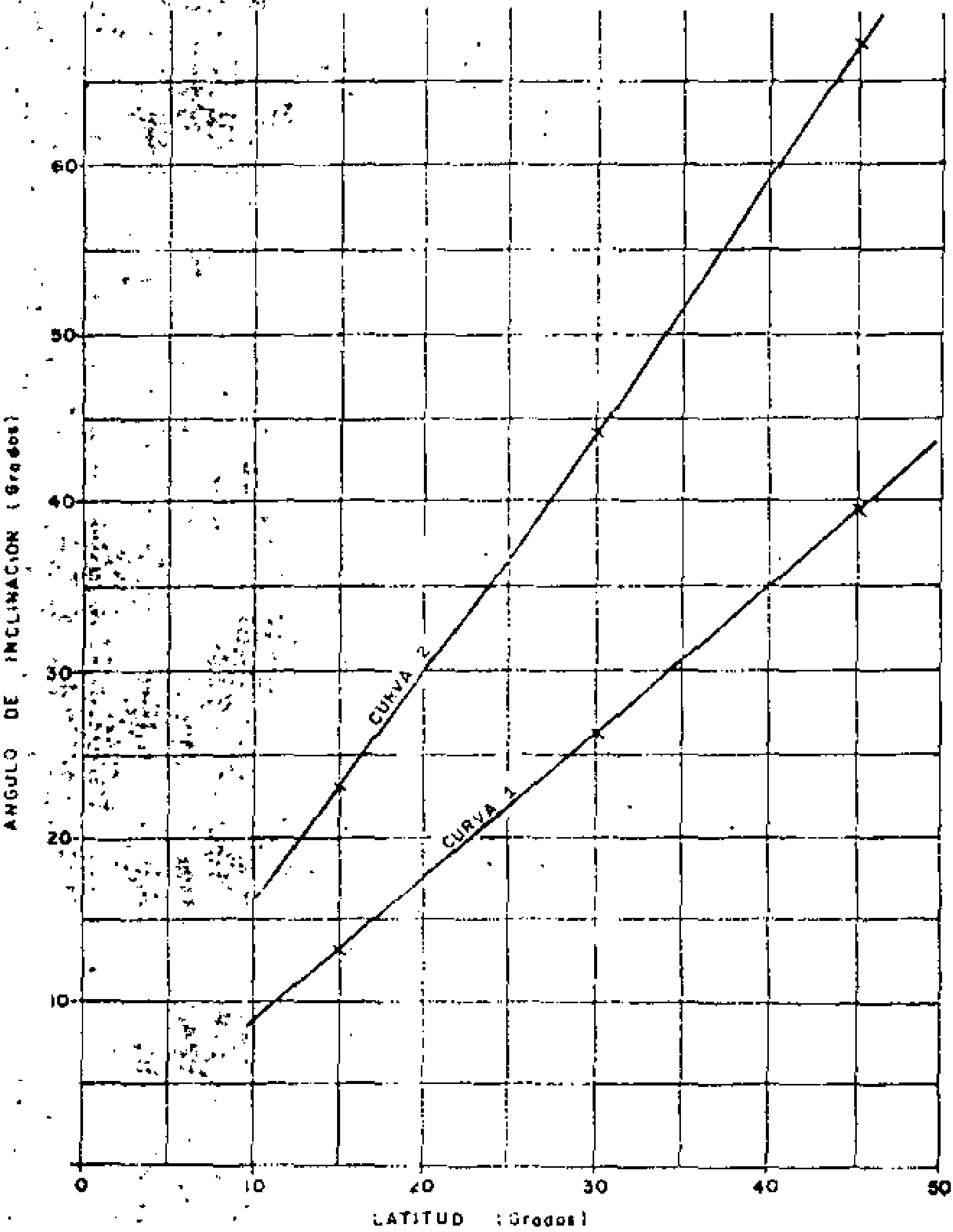


FIG. . CURVA 1. ANGULO DE INCLINACION PARA LA MAXIMA INSOLACION ANUAL

CURVA 2. ANGULO DE INCIDENCIA PARA OBTENER IDENTICA INSOLACION PARA LOS