FACULTAD DE INGENIERÍA UNAM
DIVISIÓN DE EDUCACIÓN CONTINUA

CURSOS ABIERTOS

INSTALACIONES DE GAS NATURAL

CLAVE CA- 231

TEMA

TERMODINÁMICA DE LOS GASES

DEL 26 AL 30 DE ABRIL

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PALACIO DE MINERÍA
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Programa del Curso: Instalaciones De Aprovechamiento De Gas Natural

Del 26 al 30 de abril de 2004

Tema	Día y hora
1. Termodinámica Aplicada Al Gas Natural	Duración: 4 horas Lunes 26 de abril de 2004 de 17 a 21 horas
2. Reglamentación y Normalización: a) Reglamento de Gas natural, b) Normas Nacionales Aplicadas Al Gas Natural	Duración: 4 horas Martes 27 de abril de 2004 de 17 a 21 horas
3. Diseño De Instalaciones De Aprovechamiento De Gas Natural: a) Residenciales. b) Industriales.	Duración: 6 horas Miércoles 28 de abril de 2004 de 17 a 21 horas y Jueves 29 de abril de 17 a 19 horas
4. Mantenimiento De Instalaciones de Aprovechamiento De Gas Natural.	Duración: 2 horas Jueves 29 de abril de 2004 de 19 a 21 horas
5. Pruebas En Instalaciones De Aprovechamiento De Gas Natural: a) De hermeticidad (hidrostáticas y neumáticas). b) No destructivas.	Duración: 4 horas 30 de abril de 2004 de 17 a 21 horas

División de Educación Continua de la facultad de Ingeniería
Universidad Autónoma de México.
En colaboración con el Colegio de Ingenieros Mecánicos y Electricistas (CIME)
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2.6 • ECUACIÓN DE ESTADO DE GAS IDEAL

Las tablas de propiedades proporcionan información muy exacta, pero son voluminosas y vulnerables a los errores tipográficos. Un enfoque más práctico y deseable es tener algunas relaciones simples entre las propiedades, que sean suficientemente generales y precisas.

Cualquier ecuación que relacione la presión, la temperatura y el volumen específicos de una sustancia se denomina ecuación de estado. Las relaciones de propiedades que comprenden otras propiedades de una sustancia en estados de equilibrio, también se conocen como **ecuaciones de estado**. Hay varias ecuaciones de estado, algunas sencillas y otras muy complejas. La ecuación de estado más sencilla y conocida para sustancias en la fase gaseosa es la ecuación de estado de gas ideal. Esta ecuación predice el comportamiento P-v-T de un gas con bastante exactitud, dentro de cierta región elegida adecuadamente.

Las palabras *gas* y *vapor* a menudo se utilizan como sinónimos. La fase de vapor de una sustancia suele considerarse como un *gas* cuando su temperatura es más alta que la temperatura crítica. El *vapor* implica un gas que no se encuentra muy alejado del estado de condensación.

En 1662 el inglés Robert Boyle observó durante sus experimentos con una cámara de vacío que la presión de los gases es inversamente proporcional a su volumen. En 1802, J. Charles y J. Gay-Lussac, determinaron de modo experimental que a bajas presiones el volumen de un gas es proporcional a su temperatura. Esto es,

$$P = R\left(\frac{T}{v}\right)$$

o

$$Pv = RT \tag{2.9}$$

donde la constante de proporcionalidad, R, se denomina la **constante de gas**. La ecuación 2.9 es la **ecuación de estado de gas ideal**, o sencillamente la **relación de**

gas ideal, un gas que obedece esta relación recibe el nombre de **gas ideal**. En esta ecuación, P es la presión absoluta, T es la temperatura absoluta y v es el volumen específico.

La constante de gas R es diferente para cada gas (figura 2.45) y se determina de

$$[illegible] \qquad (2.10)$$

donde R_u es la **constante universal de gas** y M es la masa molar (llamada también *peso molecular*) del gas. La constante R_u es la misma para todas las sustancias y su valor es

$$R_u = \begin{cases} 8.314 \text{ kJ/kmol}\cdot\text{K} \\ 8.314 \text{ kPa}\cdot\text{m}^3\text{/kmol}\cdot\text{K} \\ 0.08314 \text{ bar}\cdot\text{m}^3\text{/kmol}\cdot\text{K} \\ 1.986 \text{ Btu/lbmol}\cdot\text{R} \\ 10.73 \text{ psia}\cdot\text{ft}^3\text{/lbmol}\cdot\text{R} \\ 1\,545 \text{ ft}\cdot\text{lbf/lbmol}\cdot\text{R} \end{cases} \qquad (2.11)$$

La **masa molar** M se define como *la masa de un mol* (llamada también un *gramo mol*, abreviado gmol) *de una sustancia en gramos*, o, *la masa de un kmol* (llamada también un *kilogramo-mol*, abreviado kgmol) *en kilogramos*. En unidades inglesas es la masa de 1 lbmol en lbm. Advierta que la masa molar de una sustancia tiene el mismo valor numérico en ambos sistemas de unidades, por la forma en que se define. Cuando se dice que la masa molar del nitrógeno es 28, ello significa que la masa de un kmol de nitrógeno es 28 kg, o que la masa de 1 lbmol de nitrógeno es 28 lbm. Esto es, M = 28 kg/kgmol = 28 lbm/lbmol. La masa de un sistema es igual al producto de su masa molar M y el número de moles N

$$[illegible] \qquad (2.12)$$

Los valores de R y de M para varias sustancias se presentan en la tabla A.1.

La ecuación de estado de gas ideal se escribe de varias maneras diferentes

$$V = mv \longrightarrow PV = mRT \qquad (2.13)$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_uT \qquad (2.14)$$

$$V = N\bar{v} \longrightarrow P\bar{v} = R_uT \qquad (2.15)$$

donde $\bar{v}$ es el volumen específico molar, esto es, el volumen por unidad de mol (en m³/kmol o ft³/lbmol). En este texto un *guión* arriba de una propiedad denotará valores *basados en unidad de mol* (figura 2.46).

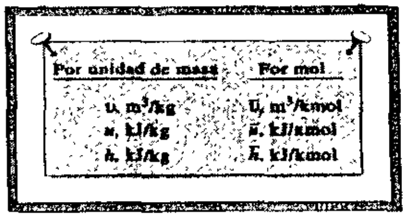
Escribiendo la ecuación 2.13 dos veces para una masa fija y simplificando, las propiedades de un gas ideal en dos estados diferentes se relacionan entre sí por medio de

$$[illegible] \qquad (2.16)$$

Un gas ideal es una sustancia *imaginaria* que obedece a la relación $Pv = RT$ (figura 2.47). Se ha observado experimentalmente que la relación de gas ideal se aproxima mucho al comportamiento P-v-T de los gases reales a bajas densidades. A bajas presiones y altas temperaturas la densidad de un gas disminuye y éste se comporta como gas ideal en estas condiciones. Lo que constituye baja presión y alta temperatura se explica en la siguiente sección.

Sustancia	R, kJ/kg·K
Aire	0.2870
Helio	2.0769
Argón	0.2081
Nitrógeno	0.2968

FIGURA 2.45
Diferentes sustancias tienen diferentes constantes de gas.



Por unidad de masa	Por mol
v, m³/kg	$\bar{v}$, m³/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

FIGURA 2.46
Las propiedades por mol se denotan con un guión en la parte superior.

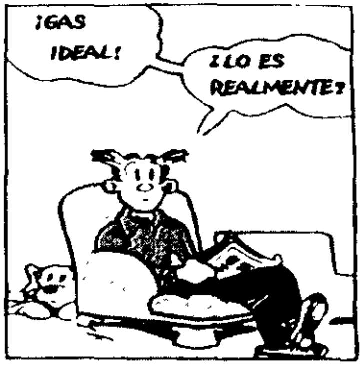


FIGURA 2.47
La relación de gas ideal a menudo no es aplicable a los gases reales, por ello debe tenerse cuidado cuando se use.

En el rango de interés práctico, muchos gases familiares como el aire, nitrógeno, oxígeno, hidrógeno, helio, argón, neón, kriptón e incluso gases más pesados como el dióxido de carbono, pueden tratarse como gases ideales con un error despreciable (con frecuencia menor de 1%). Sin embargo, los gases densos, como el vapor de agua en las centrales eléctricas y el vapor de refrigerante en los refrigeradores, no deben considerarse como gases ideales. Deben utilizarse las tablas de propiedades para estas sustancias.

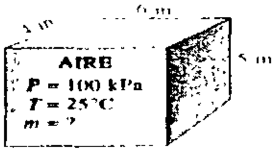


FIGURA 2.48
Dibujo para el ejemplo 2.10

EJEMPLO 2.10 **Masa del aire contenido en un espacio cerrado**

Determine la masa del aire en una habitación cuyas dimensiones son 4 m × 5 m × 6 m a 100 kPa y 25°C.

SOLUCIÓN **Determine la masa de aire contenida en un espacio cerrado.**
Análisis **En la figura 2.48 se presenta un dibujo del cuarto. El aire en las condiciones especificadas puede tratarse como un gas ideal. En la tabla A.1 la constante de gas del aire es R = 0.287 kPa · m³/kg · K, y la temperatura absoluta es T = 25°C + 273 = 298 K. El volumen del cuarto es**

$$V = (4\ \mathrm{m})(5\ \mathrm{m})(6\ \mathrm{m}) = 120\ \mathrm{m}^3$$

La masa del aire en un espacio cerrado se determina a partir de la relación de gas ideal siguiente

$$m = \frac{PV}{RT} = \frac{(100\ \mathrm{kPa})(120\ \mathrm{m}^3)}{(0.287\ \mathrm{kPa\cdot m^3/kg\cdot K})(298\ \mathrm{K})} = \mathbf{140.3\ kg}$$

¿Es el vapor de agua un gas ideal?

Esta pregunta no se contesta con un simple sí o no. El error involucrado al considerar al vapor de agua como un gas ideal se calcula y grafica en la figura 2.49. Es claro, a partir de esta figura, que a presiones menores de 10 kPa, el vapor de agua se puede considerar un gas ideal, independientemente de su temperatura, con un error despreciable (menor que 0.1%). A presiones superiores, la suposición de gas ideal produce errores inaceptables, en particular en la vecindad del punto crítico y de la línea de vapor saturado (arriba del 100%). Por tanto, en aplicaciones para acondicionamiento de aire, el vapor de agua en el aire puede tratarse como un gas en esencia ideal casi sin error, puesto que la presión del vapor de agua es muy baja. En contraste, en las aplicaciones del vapor en centrales eléctricas, las presiones implicadas son muy altas, de modo que no deben usarse las relaciones de gas ideal.

2.7 • FACTOR DE COMPRESIBILIDAD, UNA MEDIDA DE LA DESVIACIÓN DEL COMPORTAMIENTO DE GAS IDEAL

La ecuación de gas ideal es muy sencilla y por ello su uso es conveniente. Pero, como ilustra la figura 2.49, los gases se desvían del comportamiento de gas ideal, de manera significativa, en estados cercanos a la región de saturación y al punto crítico. Es posible explicar con exactitud esta desviación del comportamiento de gas ideal a una temperatura y presión determinadas mediante la introducción de un factor de corrección llamado **factor de compresibilidad Z**, definido como

$$Z = \frac{Pv}{RT} \qquad (2.17)$$

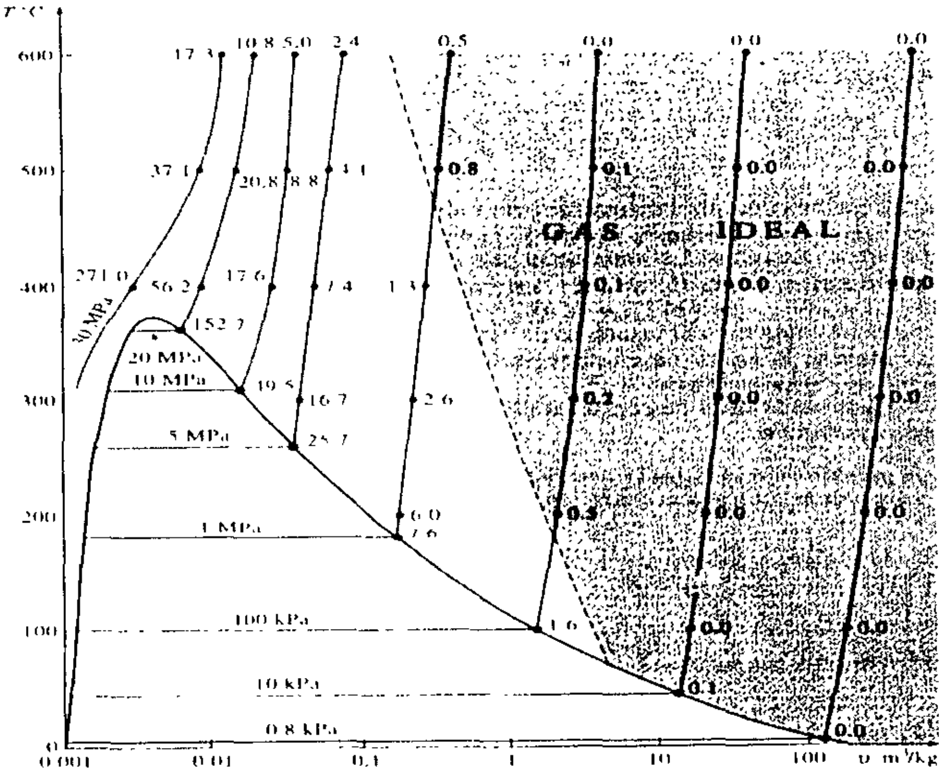


FIGURA 2.49
Porcentaje de error ($[|v_{tabla} - v_{ideal}|/v_{tabla}] \times 100$) implicado al suponer que el vapor es un gas ideal, y región donde el vapor puede tratarse como un gas ideal con un error menor de 1%

o

$$Pv = ZRT \tag{2.18}$$

También se expresa como

$$Z = \frac{v_{real}}{v_{ideal}} \tag{2.19}$$

donde $v_{ideal} = RT/P$. Es evidente que $Z = 1$ para gases ideales. Para gases reales Z puede ser mayor o menor que la unidad (figura 2.50). Cuanto más lejos se encuentra Z de la unidad, mayor es la desviación del gas del comportamiento de gas ideal.

Se ha dicho repetidas veces que los gases siguen la ecuación de gas ideal con gran precisión a bajas presiones y altas temperaturas. ¿Pero qué es exactamente lo que constituye baja presión y alta temperatura? ¿Es −100°C una temperatura baja? Es definitivo que lo es para muchas sustancias, pero no para el aire. El aire (o el nitrógeno) puede tratarse como gas ideal a esta temperatura y a la presión atmosférica con un error menor de 1% debido a que el nitrógeno se encuentra bastante arriba de su temperatura crítica (−147°C) y lejos de la región de saturación. A esta temperatura y presión, sin embargo, la mayor parte de las sustancias existirían en la fase sólida. Por consiguiente, la presión o temperatura de una sustancia es alta o baja en relación con su temperatura o presión crítica.

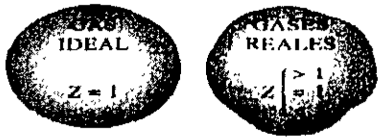


FIGURA 2.50
El factor de compresibilidad es la unidad para los gases ideales.

Los gases se comportan de manera diferente a una temperatura y presión determinadas, pero se comportan de manera muy parecida a temperaturas y presiones normalizadas respecto de sus temperaturas y presiones críticas. La normalización se efectúa como

$$P_R = \frac{P}{P_{cr}} \quad \text{y} \quad T_R = \frac{T}{T_{cr}} \tag{2.20}$$

Aquí P_R recibe el nombre de **presión reducida** y T_R de **temperatura reducida**. El factor Z para todos los gases es aproximadamente el mismo a la misma presión y temperatura reducidas. Lo anterior recibe el nombre de **principio de estados correspondientes**. En la figura 2.51 los valores de Z determinados experimentalmente se grafican para el caso de P_R y T_R para varios gases. Los gases parecen obedecer bastante bien al principio de estados correspondientes. Al ajustar los datos se obtiene la **carta de compresibilidad generalizada**, que puede utilizarse para todos los gases (figura A.30).

A partir de la carta de compresibilidad generalizada son posibles las siguientes observaciones:

1. A presiones muy bajas ($P_R \ll 1$) los gases se comportan como un gas ideal sin considerar la temperatura (figura 2.52).

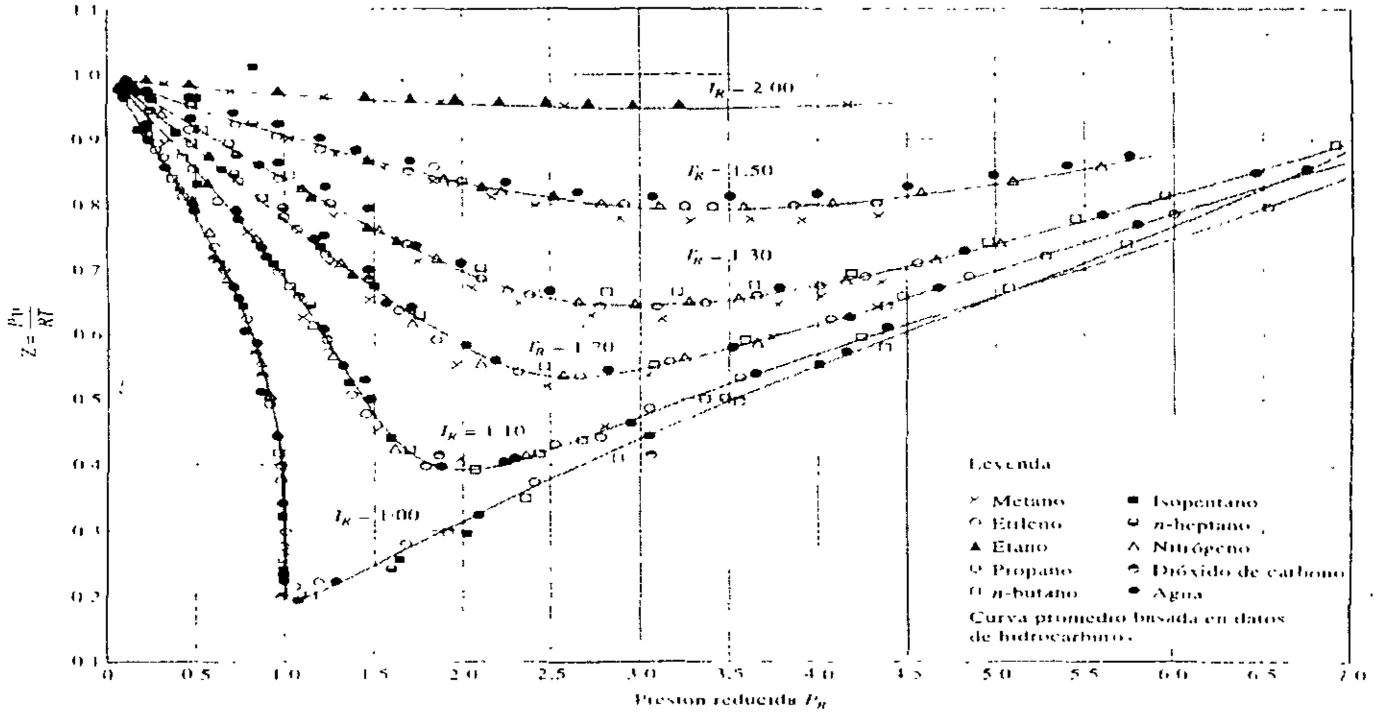


FIGURA 2.51

Comparación de los factores Z para diferentes gases.