SOLSTICIOS DE VERANO E INVIERNO

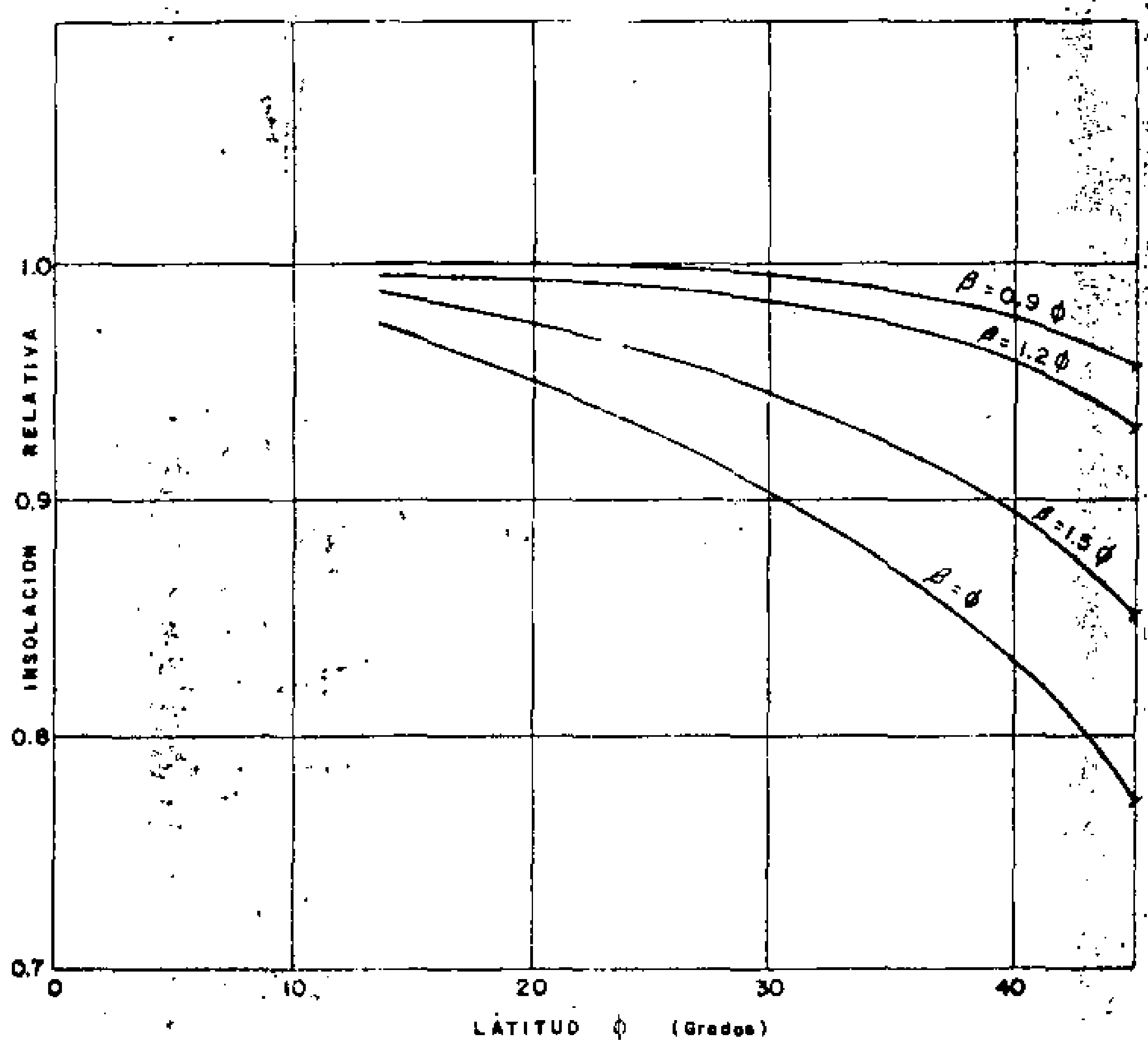


FIG. - INSOLACION ANUAL RELATIVA SOBRE SUPERFICIES INCLINADAS ORIENTADAS HACIA EL SUR A DIFERENTES INCLINACIONES β.