(Fuente: Gouq-Jen Su, "Modified Law of Corresponding States", en Ind. Eng. Chem. (ed. internacional) 38 (1946), p. 803.)

2. A elevadas temperaturas ($T_R > 2$), el comportamiento de gas ideal puede suponerse con buena precisión sin importar la presión (excepto cuando $P_R \gg 1$).
3. La desviación de un gas del comportamiento de gas ideal es mayor cerca del punto crítico (figura 2-53).

EJEMPLO 2.11 El uso de cartas generalizadas

Determine el volumen específico del refrigerante 134a a 1 MPa y 50°C, utilizando: *a)* la ecuación de estado de gas ideal y *b)* la carta de compresibilidad generalizada. Comparar los valores obtenidos con el valor real de 0.02171 m³/kg y determinar el error implicado en cada caso.

SOLUCIÓN Se debe determinar el volumen específico del refrigerante 134a suponiendo un comportamiento tanto de gas ideal como de gas no ideal.

Análisis La constante de gas, la presión crítica y la temperatura crítica del refrigerante 134a se determinan a partir de la tabla A.1:

$$\begin{aligned} R &= 0.0815\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K} \\ P_{cr} &= 4.067\ \text{MPa} \\ T_{cr} &= 374.3\ \text{K} \end{aligned}$$

a) El volumen específico del refrigerante 134a bajo la suposición de gas ideal es

$$v = \frac{RT}{P} = \frac{(0.0815\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(323\ \text{K})}{1\,000\ \text{kPa}} = \mathbf{0.02632\ m^3/kg}$$

Por lo tanto, considerando el vapor del refrigerante 134a como un gas ideal se obtendría un error de (0.02632 − 0.02171)/0.02171 = **0.212** o 21.2% para este caso.

b) Para determinar el factor de corrección Z a partir de la carta de compresibilidad es necesario calcular la presión y temperatura reducidas:

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} = \frac{1\ \text{MPa}}{4.067\ \text{MPa}} = 0.246 \\ T_R &= \frac{T}{T_{cr}} = \frac{323\ \text{K}}{374.3\ \text{K}} = 0.863 \end{aligned}\right\} \quad Z = 0.84$$

Entonces

$$v = Zv_{\text{ideal}} = (0.84)(0.02632\ \text{m}^3/\text{kg}) = \mathbf{0.02211\ m^3/kg}$$

Discusión El error en este resultado es menor de 2%. Por tanto, ante la ausencia de datos tabulados, la carta de compresibilidad generalizada puede emplearse con confianza.

Incluso cuando P y v, o T y v, se dan en lugar de P y T, la carta de compresibilidad generalizada puede utilizarse para determinar la tercera propiedad, pero implicaría el tedioso método de ensayo y error. En consecuencia, resulta conveniente definir una propiedad reducida más, llamada el **volumen específico pseudorreducido** v_R como

[illegible] (2-21)

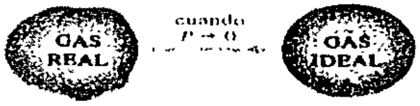


FIGURA 2.52
A presiones muy bajas todos los gases se acercan al comportamiento de gas ideal (sin importar su temperatura)

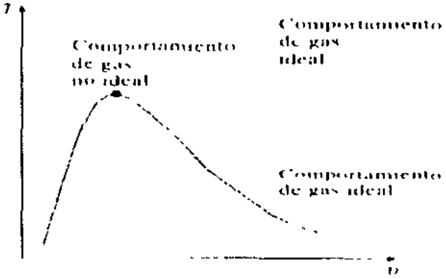


FIGURA 2.53
Los gases se desvían del comportamiento de gas ideal en la cercanía del punto crítico

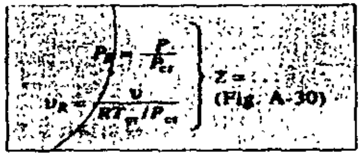


FIGURA 2.54
El factor de compresibilidad también puede determinarse a partir del conocimiento de P_R y v_R.

Observe que v_R se define de manera diferente que P_R y T_R. Se relaciona con T_{cr} y P_{cr} en vez de v_{cr}. También se añaden líneas de v_R constante a las cartas de compresibilidad, y esto permite determinar T o P sin tener que recurrir a las tediosas iteraciones (figura 2.54).

EJEMPLO 2.12 **Uso de las cartas generalizadas para determinar la presión**

Determine la presión de vapor de agua a 600°F y 0.514 ft³/lbm, empleando: *a)* las tablas de vapor, *b)* la ecuación de gas ideal y *c)* la carta de compresibilidad generalizada.

SOLUCIÓN Se determinará la presión del vapor de agua por tres maneras diferentes.

Análisis En la figura 2.55 se presenta un dibujo del sistema. La constante de gas, la presión crítica y la temperatura crítica del vapor se obtienen de la tabla A.1E:

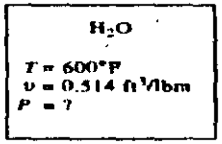


FIGURA 2.55
Dibujo para el ejemplo 2.12.

$$R = 0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}$$
$$P_{cr} = 3\,204 \text{ psia}$$
$$T_{cr} = 1\,165.3 \text{ R}$$

a) De la tabla A.6E se obtiene que la presión del vapor en el estado especificado es igual a

$$\left.\begin{array}{l} v = 0.514 \text{ ft}^3/\text{lbm} \\ T = 600°\text{F} \end{array}\right\} \quad P = \mathbf{1\,000 \text{ psia}}$$

Éste es el valor determinado experimentalmente y, por ello, el más preciso.

b) A partir de la relación de gas ideal se determina que la presión del vapor bajo la suposición de gas ideal es

$$P = \frac{RT}{v} = \frac{(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1\,060 \text{ R})}{0.514 \text{ ft}^3/\text{lbm}} = \mathbf{1\,228 \text{ psia}}$$

Por tanto, tratar al vapor como un gas ideal resultaría en un error de (1 228 − 1 000)/1 000 = 0.228, o 22.8% en este caso.

c) Para determinar el factor de corrección Z a partir de la carta de compresibilidad (figura A.30), primero se debe calcular el volumen específico pseudorreducido y la temperatura reducida:

$$\left.\begin{array}{l} v_R = \dfrac{v_{\text{actual}}}{RT_{cr}/P_{cr}} = \dfrac{(0.514 \text{ ft}^3/\text{lbm})(3\,204 \text{ psia})}{(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1\,165.3 \text{ R})} = 2.373 \\ T_R = \dfrac{T}{T_{cr}} = \dfrac{1\,060 \text{ R}}{1\,165.3 \text{ R}} = 0.91 \end{array}\right\} \quad P_R = 0.33$$

Por tanto,

$$P = P_R P_{cr} = (0.33)(3\,204 \text{ psia}) = \mathbf{1\,057 \text{ psia}}$$

Discusión El empleo de la carta de compresibilidad reduce el error de 22.8 a 5.7%, que es aceptable para la mayor parte de los propósitos de la ingeniería (figura 2.56). Un diagrama más grande, desde luego, brindaría mejor resolución y reduciría los errores de lectura. Advierta que no fue necesario determinar Z en este problema puesto que P_R se lee directamente del diagrama.

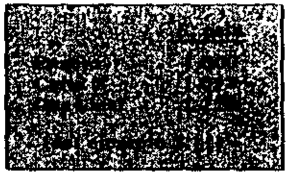


FIGURA 2.56
Los resultados obtenidos al utilizar la carta de compresibilidad suelen estar dentro de un pequeño porcentaje de los valores determinados experimentalmente.

TABLA A.1

Masa molar, constante de gas y propiedades del punto-crítico

				Propiedades del punto crítico		
Sustancia	Fórmula	Masa molar, *M* kg/kmol	Constante de gas, *R* kJ/kg · K*	Temperatura, K	Presión, MPa	Volumen, m^3/kmol
Agua	H_2O	18.015	0.4615	647.3	22.09	0.0568
Aire	—	28.97	0.2870	132.5	3.77	0.0883
Alcohol etílico	C_2H_5OH	46.07	0.1805	516	6.38	0.1673
Alcohol metílico	CH_3OH	32.042	0.2595	513.2	7.95	0.1180
Amoniaco	NH_3	17.03	0.4882	405.5	11.28	0.0724
Argón	Ar	39.948	0.2081	151	4.86	0.0749
Benceno	C_6H_6	78.115	0.1064	562	4.92	0.2603
Bromo	Br_2	159.808	0.0520	584	10.34	0.1355
Cloro	Cl_2	70.906	0.1173	417	7.71	0.1242
Cloroformo	$CHCl_3$	119.38	0.06964	536.6	5.47	0.2403
Cloruro metílico	CH_3Cl	50.488	0.1647	416.3	6.68	0.1430
Diclorodifluorometano (R-12)	CCl_2F_2	120.91	0.06876	384.7	4.01	0.2179
Diclorofluorometano (R-21)	$CHCl_2F$	102.92	0.08078	451.7	5.17	0.1973
Dióxido de carbono	CO_2	44.01	0.1889	304.2	7.39	0.0943
Dióxido de sulfuro	SO_2	64.063	0.1298	430.7	7.88	0.1217
Etano	C_2H_6	30.070	0.2765	305.5	4.48	0.1480
Etileno	C_2H_4	28.054	0.2964	282.4	5.12	0.1242
Helio	He	4.003	2.0769	5.3	0.23	0.0578
Hidrógeno (normal)	H_2	2.016	4.1240	33.3	1.30	0.0649
Kriptón	Kr	83.80	0.09921	209.4	5.50	0.0924
Metano	CH_4	16.043	0.5182	191.1	4.64	0.0993
Monóxido de carbono	CO	28.011	0.2968	133	3.50	0.0930
n-Butano	C_4H_{10}	58.124	0.1430	425.2	3.80	0.2547
Neón	Ne	20.183	0.4119	44.5	2.73	0.0417
n-Hexano	C_6H_{14}	86.179	0.09647	507.9	3.03	0.3677
Nitrógeno	N_2	28.013	0.2968	126.2	3.39	0.0899
Óxido nitroso	N_2O	44.013	0.1889	309.7	7.27	0.0961
Oxígeno	O_2	31.999	0.2598	154.8	5.08	0.0780
Propano	C_3H_8	44.097	0.1885	370	4.26	0.1998
Propileno	C_3H_6	42.081	0.1976	365	4.62	0.1810
Tetracloruro de carbono	CCl_4	153.82	0.05405	556.4	4.56	0.2759
Tetrafluoroetano (R-134a)	CF_3CH_2F	102.03	0.08149	374.3	4.067	0.1847
Triclorofluorometano (R-11)	CCl_3F	137.37	0.06052	471.2	4.38	0.2478
Xenón	Xe	131.30	0.06332	289.8	5.88	0.1186

*La unidad en kJ/(kg · K) es equivalente a kPa · m^3/(kg · K). La constante de gas se calcula de $R = R_u/M$, donde R_u = 8.314 kJ/(kmol · K) y *M* es la masa molar.

Fuente. K. A. Kobe y R. F. Lynn, *Chemical Review* 52 (1953), pp. 117-236, y ASHRAE [Sociedad Americana de Ingenieros de Calefacción, Refrigeración y Acondicionamiento de Aire], *Handbook of Fundamentals* (Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., 1993), pp.

TABLA A.2

Calores específicos de gas ideal de varios gases comunes

a) A 300 K

Gas	Fórmula	Constante de gas, *R* kJ/kg · K	C_p kJ/kg · K	C_v kJ/kg · K	*k*
Aire	—	0.2870	1.005	0.718	1.400
Argón	Ar	0.2081	0.5203	0.3122	1.667
Butano	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Dióxido de carbono	CO_2	0.1889	0.846	0.657	1.289
Etano	C_2H_6	0.2765	1.7662	1.4897	1.186
Etileno	C_2H_4	0.2964	1.5482	1.2518	1.237
Helio	He	2.0769	5.1926	3.1156	1.667
Hidrógeno	H_2	4.1240	14.307	10.183	1.405
Metano	CH_4	0.5182	2.2537	1.7354	1.299
Monóxido de carbono	CO	0.2968	1.040	0.744	1.400
Neón	Ne	0.4119	1.0299	0.6179	1.667
Nitrógeno	N_2	0.2968	1.039	0.743	1.400
Octano	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxígeno	O_2	0.2598	0.918	0.658	1.395
Propano	C_3H_8	0.1885	1.6794	1.4909	1.126
Vapor	H_2O	0.4615	1.8723	1.4108	1.327

Nota. La unidad kJ/(kg · K) es equivalente a kJ/kg · °C

Fuente: Gordon J. Van Wylen y Richard E. Sonntag, *Fundamentals of Classical Thermodynamics*, versión inglés/SI, 3a. ed. (Nueva York: John Wiley & Sons, 1986), p. 687, tabla A.8SI.

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ABRIL DE 2004

Section 16

Physical Properties

Introduction

This section contains a number of charts, correlations, and discussions concerning the physical properties of hydrocarbons and related compounds.

Fig. 16-1 is a table of physical constants of a number of hydrocarbon compounds, other common chemicals, and some common gases. Fig. 16-2 is an abridgement of GPA Publication 2145, an official industry standard that is widely referenced in contracts for custody transfer and other commercial purposes.

These two tables are followed by correlations on compressibility of gases. Then additional correlations follow on hydrocarbon fluid densities, boiling points, ASTM distillation, critical properties, acentric factor, vapor pressures, viscosity, thermal conductivity, surface tension, and gross heating value of natural gases.

Compressibility of gases

PRESSURE-VOLUME-TEMPERATURE

In dealing with gases at low pressure, the ideal gas relationship has been, and is, a convenient and generally satisfactory tool. But when faced with measurement and calculations for gases under high pressure the use of the ideal gas relationship may lead to errors as great as 500%, as compared with 2 or 3% at atmospheric pressure.

Many equations of state which have been proposed for representing the pressure-volume-temperature relationship of gases are complicated and inconvenient in practical use. The compressibility factor is reasonably convenient and sufficiently accurate for many engineering requirements. It corresponds to a multiplying correction factor (Z) by which the volume computed from the ideal gas equation is converted to the correct actual volume.

Thus:

$$PV = ZNRT$$

Where:

P = pressure, kPa (abs)

V = volume, m^3

Z = compressibility factor

N = No. of moles, kmols

R = gas constant, 8.3145

T = absolute temperature, K = 273.15 + °C

The compressibility factor Z is a dimensionless factor independent of the extent or mass of the gas and determined by the character of the gas, the temperature, and pressure. Once Z is known or determined, the calculation of pressure-temperature-volume relationships may be made with as much ease at high pressure as at low pressure.

The equation to calculate gas density is

$$\rho_v = \frac{MP}{8.3145\,TZ}$$

Where:

ρ_v = gas density, kg/m^3

M = molecular mass, kg/kmol

Other symbols described above

Since molecular mass, pressure, and temperature are set by process considerations, it is necessary to determine compressibility factor Z to obtain gas density.

According to the theorem of corresponding states the deviation of any actual gas from the ideal gas law is the same for different gases when at the same corresponding state. The same corresponding states are found at the same fraction of the absolute critical temperature and pressure, which are known as the

Reduced temperature, $T_r = T/T_c$

Reduced pressure, $P_r = P/P_c$

Where:

T_c = absolute critical temperature

P_c = absolute critical pressure

T = absolute temperature at which the gas exists

P = the absolute pressure at which the gas exists

Any units of temperature or pressure may be used provided only that the same absolute units be used for T as for T_c and for P as P_c.