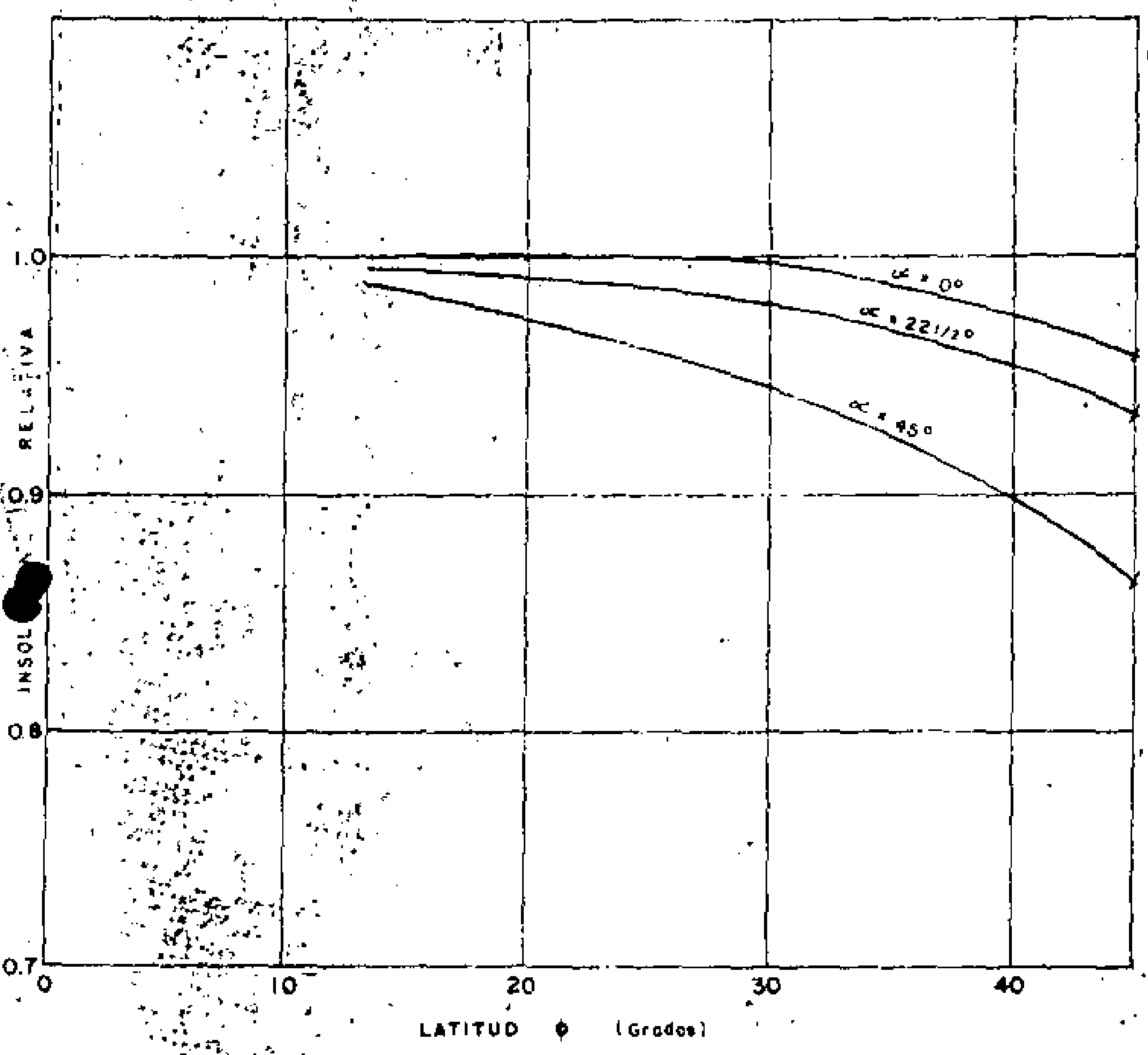


FIG. - INSOLACION ANUAL RELATIVA SOBRE SUPERFICIES INCLINADAS A $\beta = 0.9\phi$ ORIENTADAS HACIA EL ECUADOR A DIFERENTES ANGULOS ACIMUTALES α