GASEOUS MIXTURES

Fig. 16-3 represents the compressibility factor as a function of pseudo reduced pressure and pseudo

FIG. 16-1

PHYSICAL CONSTANTS OF HYDROCARBONS(27)

	See Note No. →		1.	2.		3			
							Critical constants		
No.	Compound	Formula	Molecular mass	Boiling point, °C 101.3250 kPa (abs)	Vapor pressure, kPa (abs) 40 °C	Freezing point, °C 101.3250 kPa (abs)	Pressure, kPa (abs)	Temperature, K	Volume, m^3/kg
1	Methane	CH_4	16.043	-161.52(28)	(35 000.)	-182.47^{d}	4 604.	190.56	0.006 17
2	Ethane	C_2H_6	30.070	-88.58	(6 000.)	-182.80^{d}	4 880.	305.43	0.004 92
3	Propane	C_3H_8	44.097	-42.07	1 341.	-187.68^{d}	4 249.	369.82	0.004 60
4	*n*-Butane	C_4H_{10}	58.124	-0.49	377.	-138.36	3 797.	425 16	0.004 39
5	Isobutane	C_4H_{10}	58.124	-11.81	528.	-159.60	3 648.	408.13	0.004 52
6	*n*-Pentane	C_5H_{12}	72.151	36.06	115.66	-129.73	3 369.	469.6	0.004 21
7	Isopentane	C_5H_{12}	72.151	27.84	151.3	-159.90	3 381	460.39	0.004 24
8	Neopentane	C_5H_{12}	72.151	9.50	269.	-16.55	3 199	433.75	0.004 20
9	*n*-Hexane	C_6H_{14}	86.178	68.74	37.28	-95.32	3 012.	507 4	0.004 29
10	2-Methylpentane	C_6H_{14}	86.178	60.26	50.68	-153.66	3 010.	497.45	0.004 26
11	3-Methylpentane	C_6H_{14}	86.178	63.27	45.73	—	3 124.	504.4	0.004 26
12	Neohexane	C_6H_{14}	86.178	49.73	73.41	-99.870	3 081.	488.73	0.004 17
13	2,3-Dimethylbutane	C_6H_{14}	86.178	57.98	55.34	-128.54	3 127.	499.93	0.004 15
14	*n*-Heptane	C_7H_{16}	100.205	98.42	12.34	-90.582	2 736.	540.2	0.004 31
15	2-Methylhexane	C_7H_{16}	100.205	90.05	17.22	-118.27	2 734.	530.31	0.004 20
16	3-Methylhexane	C_7H_{16}	100.205	91.85	16.16	—	2 814.	535 19	0.004 03
17	3-Ethylpentane	C_7H_{16}	100.205	93.48	15.27	-118.60	2 891	540.57	0.004 15
18	2,2-Dimethylpentane	C_7H_{16}	100.205	79.19	26.32	-123.81	2 773.	520.44	0.004 15
19	2,4-Dimethylpentane	C_7H_{16}	100.205	80.49	24.84	-119.24	2 737.	519.73	0.004 17
20	3,3-Dimethylpentane	C_7H_{16}	100.205	86.06	20.93	-134.46	2 946.	536.34	0.004 13
21	Triptane	C_7H_{16}	100.205	80.88	25.40	-24.91	2 954.	531.11	0.003 97
22	*n*-Octane	C_8H_{18}	114.232	125.67	4.143	-56.76	2 486.	568.76	0.004 31
23	Diisobutyl	C_8H_{18}	114.232	109.11	8.417	-91.200	2 486.	549.99	0.004 22
24	Isooctane	C_8H_{18}	114.232	99.24	12.96	-107.38	2 568.	543.89	0.004 10
25	*n*-Nonane	C_9H_{20}	128.259	150.82	1.40	-53.49	2 288.	594.56	0.004 27
26	*n*-Decane	$C_{10}H_{22}$	142.286	174.16	0.4732	-29.64	2 099.	617.4	0.004 24
27	Cyclopentane	C_5H_{10}	70.135	49.25	73.97	-93.866	4 502.	511.6	0.003 71
28	Methylcyclopentane	C_6H_{12}	84.162	71.81	33.85	-142.46	3 785.	532.73	0.003 79
29	Cyclohexane	C_6H_{12}	84.162	80.73	24.63	6.554	4 074.	553.5	0.003 68
30	Methylcyclohexane	C_7H_{14}	98.189	100.93	12.213	-126.59	3 472.	572 12	0.003 75
31	Ethene (Ethylene)	C_2H_4	28.054	-103.77(29)	—	-169.15^{d}	5 041.	282.35	0.004 67
32	Propene (Propylene)	C_3H_6	42.081	-47.72	1 596.	-185.25^{d}	4 600.	364.85	0.004 30
33	1-Butene (Butylene)	C_4H_8	56.108	-6.23	451.9	-185.35^{d}	4 023.	419.53	0.004 28
34	*cis*-2-Butene	C_4H_8	56.108	3.72	337.6	-138.91	4 220.	435.58	0.004 17
35	*trans*-2-Butene	C_4H_8	56.108	0.88	365.8	-105.55	4 047.	428.63	0.004 24
36	Isobutene	C_4H_8	56.108	-6.91	452.3	-140.36	3 999.	417.90	0.004 26
37	1-Pentene	C_5H_{10}	70.135	29.96	141.65	-165.22	3 529	464.78	0.004 22
38	1,2-Butadiene	C_4H_6	54.092	10.85	269.	-136.19	(4 502.)	(444.)	(0.004 05)
39	1,3-Butadiene	C_4H_6	54.092	-4.41	434.	-108.91	4 330.	425.	0.004 09
40	Isoprene	C_5H_8	68.119	34.07	123.77	-145.95	(3 850.)	(484.)	(0.004 06)
41	Acetylene	C_2H_2	26.038	-84.88^{e}	—	-80.8^{d}	6 139.	308.33	0.004 34
42	Benzene	C_6H_6	78.114	80.09	24.38	5.533	4 898.	562.16	0.003 28
43	Toluene	C_7H_8	92.141	110.63	7.895	-94.991	4 106.	591.80	0.003 43
44	Ethylbenzene	C_8H_{10}	106.168	136.20	2.87	-94.975	3 609.	617.20	0.003 53
45	*o*-Xylene	C_8H_{10}	106 168	144.43	2.05	-25.18	3 734.	630.33	0.003 48
46	*m*-Xylene	C_8H_{10}	106.168	139.12	2.53	-47.87	3 536.	617.05	0.003 54
47	*p*-Xylene	C_8H_{10}	106.168	138.36	2.65	13.26	3 511.	616.23	0.003 56
48	Styrene	C_8H_8	104.152	145.14	1.85	-30.61	3 999.	647.6	0.003 38
49	Isopropylbenzene	C_9H_{12}	120.195	152.41	1.47	-96.036	3 209.	631.1	0.003 57
50	Methyl alcohol	CH_4O	32.042	64.54	35.43	-97.68	8 096.	512.64	0.003 68
51	Ethyl alcohol	C_2H_6O	46.069	78.29	17.70	-114.1	6 383	513.92	0.003 62
52	Carbon monoxide	CO	28.010	-191.49	—	-205.0^{d}	3 499.(33)	132.92(33)	0.003 32(33)
53	Carbon dioxide	CO_2	44.010	-78.51^{e}	—	-56.57^{d}	7 382.(33)	304.19(33)	0.002 14(33)
54	Hydrogen sulfide	H_2S	34.076	-60.31	2 881.	-85.53^{d}	9 005.	373.5	0.002 87
55	Sulfur dioxide	SO_2	64.059	-10.02	630.8	-75.48^{d}	7 884.	430.8	0.001 90
56	Ammonia	NH_3	17.031	-33.33(30)	1 513.	-77.74^{d}	11 280.	405.6	0.004 25
57	Air	$N_2 + O_2$	28.964	-194.2(2)	—	—	3 771.(2)	132.4(2)	0.003 23(3)
58	Hydrogen	H_2	2.016	-252.87^{v}	—	-259.2^{d}	1 297.	33.2	0.032 24
59	Oxygen	O_2	31.999	-182.962^{v}	—	-218.8^{d}	5 081.	154.7(33)	0.002 29
60	Nitrogen	N_2	28.013	-195.80(31)	—	-210.0^{d}	3 399.	126.1	0.003 22
61	Chlorine	Cl_2	70.906	-34.03	1 134.	-101.0^{d}	7 711	417	0.001 75
62	Water	H_2O	18.015	100.00^{v}	7.377	0.00	22 118.	647.3	0.003 18
63	Helium	He	4.003	-268.93(32)	—	—	227.5(32)	5.2(32)	0.014 36(32)
64	Hydrogen chloride	HCl	36.461	-85.00	6 304	-114.18^{d}	8 309.	324.7	0.002 22

FIG. 16-2

PHYSICAL CONSTANTS OF PARAFFIN HYDROCARBONS AND OTHER COMPONENTS OF NATURAL GAS

GPA Publication 2145 SI-80(27) International System (SI) Units

ABRIDGED — APPROVAL PENDING

Component	Notes	Methane	Ethane	Propane	Iso-Butane	*n*-Butane	Iso-Pentane	*n*-Pentane	*n*-Hexane	*n*-Heptane	*n*-Octane	*n*-Nonane	*n*-Decane
Molecular Weight	•	16.043	30.070	44.097	58.124	58 124	72 151	72.151	86 178	100.205	114.232	128.259	142.286
Boiling Point @ 101.3250 kPa (abs), K		111 63(28)	184 57	231.08	261.34	272.66	300 99	309.21	341 89	371.57	398.82	423.97	447.31
Freezing Point @ 101.3250 kPa (abs), K		90 68[d]	90.35[d]	85.47[d]	113.55	134 79	113.25	143 42	177 83	182 57	216.39	219.66	243.51
Vapor Pressure @ 313.15 K, kPa (abs)		(35 000)	(6000.)	1341	528	377.	151.3	115 66	37.28	12.34	4 143	1.40	0.4732
Density of Liquid @ 288.15 K & 101.3250 kPa (abs)													
Relative density (water = 1)	a,b	(0 3)[i]	0.3581[h]	0.5083[h]	0.5637[h]	0.5847[h]	0 6250	0.6316	0 6644	0 6886	0.7073	0 7224	0.7346
Absolute density, kg/m^3 (in vacuum)	•	(300)[i]	357.8[h,x]	507.8[h,x]	563 2[h]	584.2[h]	624 4	631 0	663.8	688.0	706 7	721.7	733.9
Apparent density, kg/m^3 (in air)	•,c	(300)[i]	356.6[h]	506.7[h]	562 1[h]	583.1[h]	623.3	629 9	662.7	686.9	705 6	720.6	732.8
Density of Gas @ 288.15 K & 101 3250 kPa (abs)													
Relative density (air = 1), ideal gas	•	0 5539	1.0382	1.5225	2.0068	2 0068	2 4911	2 4911	2 9753	3.4596	3.9439	4.4282	4.9125
Kilogram per cubic metre, kg/m^3, ideal gas	•	0.6784	1.2718	1.8650	2.4582	2 4582	3.0516	3.0516	3 6443	4.2373	4 8309	5.4259	6.0168
Volume @ 288 15 K & 101.3250 kPa (abs)													
Liquid, cm^3/mol	•	(50.)[i]	84 04[h]	86 84[h]	103.2[h]	99 49[h]	115 6	114 3	129 8	145 6	161 6	177.7	193.9
Ratio, gas/(liquid in vacuum)	•	(442.)[i]	281.3[h]	272.3[h]	229.1[h]	237 6[h]	204 6	206 8	182.1	162.4	146.3	133.0	122.0
Critical Conditions													
Temperature, K		190 55	305.43	369 82	408.13	425 16	460.39	469 6	507 4	540.2	568.76	594.56	617.4
Pressure, kPa (abs)		4604.	4880.	4249.	3648	3797.	3381.	3369.	3012	2736	2486.	2288.	2099.
Gross Calorific Value, Combustion @ 288 15 K & Constant Pressure													
Megajoule per kilogram, MJ/kg, liquid	•		51.586[h]	50.008[h]	49.044[h]	49.158[h]	48.579	48 667	48.344	48 104	47 919	47.783	47.670
Megajoule per kilogram, MJ/kg, ideal gas	•	55 563	51 920	50.387	49.396	49.540	48.931	49.041	48 722	48 482	48.290	48.137	48.043
Megajoule per cubic metre, MJ/m^3, ideal gas	•,p,t	37.694	66 032	93 972	121.426	121.779	149 319	149.654	177 556	205 431	233.286	261.189	289.066
Megajoule per cubic metre, MJ/m^3, liquid	•,t	—	18 458.[h]	25 394.[h]	27 621.[h]	28 718 [h]	30 333.	30 709.	32 091.	33 095.	33 865.	34 485.	34 985.
Volume air to burn one volume gas, ideal gas		9 54	16.70	23.86	31.02	31.02	38.18	38.18	45.34	52.50	59.66	66 81	73.97
Flammability Limits @ 310.93 K & 101.3250 kPa (abs)													
Lower, volume % in air		5.0	2 9	2 1	1.8	1.8	1.4	1.4	1 2	1 0	0 96	0.87[e]	0 78[e]
Upper, volume % in air		15 0	13.0	9.5	8.4	8.4	(8.3)	8.3	7 7	7 0	—	2.9	2.6
Heat of Vaporization @ 101 3250 kPa (abs)													
kJ/kg @ boiling point		509.86	489.36	425.73	366.40	385.26	342 20	357.22	334 81	316 33	301.26	288.82	276.06
Specific Heat @ 288.15 K & 101.3250 kPa (abs)													
C_p gas, kJ/(kg · K), ideal gas		2.204	1.706	1 625	1 616	1.652	1.600	1 622	1 613	1 606	1 601	1 598	1.595
C_v gas, kJ/(kg · K), ideal gas		1.686	1.429	1 436	1.473	1.509	1 485	1.507	1 517	1 523	1 528	1.533	1.537
$N = C_p/C_v$, ideal gas		1.307	1.194	1.132	1.097	1.095	1.077	1.076	1 063	1 054	1 048	1 042	1.038
C_p liquid, kJ/(kg · K)	•	—	3 807	2 476	2.366(41)	2.366(41)	2.239	2 292(41)	2 231	2.209	2.191	2.184	2.179

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NOTES

a Air saturated liquid.

b Absolute values from weights in vacuum.

c The apparent values from weight in air are shown for users' convenience and compliance with ASTM-IP Petroleum Measurement Tables. In the United States and Great Britain, all commercial weights are required by law to be weights in air. All other mass data are on an absolute mass (weight in vacuum) basis.

d At saturation pressure (triple point).

e Sublimation point.

f The + sign and number following signify the ASTM octane number corresponding to that of 2,2,4-trimethylpentane with the indicated number of cm^3 of TEL added per gal.

g Determined at 100°C.

h Saturation pressure and 15°C.

i Apparent value at 15°C.

j Average value from octane numbers of more than one sample.

k Relative density (specific gravity), 48.3°C/15°C (sublimation point; solid C_2H_4/liquid H_2O).

m Densities of liquid at the boiling point

n Heat of sublimation.

p See Note 10.

s Extrapolated to room temperature from higher temperature.

t Gross calorific values shown for ideal gas volumes are not direct conversions of each other using only the gas volume per liquid volume value shown herein. The values differ by the heat of vaporization to ideal gas at 288.15 K.

v Fixed points on the 1968 International Practical Temperature Scale (IPTS-68)

w Value for normal hydrogen (25% para, 75% ortho). The value for equilibrium mixture of para and ortho is −0.218; however in most correlations, 0 is used

x Densities at the boiling point in kg/m^3 for: Ethane, 546.4; propane, 581.0, propene, 608.8; hydrogen sulfide, 960.; sulfur dioxide, 1462; ammonia, 681.6; hydrogen chloride, 1192.

* Calculated values

() Estimated values.

† Values are estimated using 2nd virial coefficients.

1. Molecular mass (M) is based on the following atomic weights. C = 12.011; H = 1.008; O = 15.9995, N = 14.0067, S = 32.06; Cl = 35.453

2. Boiling point—the temperature at equilibrium between the liquid and vapor phases at 101.3250 kPa (abs).

3. Freezing point—the temperature at equilibrium between the crystalline phase and the air saturated liquid at 101.3250 kPa (abs).

4. All values for the density and molar volume of liquids refer to the air saturated liquid at 101.3250 kPa(abs), except when the boiling point is less than 15°C. In such cases, the density and molar volume are given for the liquid in equilibrium with its vapor at 15°C.

   The relative density 15°C is defined as $\dfrac{\rho(\text{liquid, }15°C)}{\rho(\text{water, }15°C)}$

   The density of water at 15°C is taken as 999.10 kg/m^3.

   The apparent density in air, ρ(mass in air), is related to the density in vacuum, ρ(mass in vacuum) by

   $$\rho(\text{mass in air}) = [\rho(\text{mass in vacuum}) - \rho(\text{air})]\,\frac{\rho(\text{brass})}{\rho(\text{brass}) - \rho(\text{air})}$$

   "Mass in air" is the ratio of gravitational force on the object to the force of a standard brass weight, with both objects immersed in air.

   The density of air at 15°C and 101.3250 kPa(abs) is taken as 1.22 kg/m^3, and the density of brass as 8700 kg/m^3.

   The molar volume is related to density by

   $$V(m^3/kmol) = \frac{M}{\rho(kg/m^3)}$$

5. The temperature coefficient of density is related to the expansion coefficient by $\dfrac{1}{\rho}\left(\dfrac{\partial\rho}{\partial T}\right)_P = -\dfrac{1}{V}\left(\dfrac{\partial V}{\partial T}\right)_P$ in units of −1/°C

6. Pitzer acentric factor ω $$\omega = -\log_{10}\left(\frac{P}{P_c}\right) - 1 \quad \text{at } T_r = \frac{T}{T_c} = 0.7$$

   P is calculated at T from same vapor pressure equation used to calculate vapor pressure at 40°C in Fig. 16-1

7. The compressibility factor of the real gas, Z, is $$Z = \frac{PV}{RT}$$

8. The density of an ideal gas relative to air is M(gas)/M(air). The molecular mass of air is taken as 28.964.

   The specific volume of an ideal gas is $$V = \frac{RT}{MP}$$

   The volume ratio is V(ideal gas)/V(liquid in vacuum)

9. The specific heat capacity of the ideal gas was calculated from the constant pressure molar heat capacity reported in the references cited. These were calculated from the molecular partition functions. This quantity is independent of pressure. The specific heat capacities of liquids are derived from experimental measurements. For liquids boiling below 15°C, the values given are C_s/M, where C_s is the molar heat capacity of the liquid under saturated vapor pressure conditions.

10. The heating value is the negative of the enthalpy of combustion ($-\Delta H_c^\circ$) of a gas or liquid in its standard state at 15°C to give combustion products in their standard states, all at 101.3250 kPa (abs). For a compound where the formula is $C_nH_mO_hS_jN_k$, the combustion reaction is

    $$C_nH_mO_hS_jN_k(s, l, \text{or } g) + \left(n + \frac{m}{4} - \frac{h}{2} + j\right)O_2(g) \rightarrow nCO_2(g) + \frac{m}{2}H_2O(g \text{ or } l) + \frac{k}{2}N_2(g) + jSO_2(g)$$

    For the gross heating value, the water produced by the combustion is in the liquid form, and for the net heating value, the water is in the gas state

    The enthalpies of combustion at 15°C were calculated from those at 25°C, as reported in the references cited, by

    $\Delta H_c^\circ(15°C) = \Delta H_c^\circ(25°C) - 10\Delta C_p^\circ$, where

    $$\Delta C_p^\circ = nC_p^\circ(CO_2, g) + \frac{m}{2}C_p^\circ(H_2O, g \text{ or } l) + \frac{k}{2}C_p^\circ(N_2, g) + jC_p^\circ(SO_2, g) - C_p^\circ(C_nH_mO_hS_jN_k, s, l, \text{or } g) - \left(n + \frac{m}{4} - \frac{h}{2} + j\right)C_p^\circ(O_2, g) \text{ at } 25°C$$

    $\Delta H_c^\circ(MJ/m^3) = \Delta H_c^\circ(MJ/kg)/\rho(kg/m^3, \text{vacuum})$.

    The above equations apply to the combustion of an (initially) "bone-dry" gas. The heat of combustion of 1 m^3 of an ideal gas, saturated with water vapor, is

    $$\Delta H_c^\circ(g, sat)(MJ/m^3) = 0.98292\,\Delta H_c^\circ(g)(MJ/m^3)$$

    The vapor pressure of water at 15°C is 1.70 kPa (abs). The gross heat of combustion of 1 m^3 of gas, saturated with water vapor for which all of the water is condensed to liquid in the final products, is

    $$\Delta H_c^\circ(g, sat)(MJ/m^3) = 0.98292\,\Delta H_c^\circ(g)(MJ/m^3) - 0.0315$$

    The heat of vaporization of water to an ideal gas at 15°C is 44.43 kJ/mol.