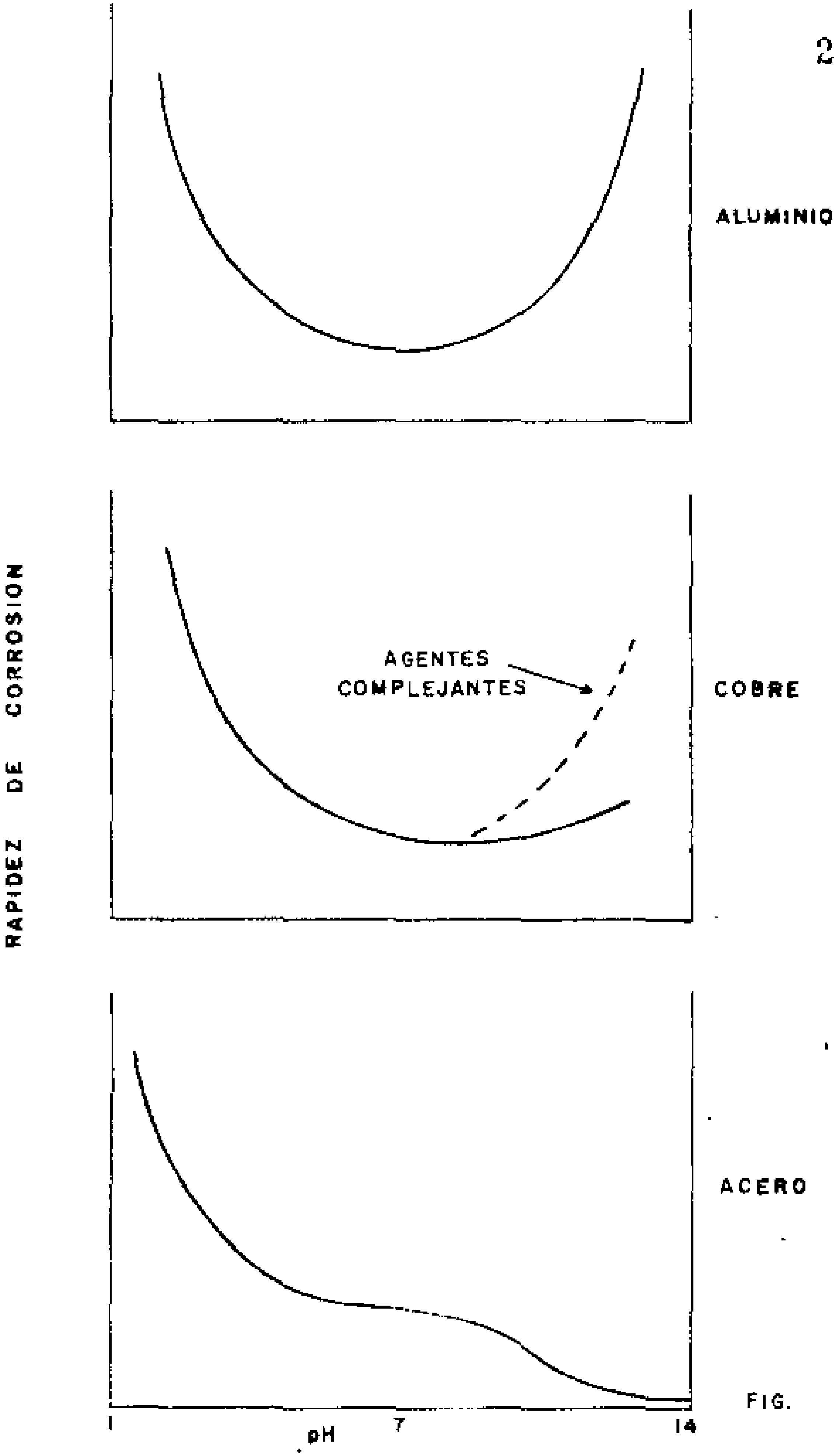

ALUMINIO
AGENTES COMPLEJANTES
COBRE
ACERO
RAPIDEZ DE CORROSION
1
pH
7
14

FIG.