11. The heat of vaporization is the enthalpy of the saturated vapor at the boiling point at 101.3250 kPa (abs) minus the enthalpy of the liquid at the same condition.

12. The refractive index reported refers to the liquid or gas and is measured for light of wavelength corresponding to the sodium D-line (589.26 nm).

13. Air required for combustion of ideal gas for compounds of formula $C_nH_mO_hS_jN_k$

    $$\frac{V(\text{air})}{V(\text{gas})} = \frac{n + {}^1/_4m - {}^1/_2h + j}{0.2095}$$

COMMENTS

Units—all dimensional values are reported in SI units, which are derived from the following basic units:

mass—kilogram, kg
length—meter, m
temperature—International Practical Temperature Scale of 1968 (IPTS-68), where 0°C = 273.15 K

Other derived units are:

volume—cubic meter, m^3
pressure—Pascal, Pa (1 Pa = N/m^2)

Physical constants for molar volume = 22.41383 ± 0.00031

gas constant, R = 8.31441 J/(K · mol)
8.31441 × 10^{-3} m^3 · kPa/(K · mol)
1.98719 cal/(K · mol)
1.98586 Btu(IT)/(°R · lb-mol)

Conversion factors

1 m^3 = 35.31467 ft^3 = 264.1720 gal
1 kg = 2.204623 lb
1 kg/m^3 = 0.06242795 lb/ft^3 = 0.001 g/cm^3
1 kPa = 0.01 bar = 9.869233 × 10^{-3} atm = 0.1450377 lb/in^2
1 atm = 101.3250 kPa = 14.69595 lb/in^2 = 760 Torr
1 kJ = 0.2390057 kcal(thermochemical) = 0.2388459 kcal(IT) = 0.9478171 Btu(IT)

see Rossini, F. D. "Fundamental Measures and Constants for Science and Technology"; CRC Press: Cleveland, Ohio, 1974 reduced temperature for natural gases. It was prepared from data on binary mixtures of methane with propane, ethane and butane, and natural gases, covering a wide range in composition of hydrocarbon mixtures containing methane. No mixtures having molecular mass in excess of 40 were included in preparing this plot although mixtures of cyclohexane and benzene as well as the paraffin series and up to three or four per cent of nitrogen were included.

This plot is entirely satisfactory for all engineering computations involving natural gases with minor amounts of nonhydrocarbon constituents up to pressures of about 70 000 kPa with an accuracy approaching 1%.

All the conveniences of the compressibility factor in the case of single component gases, can be extended to gaseous mixtures by use of the pseudo-critical temperature and pseudo-critical pressure of the gaseous mixture in place of the critical temperature and critical pressure for the single component gas. The molecular average critical temperature of the mixture is the pseudo-critical temperature, and the molecular average critical pressure of the mixture is the pseudo-critical pressure, which are used in the same manner as the critical temperature and critical pressure of a pure gas to determine the values of Z from Fig. 16-3.

Computation of pseudo critical temperature and pressure of a natural gas

1	2	3	4	5	6
Component	Mole fraction	Individual absolute critical temperature T_c, K	2 x 3 Pseudo-critical temperature T_c, K	Individual absolute critical pressure Pc, kPa(abs.)	2 x 5 Pseudo-critical pressure Pc, kPa(abs)
CH_4	0.8319	190.6	158.6	4604	3830
C_2H_6	0.0848	305.4	25.9	4880	414
C_3H_8	0.0437	369.8	16.2	4249	186
i-C_4H_{10}	0.0076	408.1	3.1	3648	28
n-C_4H_{10}	0.0168	425.2	7.1	3797	64
i-C_5H_{12}	0.0057	460.4	2.6	3381	19
n-C_5H_{12}	0.0032	469.6	1.5	3369	11
C_6H_{14}	0.0063	507.4	3.2	3012	19
			218.2		4571

Attempts to prepare a generalized plot suitable for application to the low molecular mass hydrocarbons, including methane, ethane, propane, indicated that an error frequently in excess of 2 to 3% was unavoidable, due to the departure from the theorem of corresponding states. At low pressures the different compounds appear to conform more closely, and the plot, Fig. 16-4, for vapors at low reduced pressures may be used with satisfactory results on practically all of the hydrocarbon gases. Fig. 16-5 is for pressures near atmospheric and is based on atmospheric density data of pure components and mixtures. The compressibility factors from Fig. 16-5 appear to be reliable within about 0.001 in most cases.

Figs. 16-3, 16-4, and 16-5 were independently developed, each based on different data sets. Compressibility factors from these charts at the same reduced conditions may differ slightly.

Fig. 16-6 graphs convenient approximations for determining the pseudo-critical pressure and pseudo-critical temperature of gases when only the gravity of the gas is available. The relative density of the gas shown in the earlier calculation of pseudo critical properties is 0.706. From Fig. 16-6, the pseudo critical temperature is 218 K compared with 218.2 K calculated; the pseudo critical pressure is 4600 kPa compared with 4571 kPa (abs) calculated.

These relationships should not be used when the natural gas contains more than 5% of nitrogen, and it should be distinctly understood that they do not apply to all types of gases. These compressibility charts cover regular hydrocarbon gases at conditions comfortably removed from liquid formations. For irregular hydrocarbons or mixtures containing significant water and/or acid gases, and for all mixtures as liquids or as saturated fluids, use Pitzer's correlations for computing Z factors.

No single correlation is satisfactory for obtaining compressibility of both natural gas and high-molecular-mass hydrocarbon vapors which occur in gas processing plants, so two methods are necessary. Further, for natural gases containing more than 50% methane and with other restrictions set out below, alternate methods can be used.

Fig. 16-7 can be used directly by choosing the closest molecular mass chart and locating temperature and pressure. Average error of about two percent can be expected unless non-hydrocarbons such as nitrogen, carbon dioxide, and hydrogen sulfide are present in substantial quantity. Concentrations up to 5% will not seriously affect accuracy. The area of largest error occurs when molecular mass is above 20 and compressibility is below 0.6; errors as large as 10% may occur in this area. Compressibilities of residue gas from rich oil deethanizers and demethanizers are predicted accurately.

Fig. 16-8 can be used to obtain compressibilities of higher molecular mass vapors such as those encountered in fractionators. Molecular mass of the vapor is used to obtain the critical pressure, Pc.

Compressibility of the dew point vapor can then be read as a function of the reduced pressure. For example, for pure propane with a molecular mass of 44, Pc = 4249 kPa(abs). At 1900 kPa(abs),

$$P_r = 1900/4249 = 0.447$$

From Fig. 16-8, Z = 0.700

Where methane is present in the vapor, it is necessary to correct the indicated Z by the equation given on Fig. 16-8. For example, for a product demethanizer reboiler vapor with molecular mass of 32.33 at 2800 kPa (abs), indicated Z is 0.638; methane content of the vapor is 10% or 0.10 mole fraction.

$$Z \text{ corrected} = (1 - 0.10)(0.638) + 0.1 = 0.674$$

PURE HYDROCARBONS

Mollier charts in Section 17 can be used to obtain gas densities & compressibilities of pure hydrocarbon

FIG. 16-3

Compressibility factors for natural gas

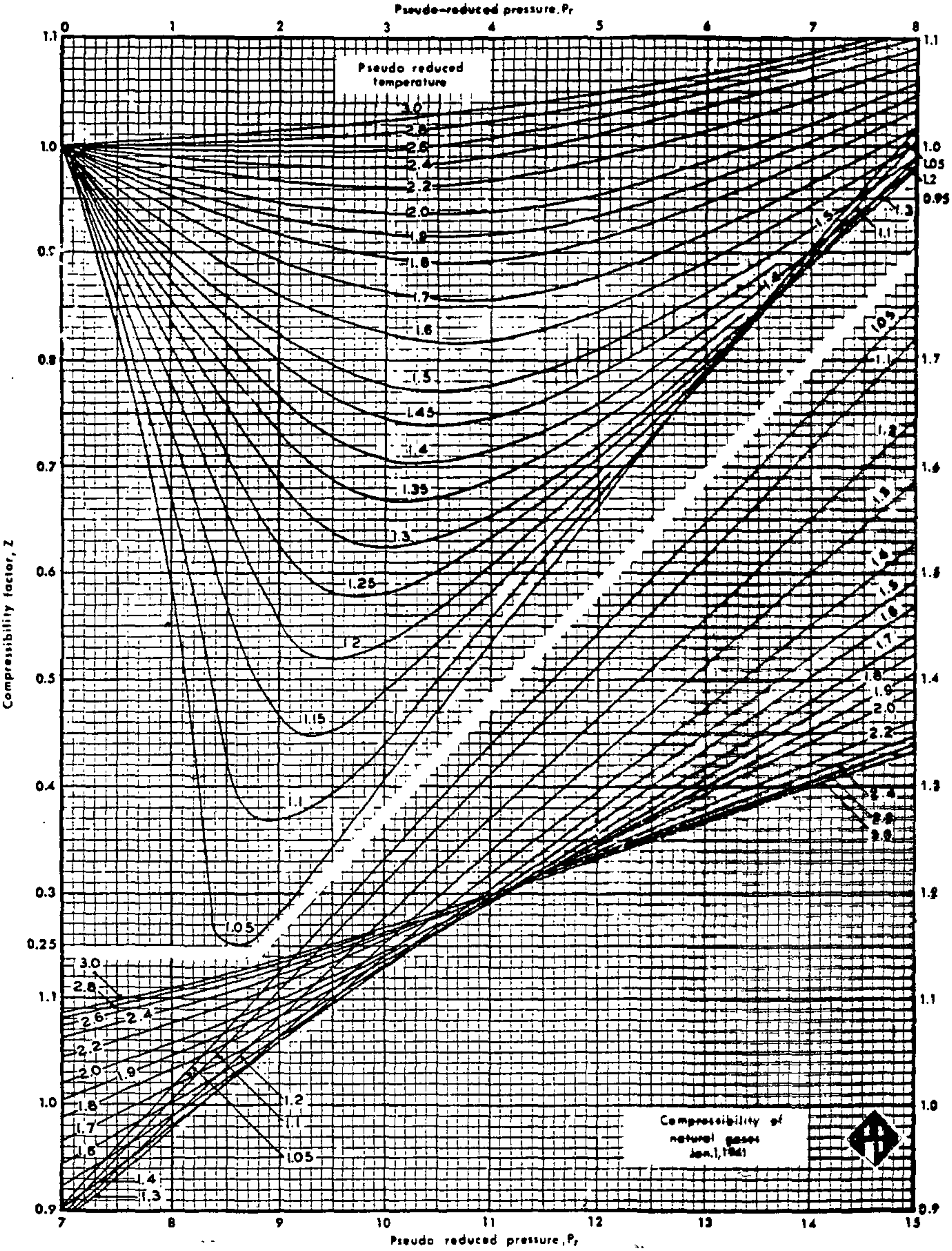


FIG. 16-4

Compressibility factors at low reduced pressures

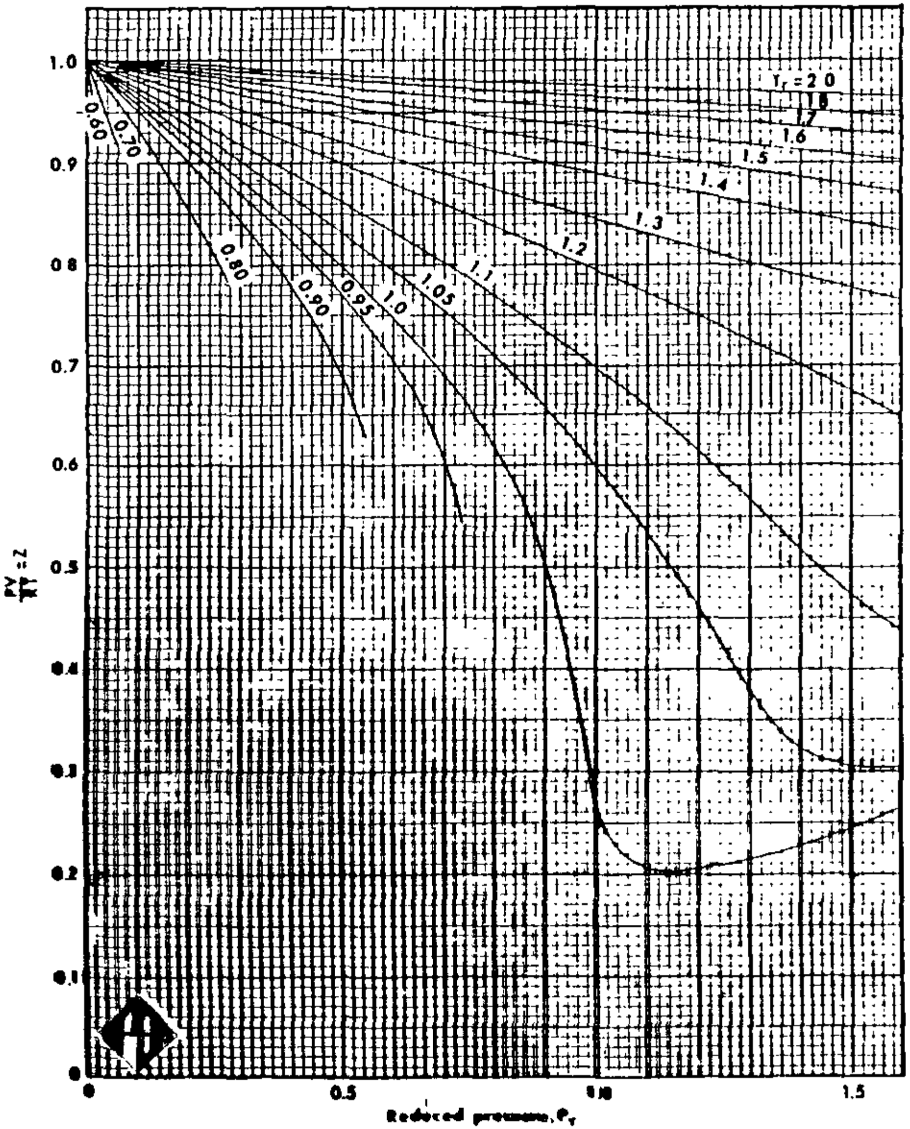
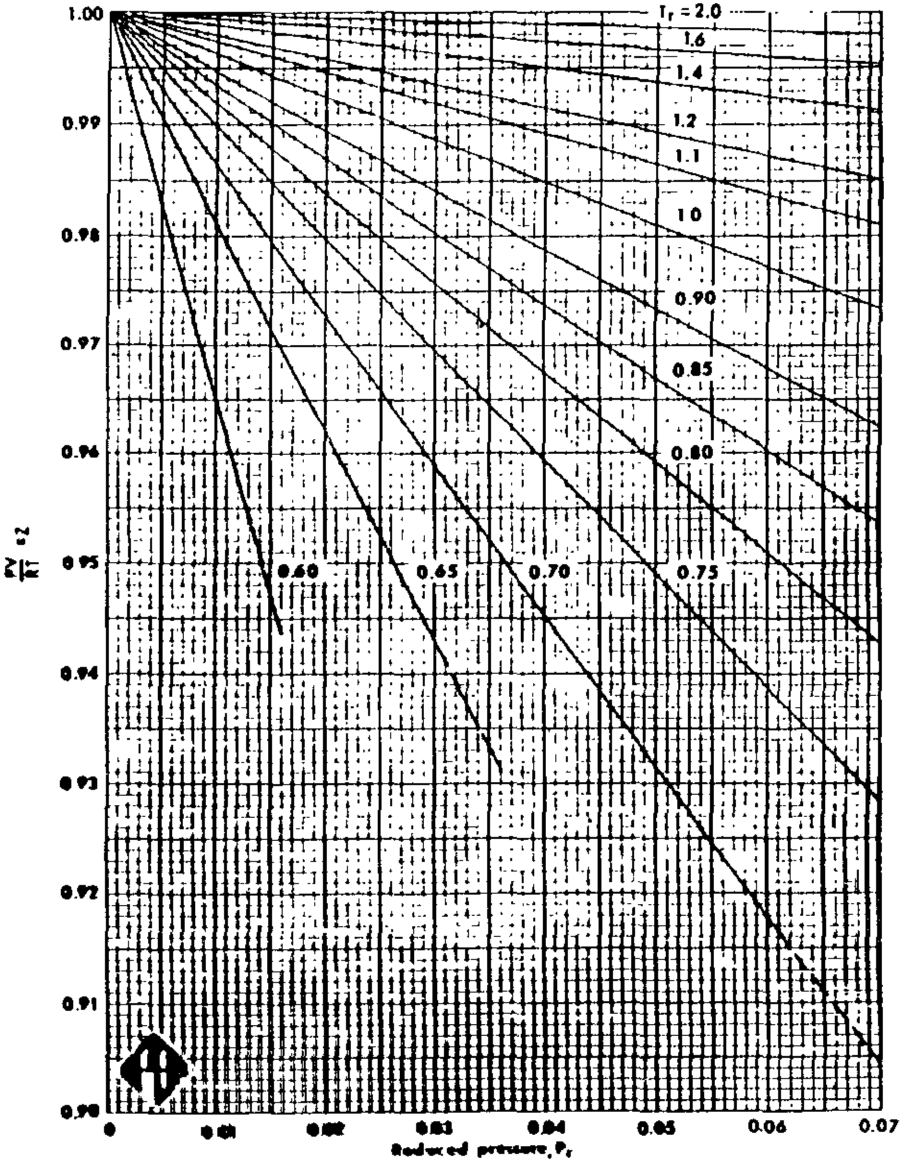


FIG. 16-5

Compressibility factors for gases near atmospheric pressure



vapors. For example for propane at 2000 kPa (abs) and 60°C, turn to the Mollier chart for propane, Fig. 17-25, locate the 2000 kPa and 60°C point, and interpolate on the constant specific volume lines to obtain 0.022 m³/kg. Dividing this into 1 gives 45.45 kg/m³ as the density, ρ_v. If the compressibility is required,

$$Z = \frac{M\,P}{8.3145\,T\,\rho_v}$$

Symbols have been defined previously. Then

$$Z = \frac{(44.097)\quad(2000)}{(8.3145)\,(273.15 + 60)\,(45.45)} = 0.70$$

ACID GASES

Natural gases which contain H_2S and/or CO_2 frequently exhibit different compressibility factor behavior than do sweet gases. Wichert and Aziz (Gas Processing/Canada, pp 20-25, January/February 1971; Hydrocarbon Processing, pp 119-122, May 1972) present a simple easy to use calculational procedure to account for these differences. The method uses the standard gas compressibility factor chart (Figure 16-3) and provides accurate sour gas compressibilities for gas compositions that contain as much as 80% total acid gas.