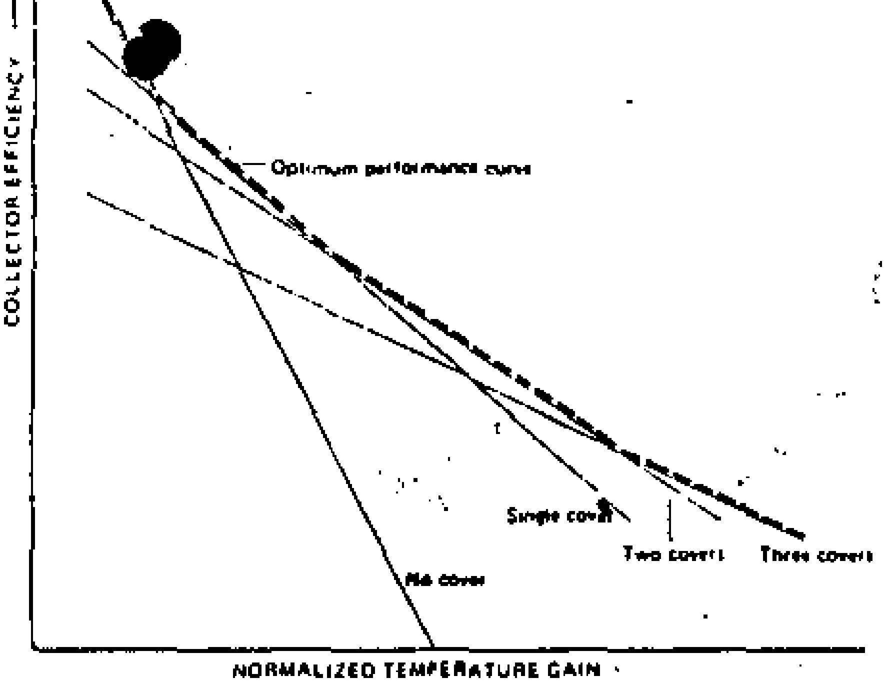


Figure Collector efficiency with various numbers of covers

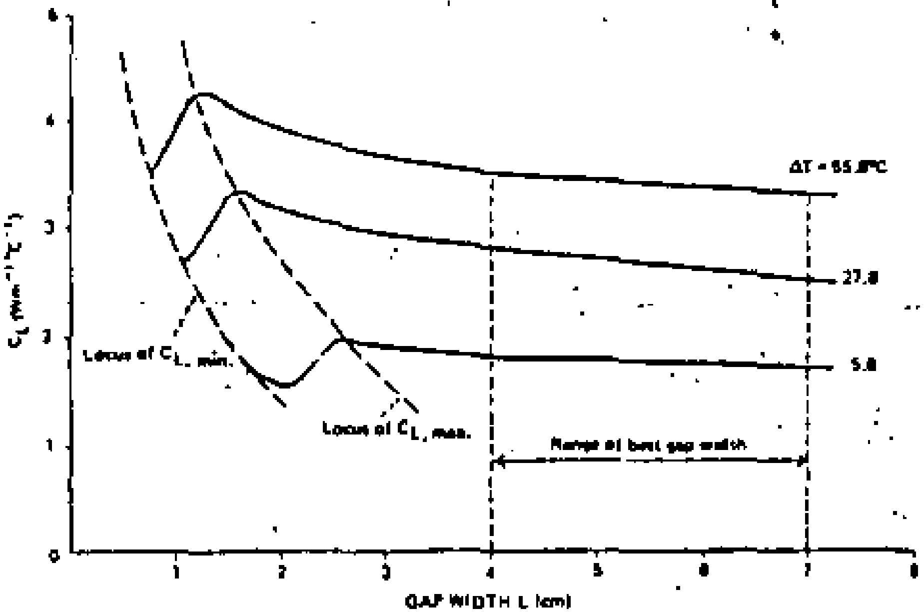


Figure Gap conductive-convective coefficient C_L as a function of gap width for $T = 70°$ C, tilt angle 40°

Coating	Solar energy absorptance α	Long wave radiation admittance[a] ε	Reference
Black enamel paint	0.83	0.83	Sabbagh, J. A. et al
Tar	0.86	0.86	Sabbagh, J. A. et al
Lamp-black	0.95	0.95	Sabbagh, J. A. et al.
Nickel black (oxides and sulphides of Ni and Zn) on polished Ni	0.91-0.94	0.11	Tabor, H. et al
Nickel black on galvanized-iron (experimental)	0.89	0.12	Tabor, H. et al
Nickel black on galvanized-iron (commercial)		0.16-0.18	Tabor, H. et al
Nickel black, two layers on electroplated Ni on mild steel (after 6-h immersion in boiling water)	0.94	0.07	Tabor, H. et al; Schmidt, R. N. et al
CuO on Ni (made by electrode deposition of Cu and subsequent oxidation)	0.81	0.17	Kokoropoulos, P. et al
Co_3O_4 on Ag (deposition and oxidation)	0.90	0.27	Kokoropoulos, P. et al
CuO on Al (by spraying dilute $Cu(NO_3)_2$ solution on hot Al plate and baking)	0.93	0.11	Hottel, H. C. and Unger, T. A.
Copper black on Cu (commercial treatment of Cu with solution of NaOH and $NaClO_2$)	0.89	0.17	Close, D. J.
Ebanol C on Cu (commercial Cu blackening treatment giving coatings mostly consisting of CuO)	0.90	0.16	Edwards, D. K. et al
CuO on anodized Al is treated (Al with hot $Cu(NO_3)_2$ - $KMnO_4$ solution and baked)	0.85	0.11	Tabor, H.
Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3 interference layers on Mo	0.91	0.085[b]	Schmidt, R. W. et al
PbS crystals on Al	0.89	0.20	Williams, D. A. et al

[a] At temperatures typical of flat-plate solar collectors
[b] Measured at 260°C (500°F).

TABLE II: PROPERTIES OF COMMONLY USED INSULATION MATERIALS IN FLAT PLATE COLLECTORS

Material	Approximate Density (kg/m³)	Thermal Conductivity (Wm^{-1}°C^{-1})
Mineral wool (clay wool, fibreglass, rock wool)	12-14	0.0332-0.0404
Hair felt	80	0.0389
Granulated cork	120	0.0476
Re-granulated cork (0.474 cm particles)	30	0.04471
Compressed cork	136-176	0.0418-0.0462
Straw	10-13	0.0576
Sawdust	13-240	0.0649
Vermiculite (granulated)	128	0.0721
Polyurethane foam (rigid)	24	0.0245
Polystyrene (expanded)	16	0.0303

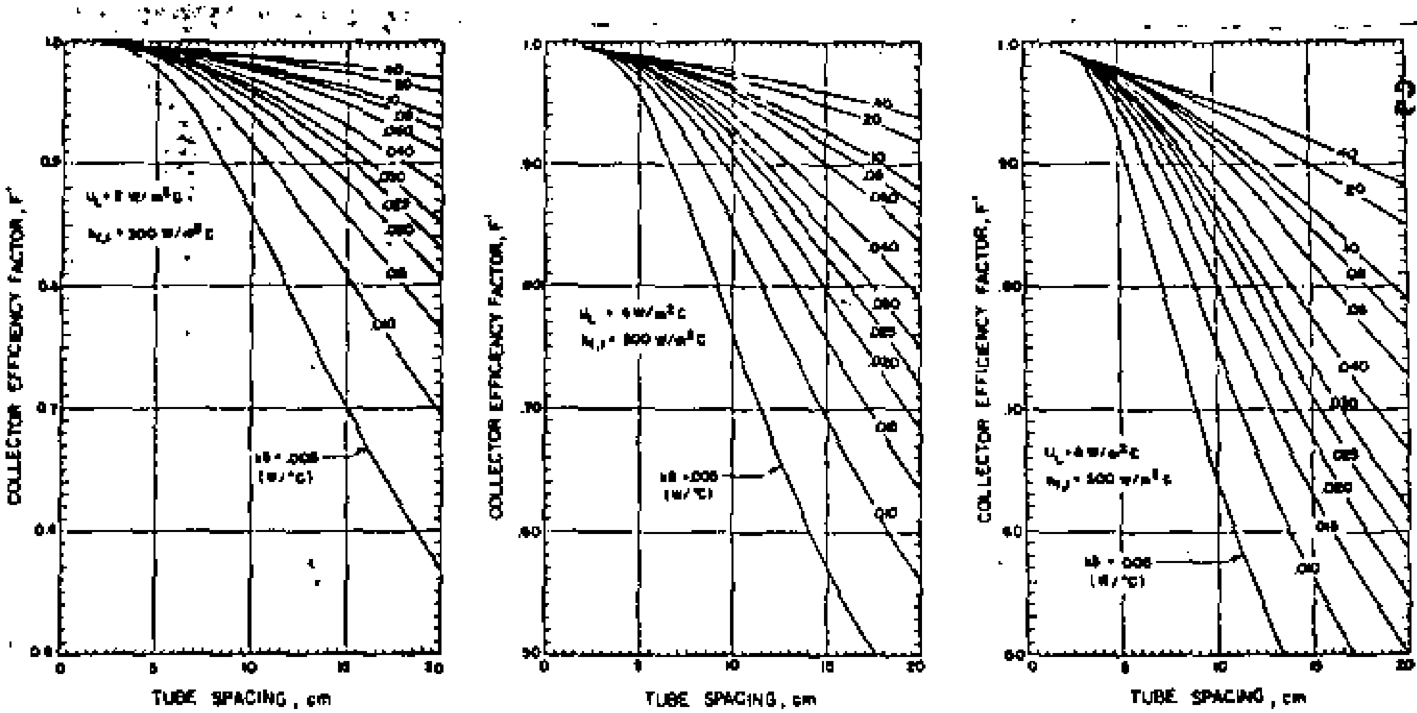


Figure .. *a,b,c* Collector efficiency factor *F'* versus tube spacing for 2 cm diameter tubes for various conditions.