Wichert and Aziz define a "Critical temperature adjustment factor" which is a function of the concentrations of CO_2 and H_2S in the sour gas. This correction factor is then used to adjust the pseudo critical temperature and pressure of the sour gases according to the equations:

$$T_c^{!} = T_c - \epsilon$$

$$P_c^{!} = \frac{P_c\,T_c^{!}}{[T_c + B\,(1-B)\,\epsilon\,]}$$

Where:

T_c = Mole fraction average pseudo critical temperature, K

P_c = Mole fraction average pseudo critical pressure, kPa (abs)

$T_c^{!}$ = Pseudo critical temperature adjusted for acid gas composition, K

(Text cont'd. p. 16-15)

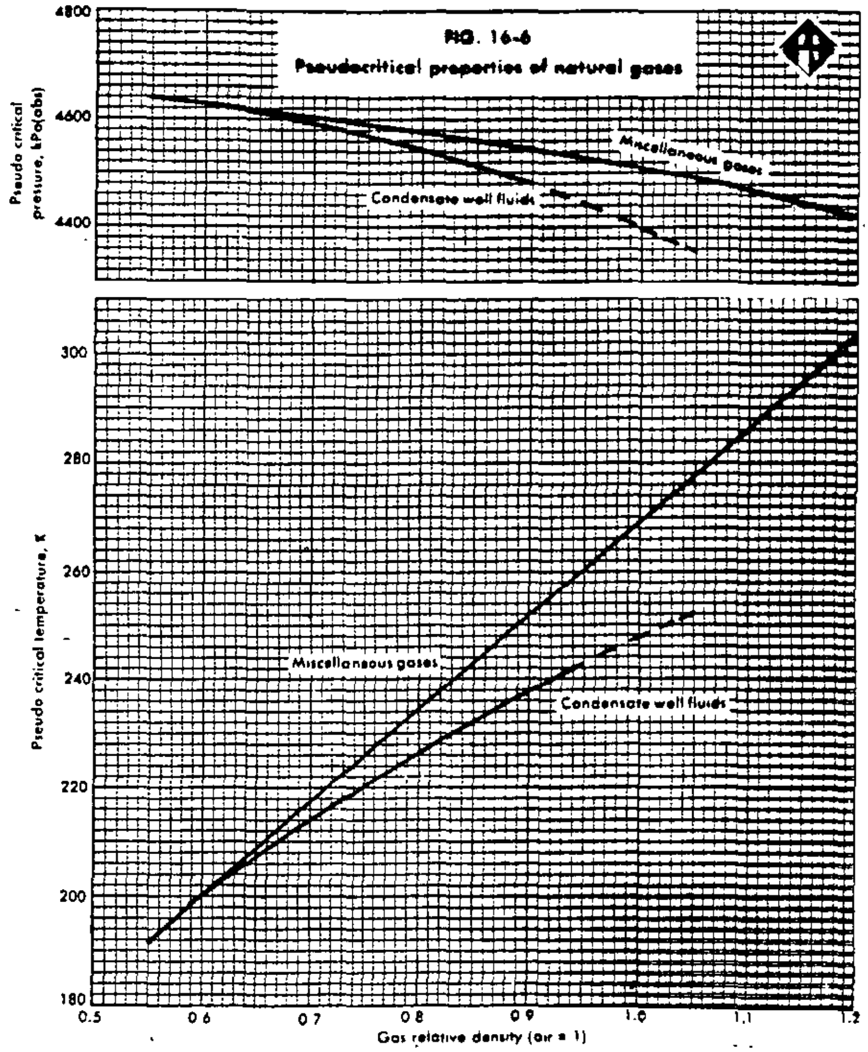
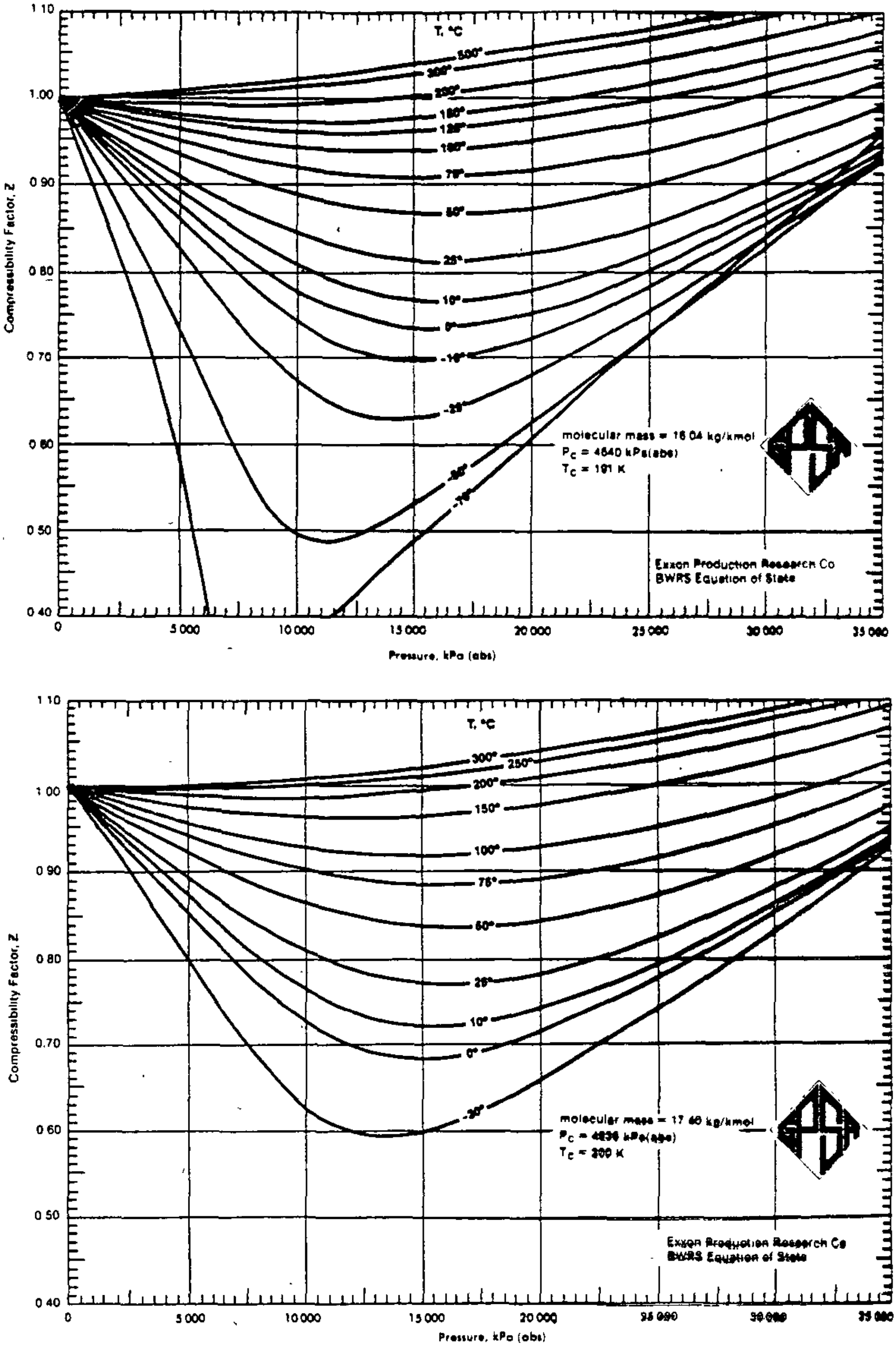


FIG. 16-6
Pseudocritical properties of natural gases

FIG. 16-7A

Compressibility of low-molecular-mass natural gases



SI

FIG. 16-7B

Compressibility of low-molecular-mass natural gases

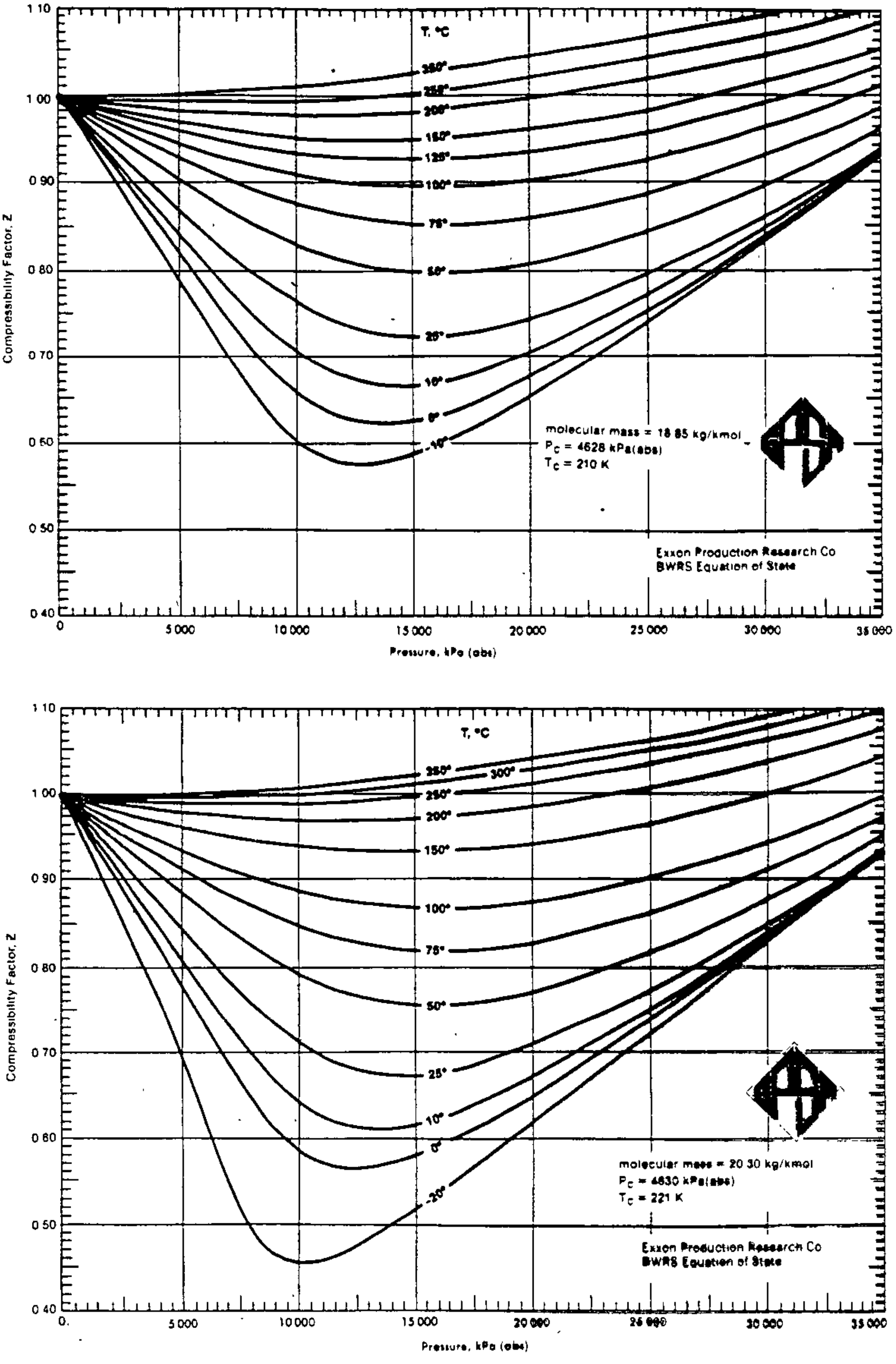
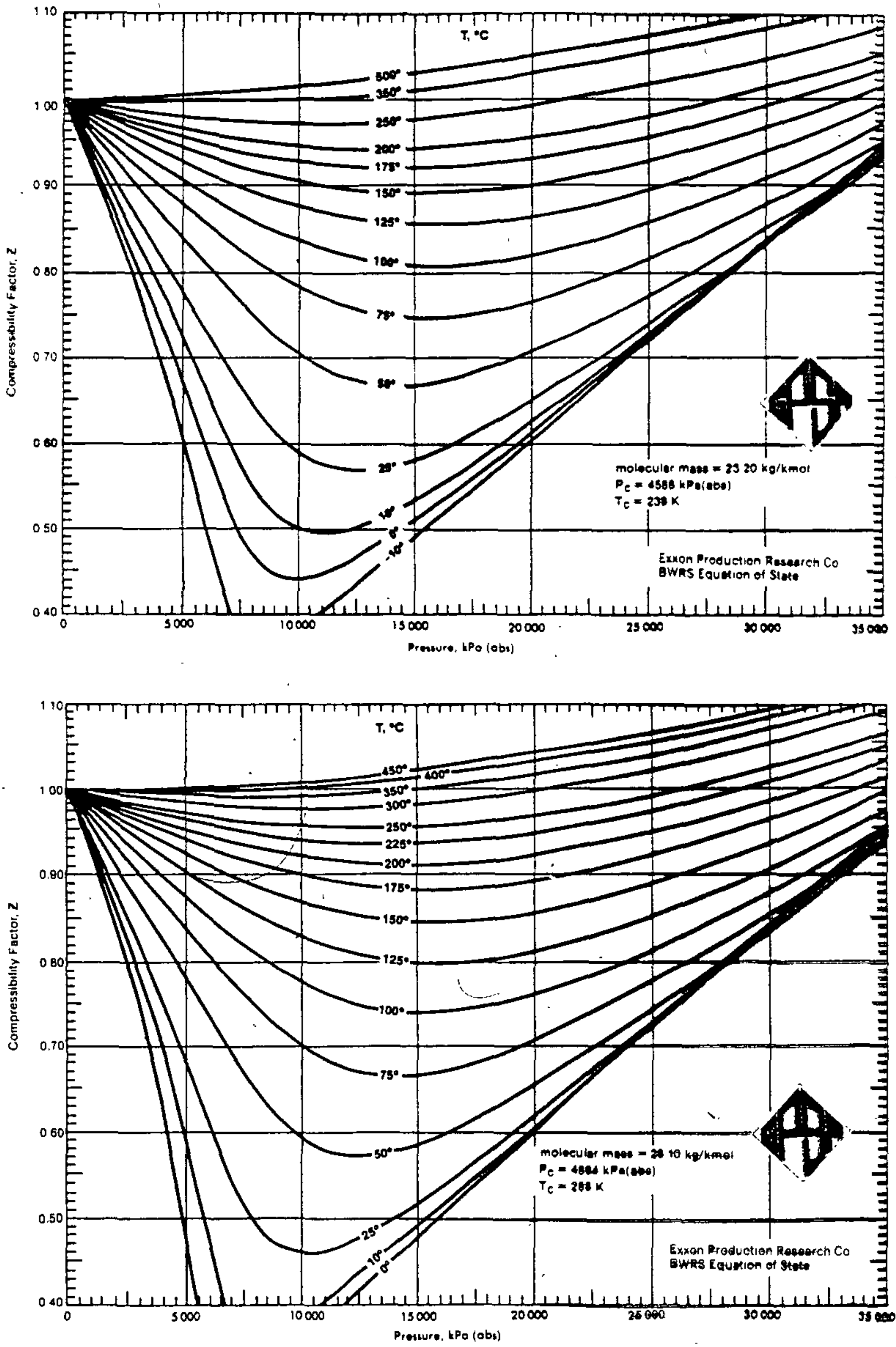


FIG. 16-7C

Compressibility of low-molecular-mass natural gases



The adjusted value for the pseudo critical pressure is:

$$P_c^1 = \frac{5716 \times 224.6}{[241.1 + 0.2\,(1 - 0.2)\,16.5]}$$

$$= 5267 \text{ kPa}$$

The reduced temperature and reduced pressure are:

$$T_r = \frac{100 + 273.15}{224.6} = 1.661$$

$$P_r = \frac{7000}{5267} = 1.329$$

From Figure 16-3 read a compressibility factor of 0.914.

REFERENCE

Wichert, E., and Aziz, K., "Compressibility Factor of Sour Natural Gases," **Can. J. of Chem. Eng.,** Vol. 49, No. 2, pp. 267-273 (1971).

"Compressibility Factor of Sour Natural Gas," Report No. CER/3, The University of Calgary, July, 1970. By Edward Wichert, Canadian Fina Oil Ltd.; and Khalid Aziz, University of Calgary.

Hydrocarbon fluid densities

Fig. 16-10 gives hydrocarbon fluid densities, and Fig. 16-11 is a plot of relative density for petroleum fractions.

The relative density of paraffinic hydrocarbons at their bubble point pressure can be obtained from Fig. 16-12. The nomograph applies to mixtures as well as to single components. The pure component alignment points on Fig. 16-12 can be used to find the relative density of the pure component. Alignment points for paraffinic mixtures are located according to molecular mass.

Fig. 16-12 generally predicts relative densities within 3% of measured values for paraffinic mixtures. However, the accuracy is somewhat less for mixtures having:

1. Reduced temperatures above 0.9.
2. Molecular mass less than 30 (low temperature region) and where methane is a significant part of the liquid and very near, at, or above its critical temperature.

Other references for density calculation are:

1. J. R. Deam, I. K. Kellizy and R. N. Maddox—"Calculating Density of Saturated Hydrocarbon Mixtures." **Proceedings of the 48th Annual Meeting of the Natural Gas Processors Association,** pp. 48-51, March, 1969 (Dallas).

2. L. D. Bagzis and R. N. Maddox — "Calculating Surface Tension of Hydrocarbon Mixtures," **Proceedings of the 49th Annual Meeting of the Natural Gas Processors Association,** pp. 41-45, March, 1970 (Denver).

Relative densities of petroleum fractions are given by Fig. 16-13 for temperatures from 0° to 550°C and pressures from atmospheric to 10000 kPa (abs). The petroleum fraction is identified within the center grid by two of three characteristics—relative density at 15°C, the characterization factor, K_w, or the mean-average boiling point. The mean average boiling point is determined from Fig. 16-16, together with the relative density and an ASTM distillation of the petroleum fraction.

Effect of temperature on hydrocarbon fluid densities is shown in Fig. 16-14, and effect of pressure is shown in Fig. 16-15.

Boiling point, ASTM distillation, critical properties, acentric factor, vapor pressure

Fig. 16-16 gives molecular mass vs boiling point and density for petroleum fractions. Fig. 16-17 is a correlation for determining critical temperatures for hydrocarbon fractions, while Figs. 16-18 and 16-19 enable the critical pressure calculation.

Fig. 16-20 gives acentric factor from boiling and critical points. This accounts for the deviation of complex mixtures from simple fluids. A full explanation of the use of acentric factors can be found on pp 22-29, Applied Hydrocarbon Thermodynamics, Wayne C Edmister.

Example problem

Determine mean average boiling point (MeABP) and molecular mass for a 0.75 relative density petroleum fraction with these ASTM distillation data:

% over	Temp °C
5	54
10	67
20	88
30	103
40	118
50	138
60	159
70	196
80	240
90	311
ep	338

Solution:

Refer to Fig. 16-16.

$$\text{Slope, } S = \frac{t_{90} - t_{10}}{80} = \frac{311 - 67}{80} = 3.05$$

$$\text{Vol. avg. bp} = \frac{t_{10} + 2t_{50} + t_{90}}{4}$$

$$= \frac{67 + 2(138) + 311}{4}$$

$$= 163.5°\text{C}$$

(Text cont'd p. 16-22)

Gross heating value of natural gases

The gross heating value, relative density, and compressibility factor of a natural gas mixture may be calculated from a complete compositional analysis of the mixture.

Heating value—The ideal gas heating value, H, is calculated:

$$H = x_1H_1 + x_2H_2 + x_3H_3 + \ldots + x_nH_n$$

Where:

$x_1, x_2 \ldots x_n$ = the mole fractions of the components

$H_1, H_2 \ldots H_n$ = ideal gas heating values of the components listed in Fig. 16-32.

The ideal gas heating value, H, is corrected to the real gas heating value, H_r, by dividing by the compressibility factor, Z, for the gas mixture at 15°C and 101.325 kPa (abs):

$$H_r = H/Z$$

Relative density—The ideal gas relative density, G, is calculated:

$$G = x_1G_1 + x_2G_2 + x_3G_3 + \ldots + x_nG_n$$

where:

$x_1, x_2, \ldots x_n$ = the mole fractions of the components

$G_1, G_2, \ldots G_n$ = ideal gas relative densities of the components listed in Fig. 16-32.

The ideal gas relative density, G, is corrected to the real gas relative density, G_r, by dividing by the compressibility factor, Z, for the gas mixture at 15°C and 101.325 kPa (abs) and multiplying by the compressibility factor of air at the same conditions:

$$G_r = (G/Z)\ (0.9996)$$

Compressibility factor—The compressibility factor, Z, at 15°C and 101.325 kPa (abs) for gas mixtures of components listed in Fig. 16-32 may be calculated from composition as follows:

$$Z = 1 - (x_1\sqrt{b_1} + x_2\sqrt{b_2} + x_3\sqrt{b_3} + \ldots x_n\sqrt{b_n})^2 + (2x_H - x_H^2)\ (0.0005)$$

Where:

$\sqrt{b_1}, \sqrt{b_2}, \ldots \sqrt{b_n}$, = summation factors for the components other than hydrogen, listed in Fig. 16-32.

x_H = mole fraction of hydrogen

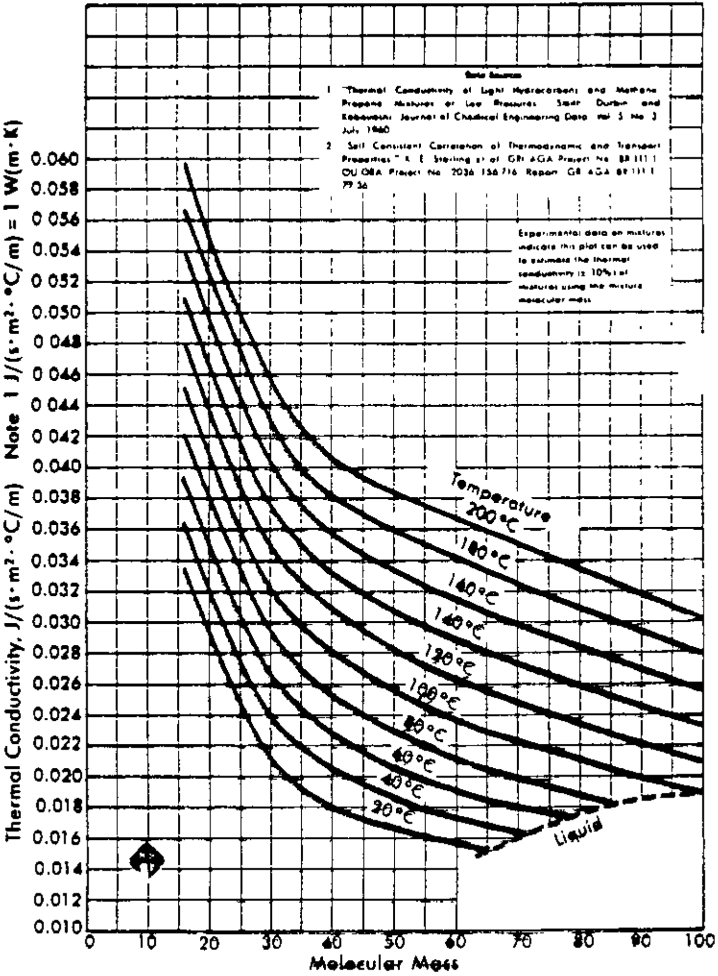
$b = 1 - Z$, except for H_2, He, and CO_2.

REFERENCES

1. "Calculation of Heating Value and Specific Gravity of Fuel Gases", Institute of Gas Technology Research Bulletin No 32, D M. Mason and B. E. Eakin, 1961.
2. GPA Publication 2172-72, "Tentative Method for Calculating Heating Value, Specific Gravity, and Compressibility of Natural Gas Mixtures From Compositional Anaysis".

FIG. 16-27

Thermal Conductivity of Natural Gases at 101.3250 kPa (abs)



Data Sources

1 "Thermal Conductivity of Light Hydrocarbons and Methane Propane Mixtures at Low Pressures" Smith, Durbin and Kobayashi, Journal of Chemical Engineering Data, Vol 5 No 3 July 1960

2 "Self Consistent Correlation of Thermodynamic and Transport Properties" K. E. Starling et al, GRI AGA Project No. BR 111-1, OU GRA Project No. 2036 156 716, Report GRI AGA BR 111-1 79 36

Experimental data on mixtures indicate this plot can be used to estimate the thermal conductivity ± 10% of mixtures using the mixture molecular mass.

FIG. 16-11

Approximate relative density of petroleum fractions

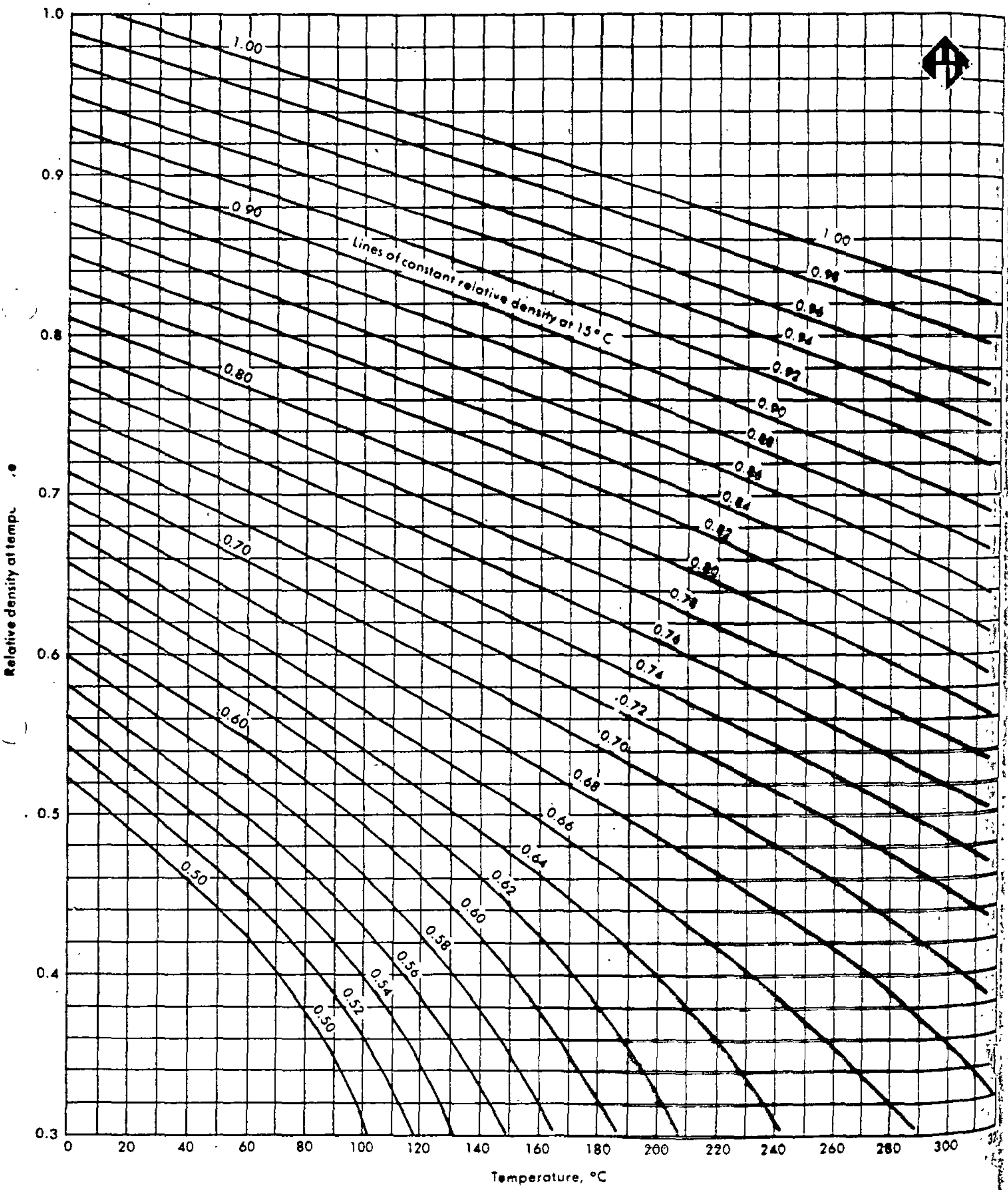
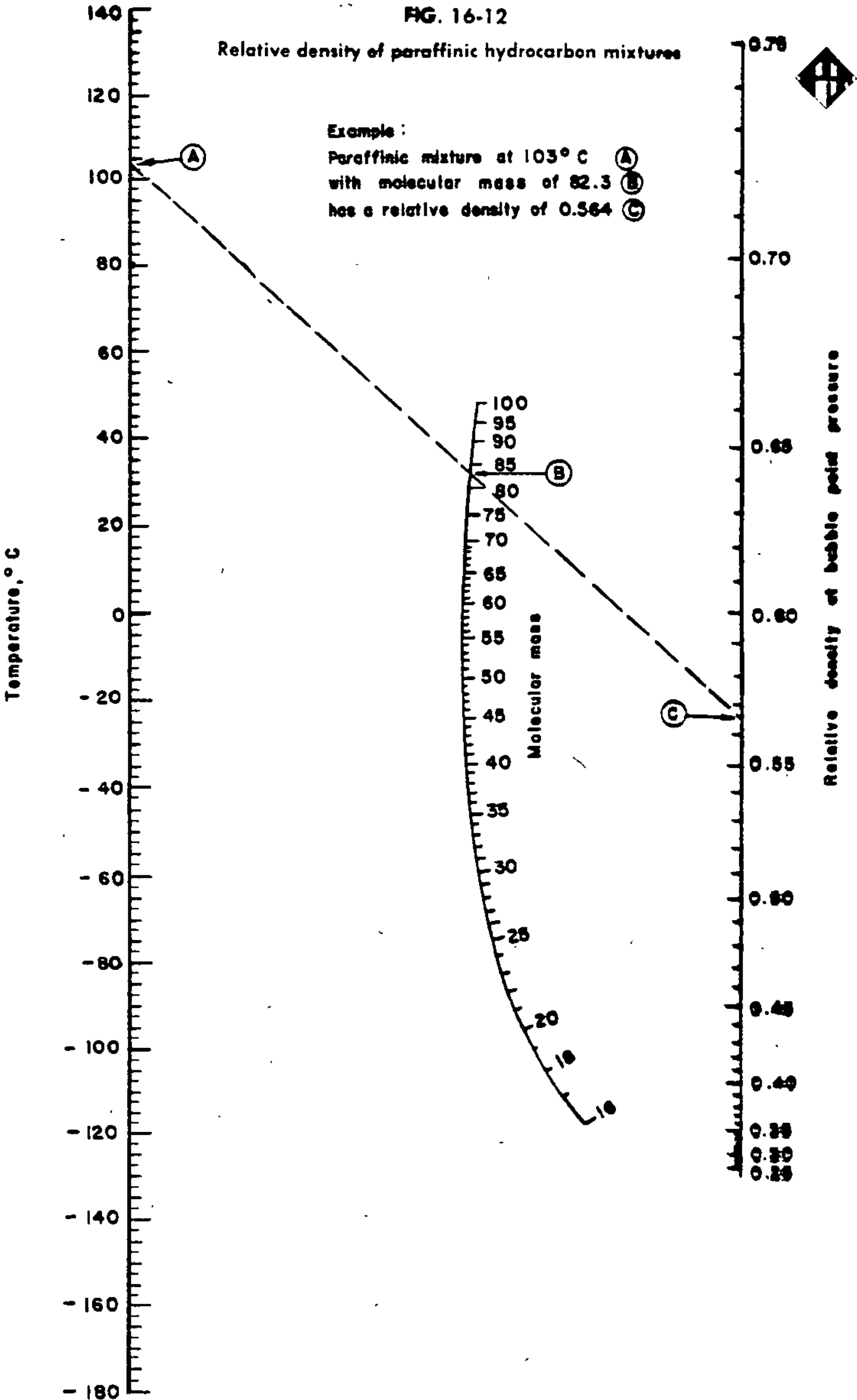


FIG. 16-12

Relative density of paraffinic hydrocarbon mixtures

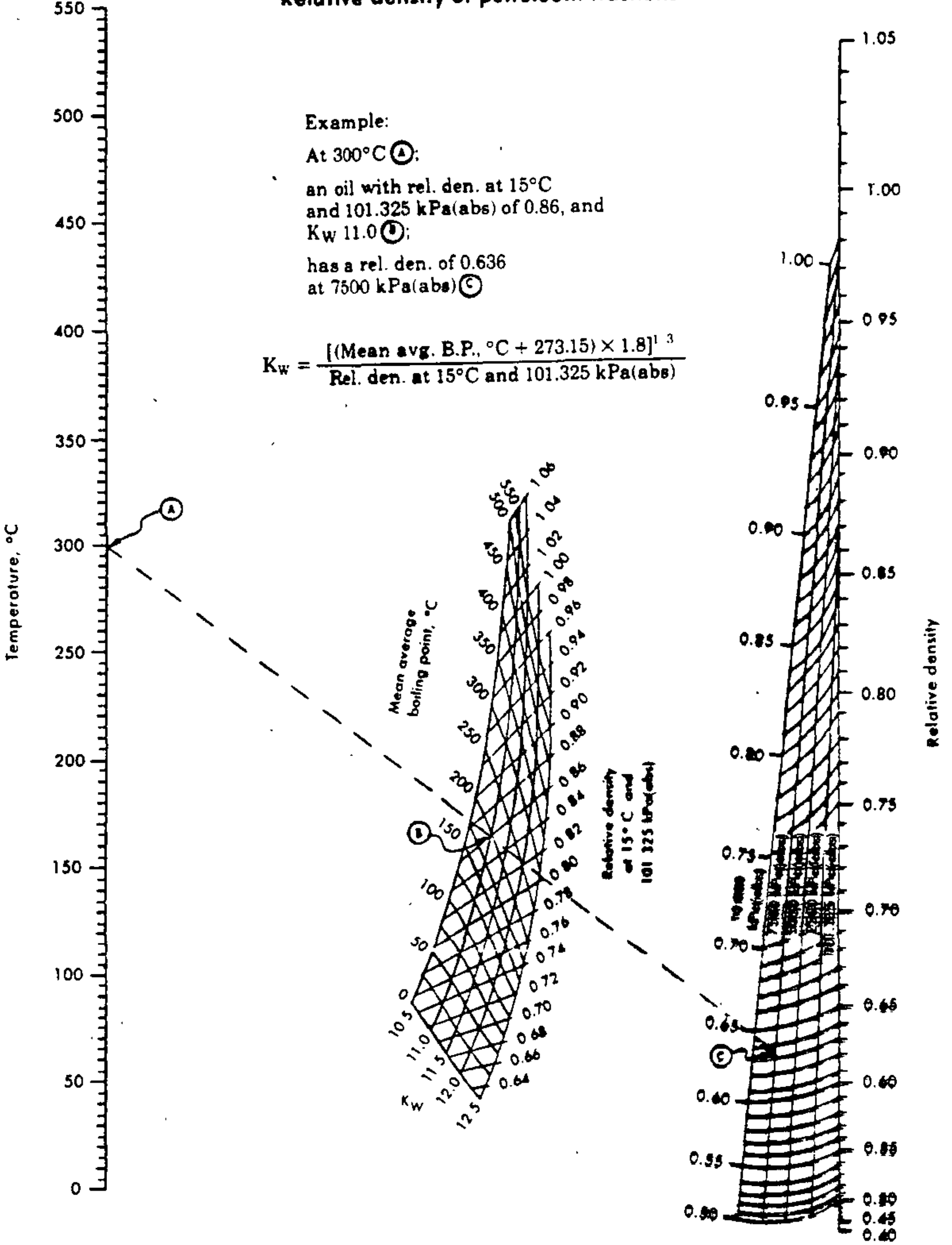


Example:
Paraffinic mixture at 103° C Ⓐ
with molecular mass of 82.3 Ⓑ
has a relative density of 0.564 Ⓒ

Adapted to SI by GPSA from
Petroleum Refiner: Ritter,
Lenoir, and Schweppe (1958)

FIG. 16-13

Relative density of petroleum fractions



Example:
At 300°C Ⓐ:
an oil with rel. den. at 15°C
and 101.325 kPa(abs) of 0.86, and
K_W 11.0 Ⓑ;
has a rel. den. of 0.636
at 7500 kPa(abs) Ⓒ