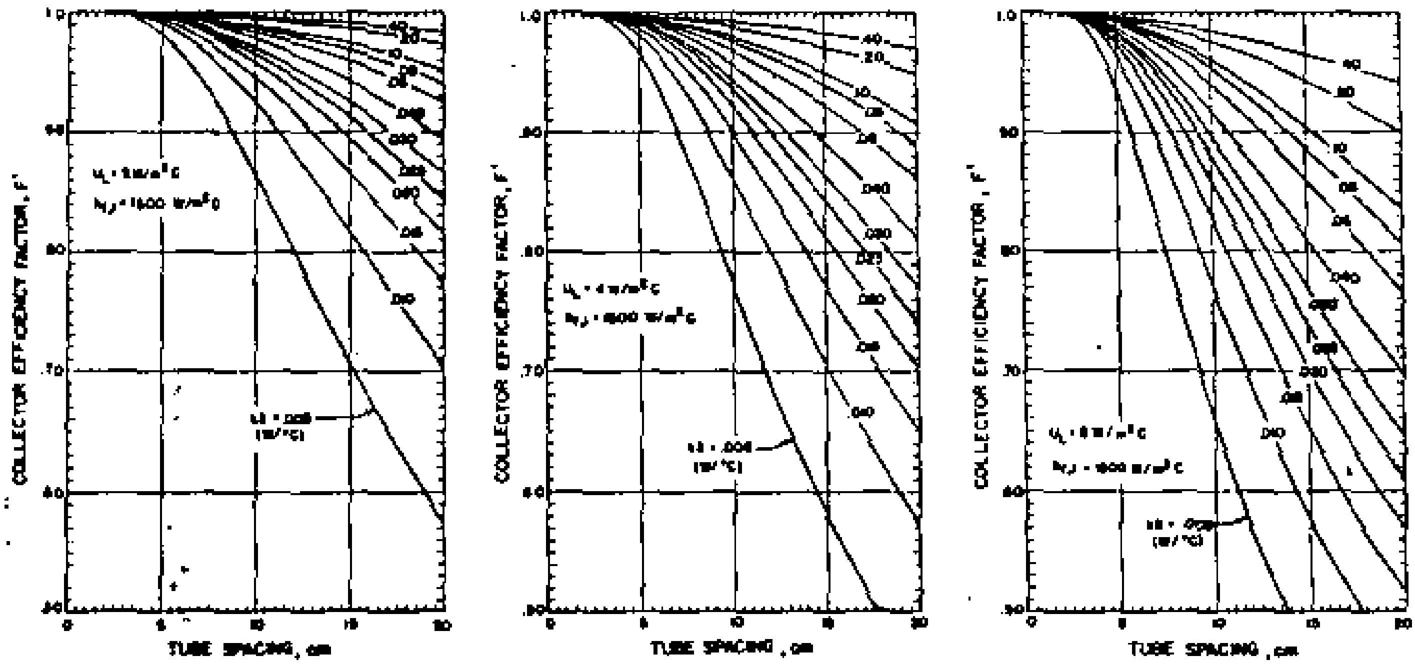
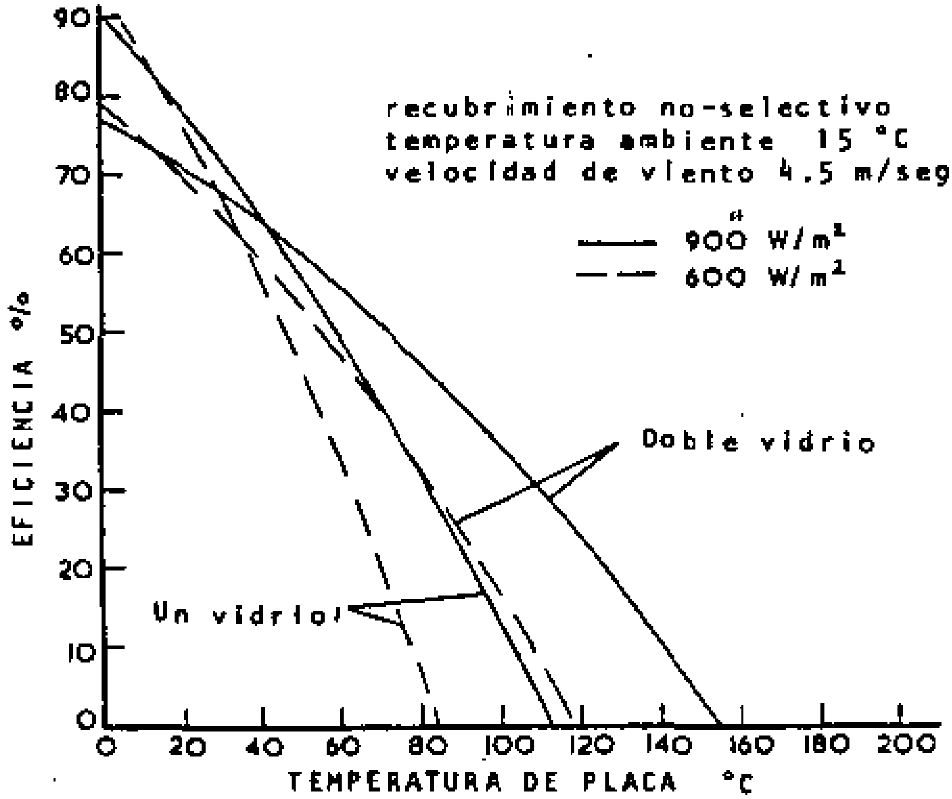


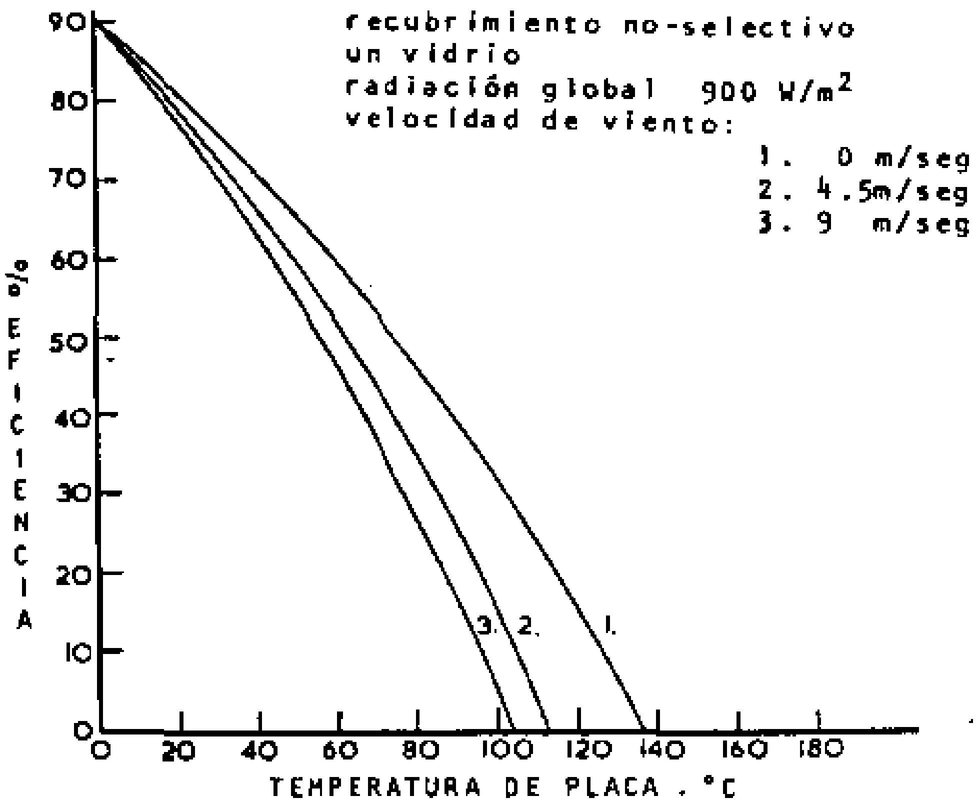
Figure . *d,e,f* Collector efficiency factor *F'* versus tube spacing for 2 cm diameter tubes for various conditions.