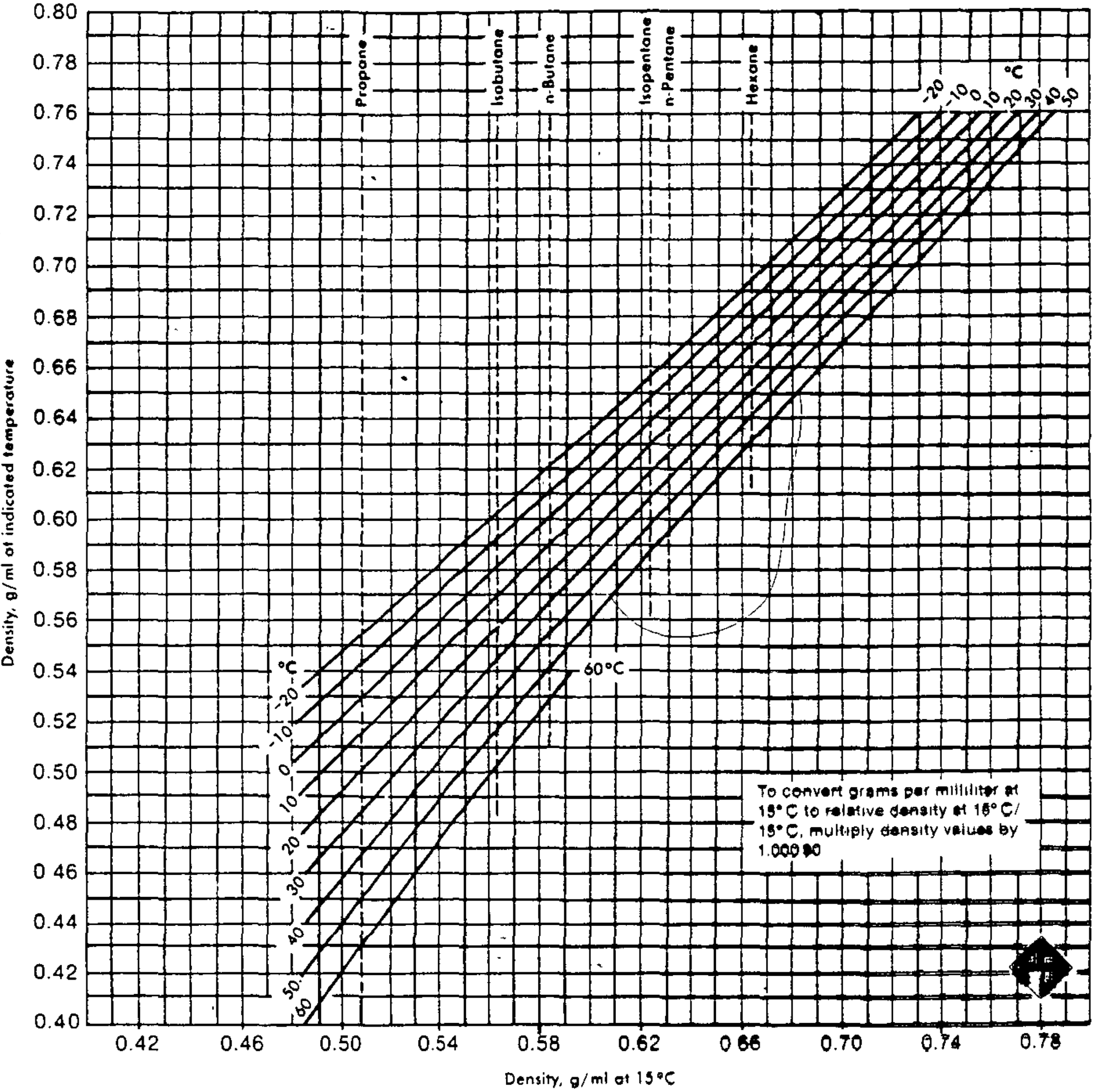
$$K_W = \frac{[(\text{Mean avg. B.P., °C} + 273.15) \times 1.8]^{1/3}}{\text{Rel. den. at 15°C and 101.325 kPa(abs)}}$$

Adapted to SI by GPSA from Ritter, Lenoir, and Schweppe, Petroleum Refiner, 1958

FIG. 16-14

Effect of Temperature on Hydrocarbon Fluid Densities

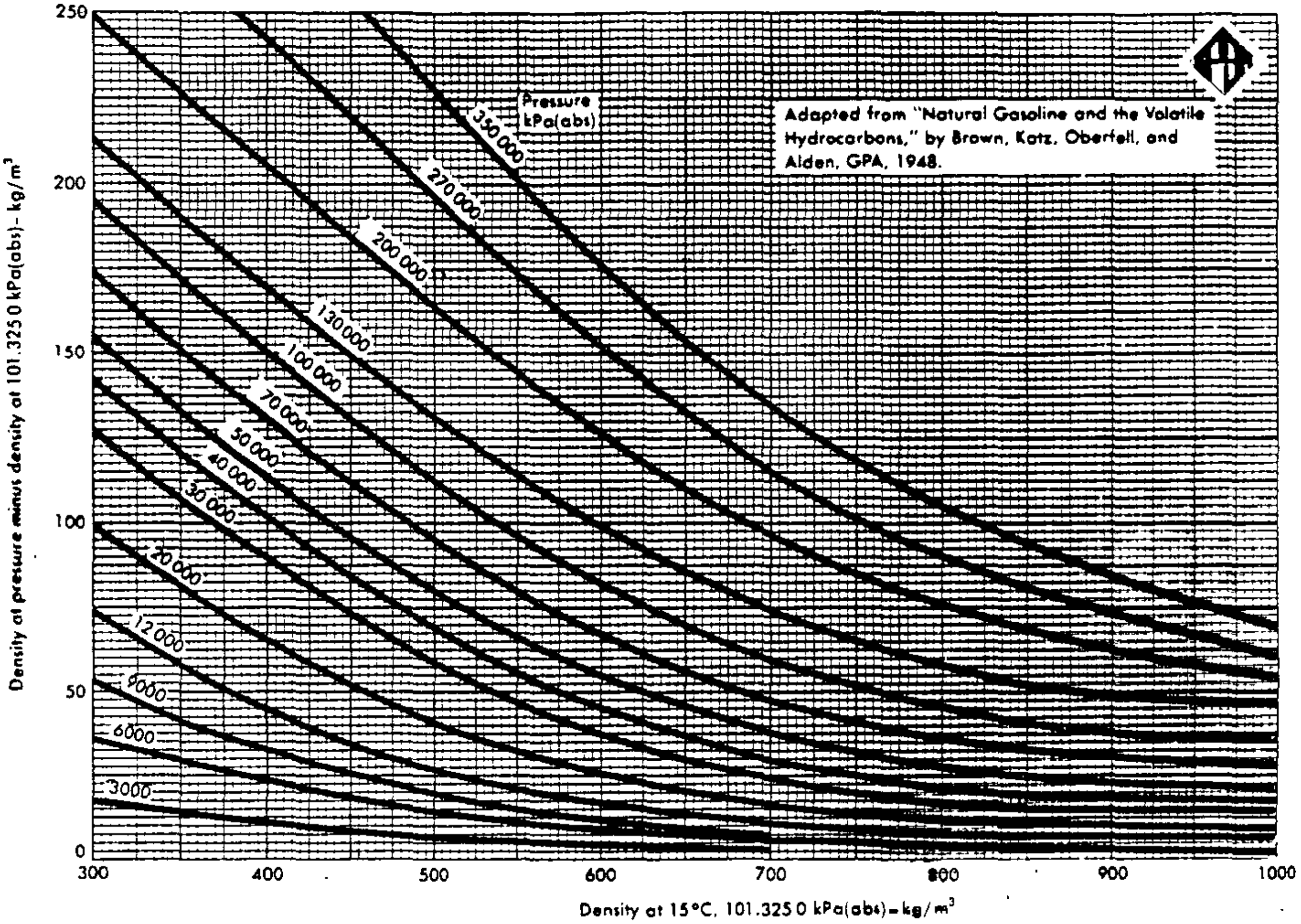
(Data from Table 53 of metric edition of Petroleum Measurement Tables, ASTM D-1250-56)



To convert grams per milliliter at 15° C to relative density at 15° C/15° C, multiply density values by 1.000 90

FIG. 16-15

Effect of pressure on hydrocarbon fluid densities



Adapted from "Natural Gasoline and the Volatile Hydrocarbons," by Brown, Katz, Oberfell, and Alden, GPA, 1948.

From Top Chart

Add −29°C to volume average boiling point to obtain mean average boiling point.

MeABP = 163.5 − 29 = 134.5°C

From lower chart at MeABP = 134.5°C and 0.75 density, molecular mass = 120

The need may arise to plot the atmospheric flash curve from an ASTM distillation curve or true-boiling-point curve. An outline of a procedure to derive the atmospheric-flash curve can be found in the Data Book on Hydrocarbons by J. B. Maxwell, p. 222 through p. 229. A method for elevating the derived atmospheric flash curve to operating pressure can be found on p. 223.

Figs. 16-21 and 16-22 are low and high-temperature vapor-pressure Cox charts for light hydrocarbons.

Viscosity

Figs. 16-23 through 16-26 give correlations for the determination of viscosities of hydrocarbon liquids and gases.

Example problem

Find viscosity of a gas of molecular mass of 22 at 7000 kPa (abs) and 40°C.

Solution:

From Fig. 16-25, the viscosity at atmospheric pressure and 40°C is 0.0105 mPa · s. Relative density of gas is 22/28.964 = 0.760. From Fig. 16-6, critical temperature is 227 K and critical pressure is 4580 kPa. Note: critical temperature and pressure should be calculated as shown in this Section 16, under heading, "Compressibility of gases," if composition of gas is available.

$$T_r = \frac{40 + 273}{227} = 1.379 \qquad P_r = 7000/4580 = 1.528$$

From Fig. 16-26, $\mu/\mu_A = 1.21$. Viscosity at 7000 kPa and 40°C is $\mu = (1.21)(0.0105) = 0.0127$.

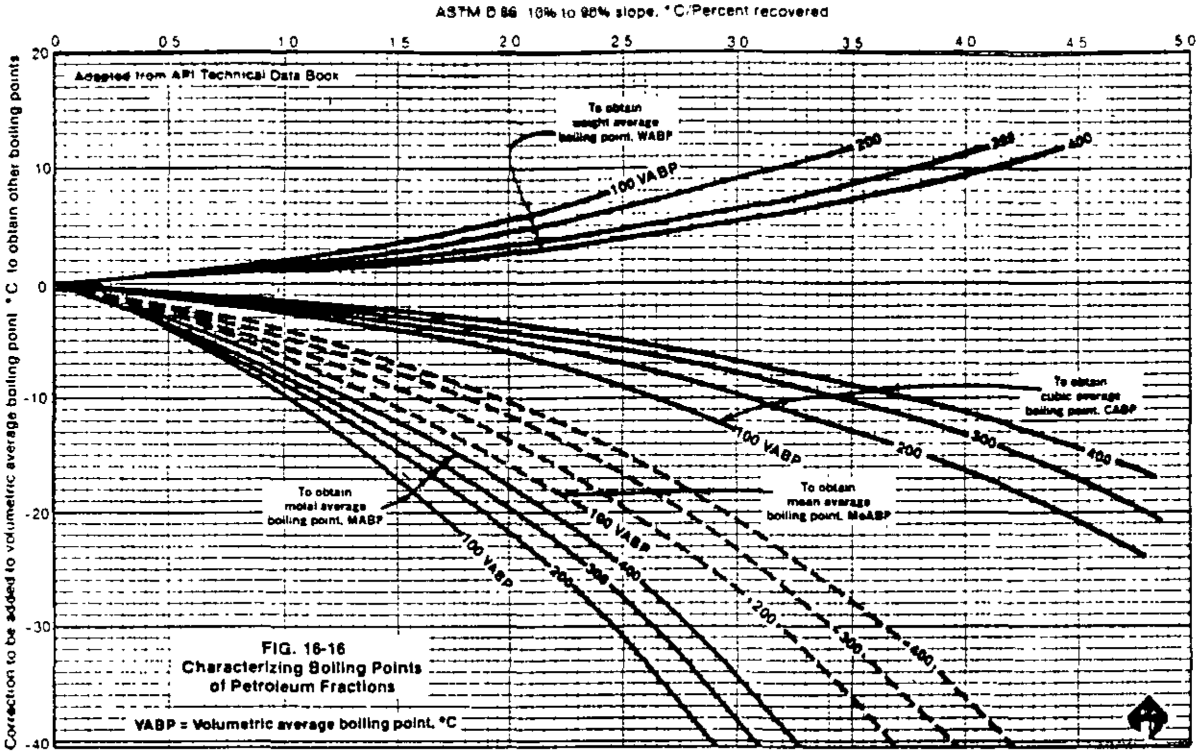


FIG. 16-16
Characterizing Boiling Points of Petroleum Fractions

VABP = Volumetric average boiling point, °C

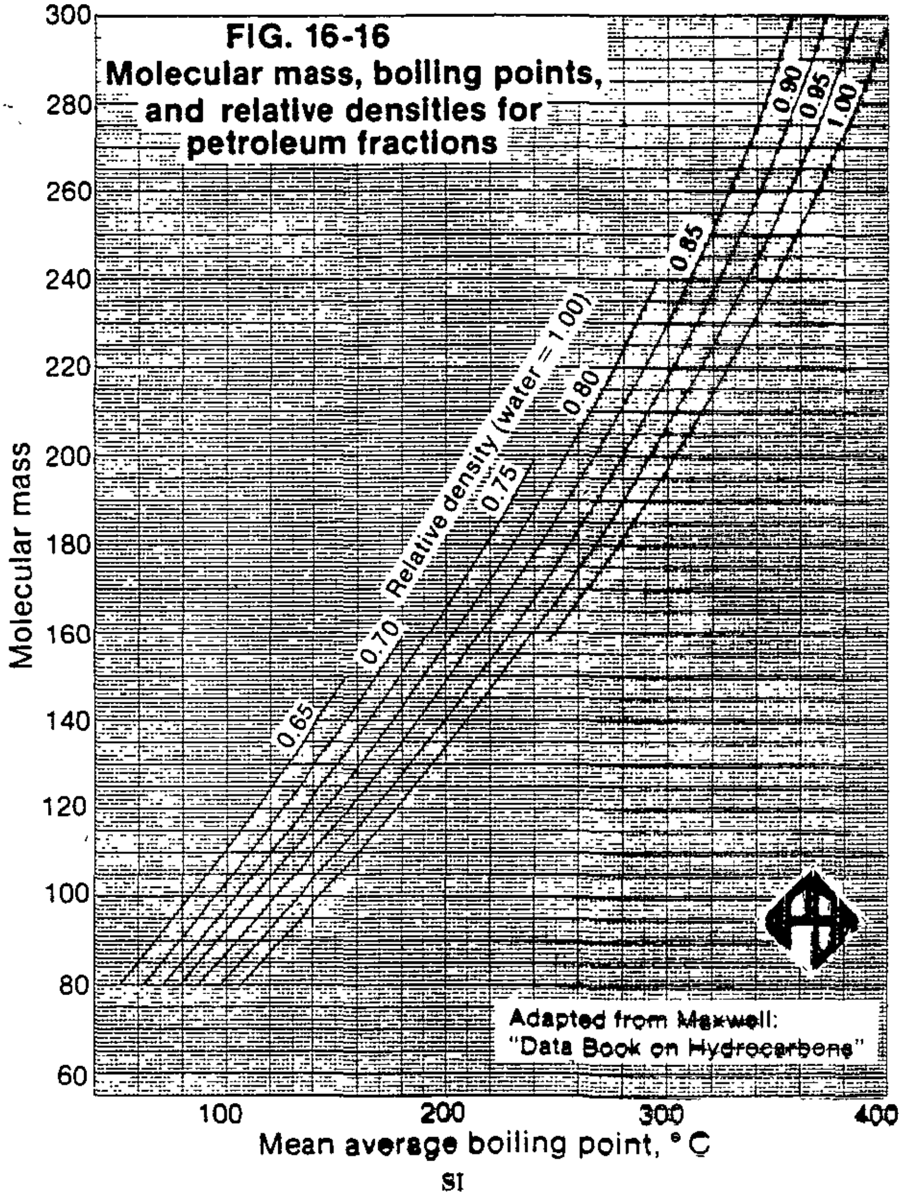


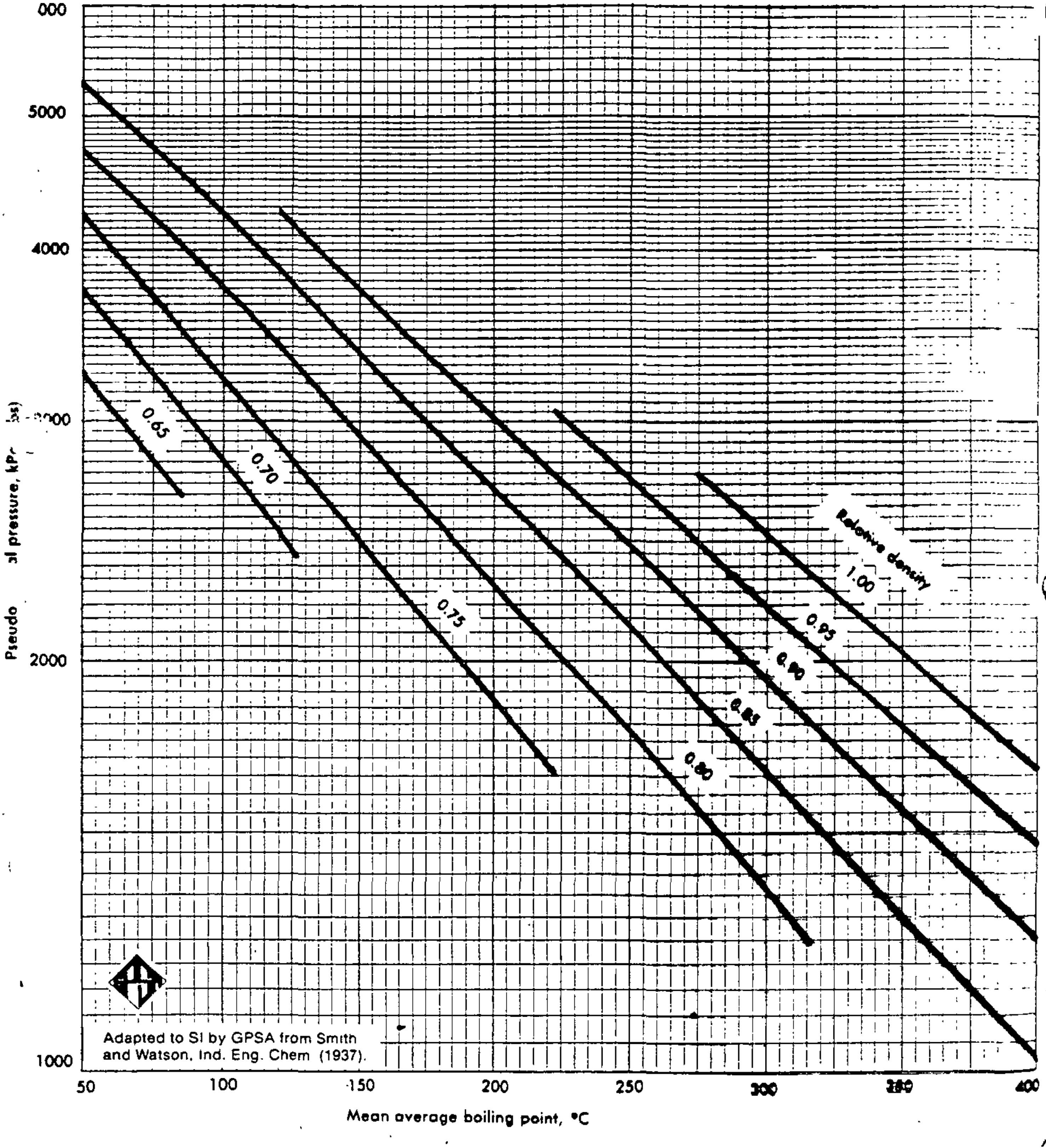
FIG. 16-16
Molecular mass, boiling points, and relative densities for petroleum fractions