Table Plate efficiencies F'

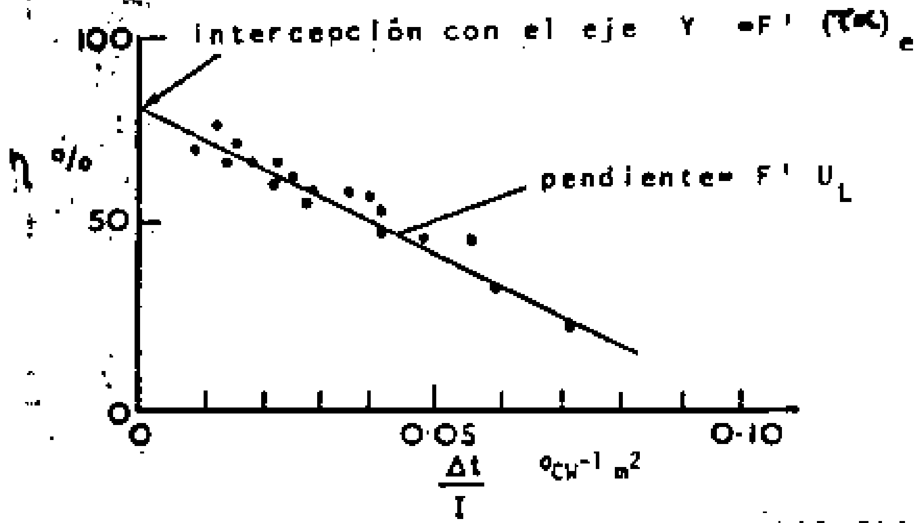
plate material and thickness	(mm)	tube spacing (mm) 75	100	125	138	160	175
copper	0·25	94·5	92	89	87	85·5	80·5
	0·35	95	92·5	90	88	87	82·5
	0·45	95·5	93	91	89	88	85
	0·55	96	93·5	91·5	90	89	86·5
	0·70	96	93·5	92	91	90	87·5
aluminium	0·60	94·5	92	88·5	87	86	82·5
	0·75	95·5	93	90·5	89	88	85
	1·00	95·5	93·5	91·5	90	89	87
steel	0·50	89	82·5	75	71·5	68	62·5
	0·75	92	87	80·5	77	74	68·5
	1·00	93	88·5	83·5	81	77·5	72·5
	1·50	95	89	84	81	79·5	74·5



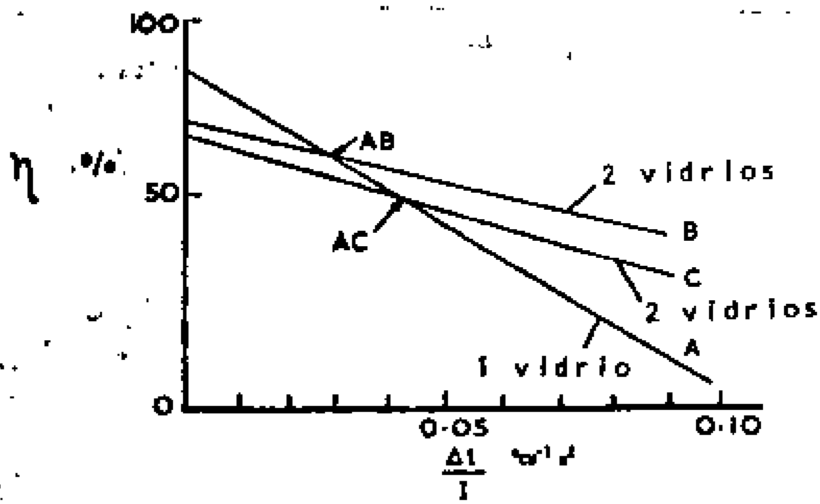
CURVAS DE EFICIENCIA PARA DOS COLECTORES SOLARES OPERANDO A DIFERENTES NIVELES DE INSOLACION



EFECTO DE LA VELOCIDAD DE VIENTO SOBRE LA EFICIENCIA TERMICA DEL COLECTOR



CURVA DE EFICIENCIA DE UN COLECTOR SOLAR PLANO OBTENIDA BAJO EL METODO DE PRUEBA NBS



CURVAS DE EFICIENCIA PARA TRES COLECTORES SOLARES OBTENIDAS BAJO EL METODO DE PRUEBA NBS

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