Adapted from Maxwell: "Data Book on Hydrocarbons"

SI

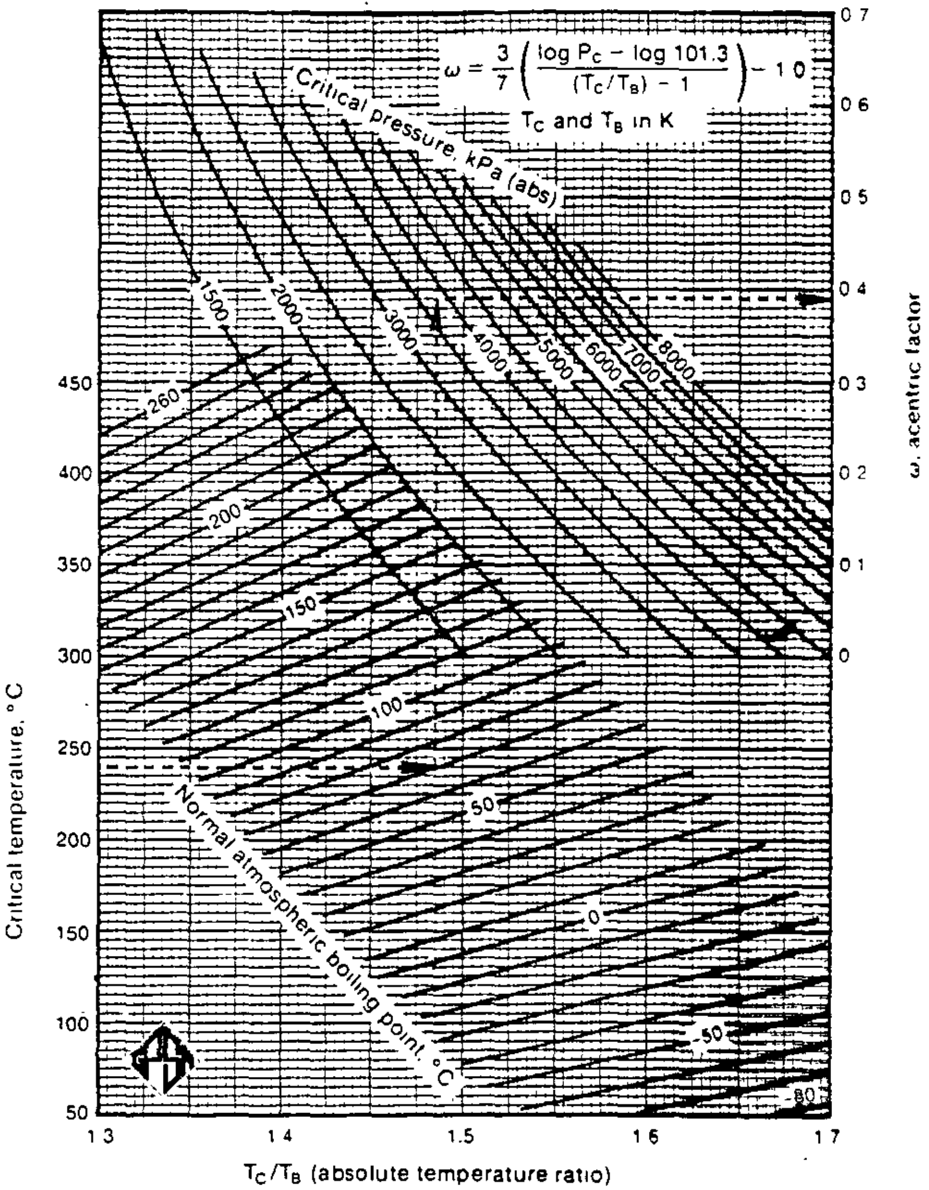
FIG. 16-19

Pseudo critical pressures of hydrocarbons



Adapted to SI by GPSA from Smith and Watson, Ind. Eng. Chem (1937).

FIG. 16-20
Acentric factor from boiling and critical points



NOTE. Use only for narrow boiling range fractions of 30°C or less.

Adapted from "Applied Thermodynamics,"
by Wayne C. Edmister
Copyright, The Gulf Publishing Co., Houston

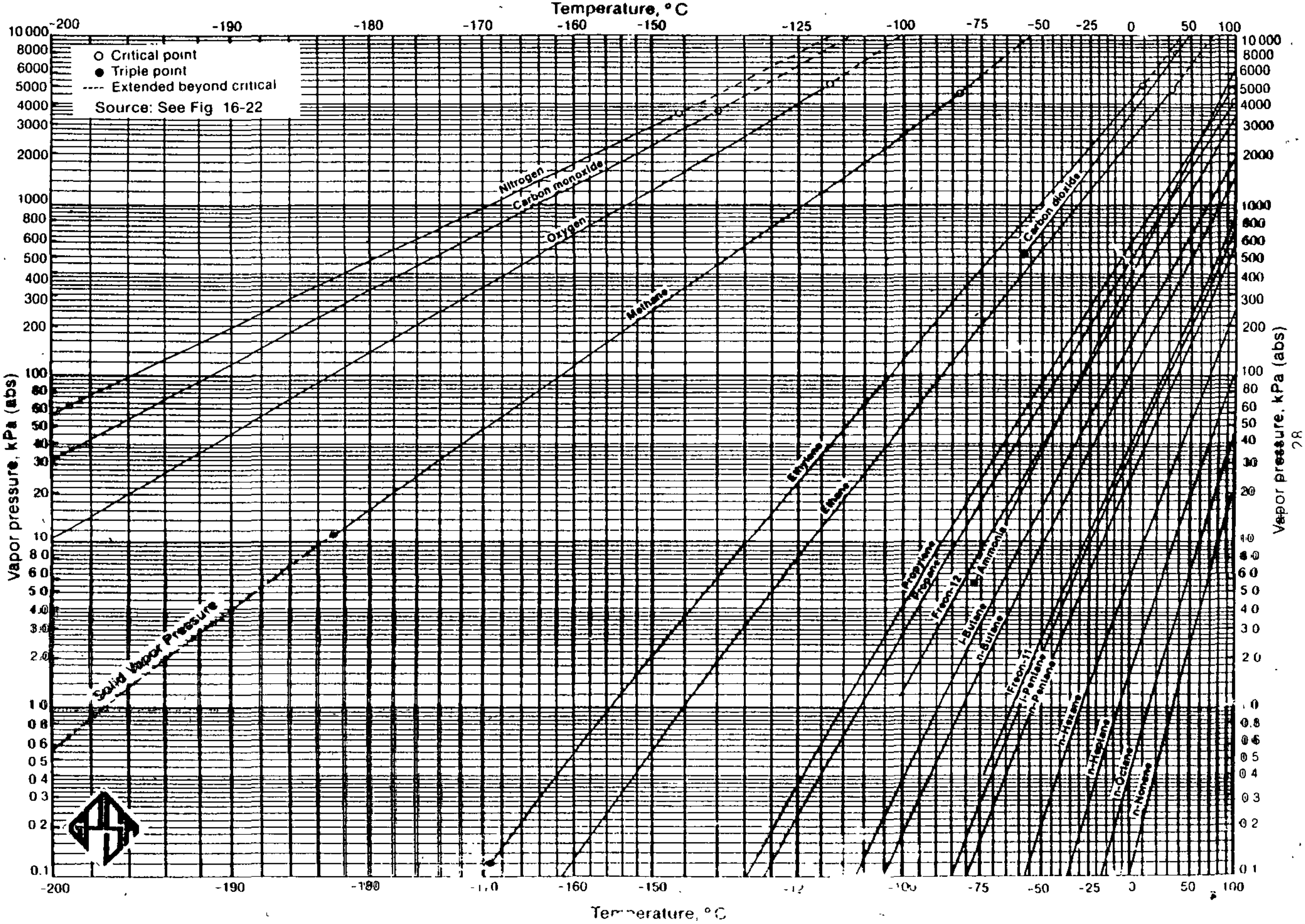
Surface tension

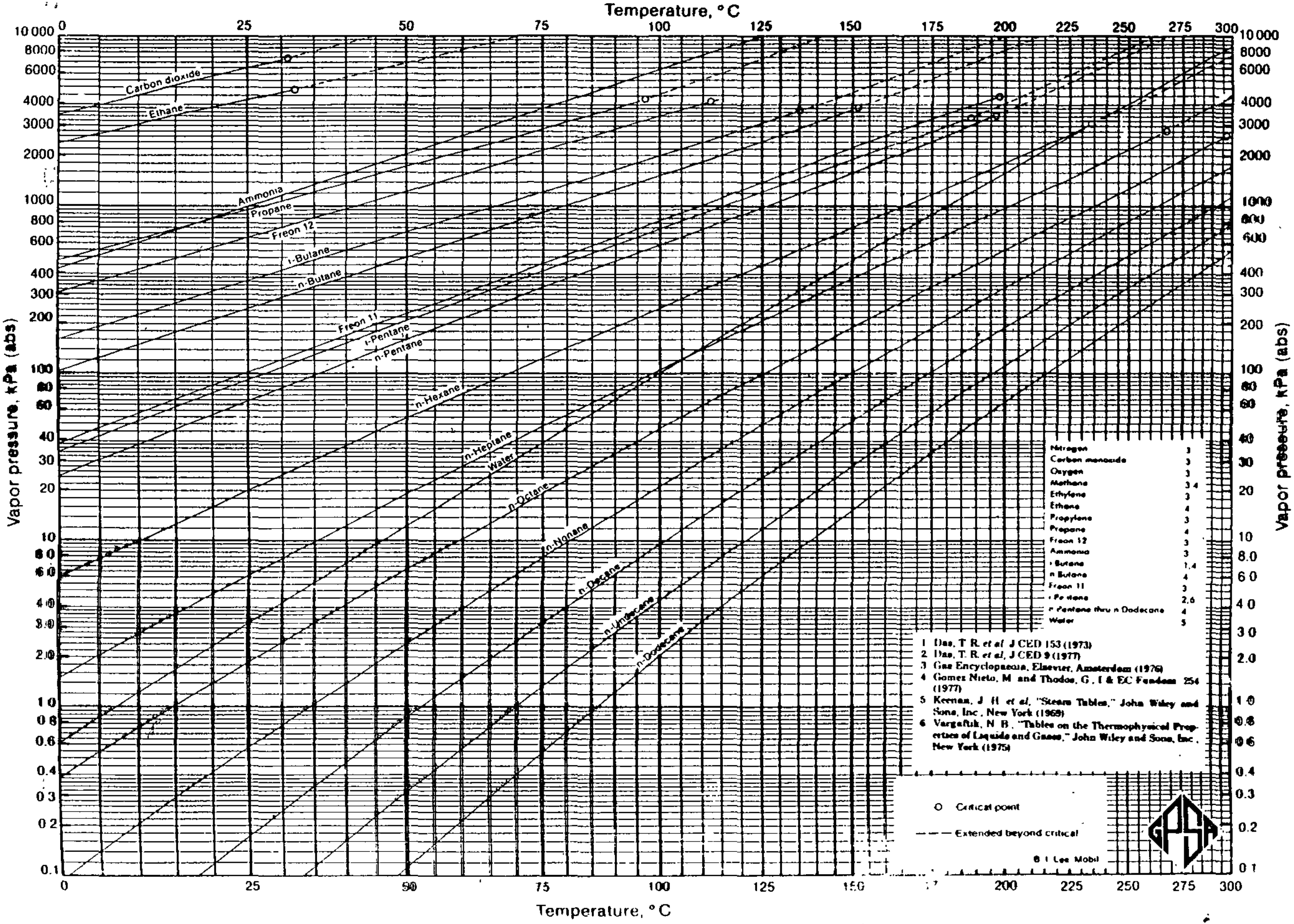
The interior molecules of a liquid exert upon the surface molecules an inward force of attraction, which tends to minimize the surface area of the liquid. The work required to enlarge the surface area by one square centimeter is called the surface free energy. The opposite force in the liquid's surface, called surface tension, exerts a force parallel to the plane of the surface.

Surface tension, an important property where wetting, foaming, emulsification, and droplet formation are encountered, is used in the design of fractionators, absorbers, and two-phase pipelines, and in reservoir calculations.

The surface tension of pure hydrocarbons as a function of temperature may be obtained from Fig. 16-29. The surface tensions of most pure hydrocarbons are known and data are available. Relatively little data are available on multicomponent mixtures. In the absence of experimental values of surface tension at the desired conditions, a sufficiently accurate value for design purposes can be estimated by the Sudgen (1) equation:

Low-temperature vapor pressures for light hydrocarbons



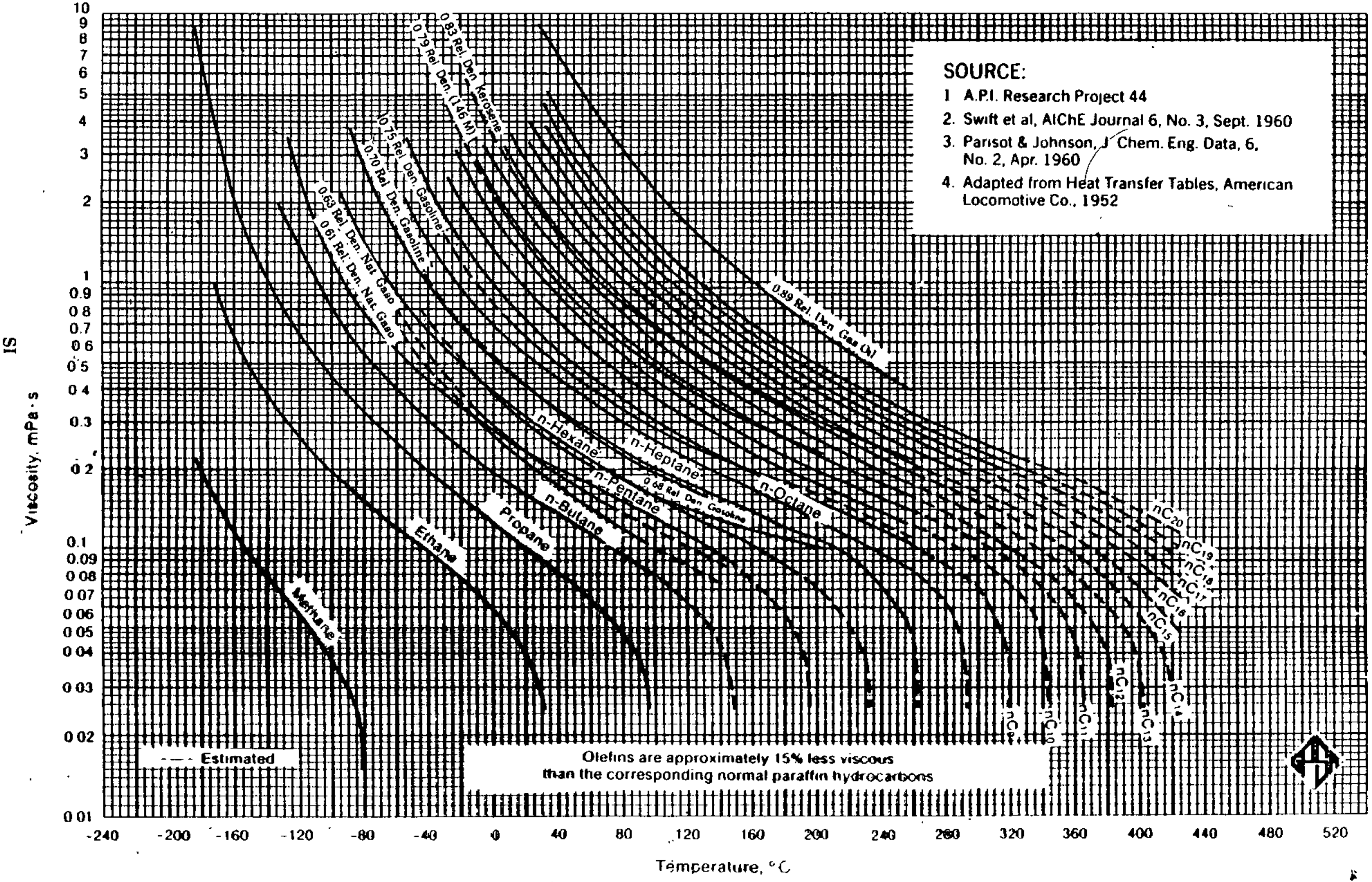


Nitrogen	3
Carbon monoxide	3
Oxygen	3
Methane	3 4
Ethylene	3
Ethane	4
Propylene	3
Propane	4
Freon 12	3
Ammonia	3
i Butane	1,4
n Butane	4
Freon 11	3
i Pentane	2,6
n Pentane thru n Dodecane	4
Water	5

1 Das, T R. *et al* J CED 153 (1973)
2 Das, T. R. *et al*, J CED 9 (1977)
3 Gas Encyclopaedia, Elsevier, Amsterdam (1976)
4 Gomez Nieto, M and Thodos, G , I & EC Fundam 254 (1977)
5 Keenan, J H *et al*, "Steam Tables," John Wiley and Sons, Inc , New York (1969)
6 Vargaftik, N B , "Tables on the Thermophysical Properties of Liquids and Gases," John Wiley and Sons, Inc , New York (1975)

FIG. 16-23

Viscosities of hydrocarbon liquids



SOURCE:

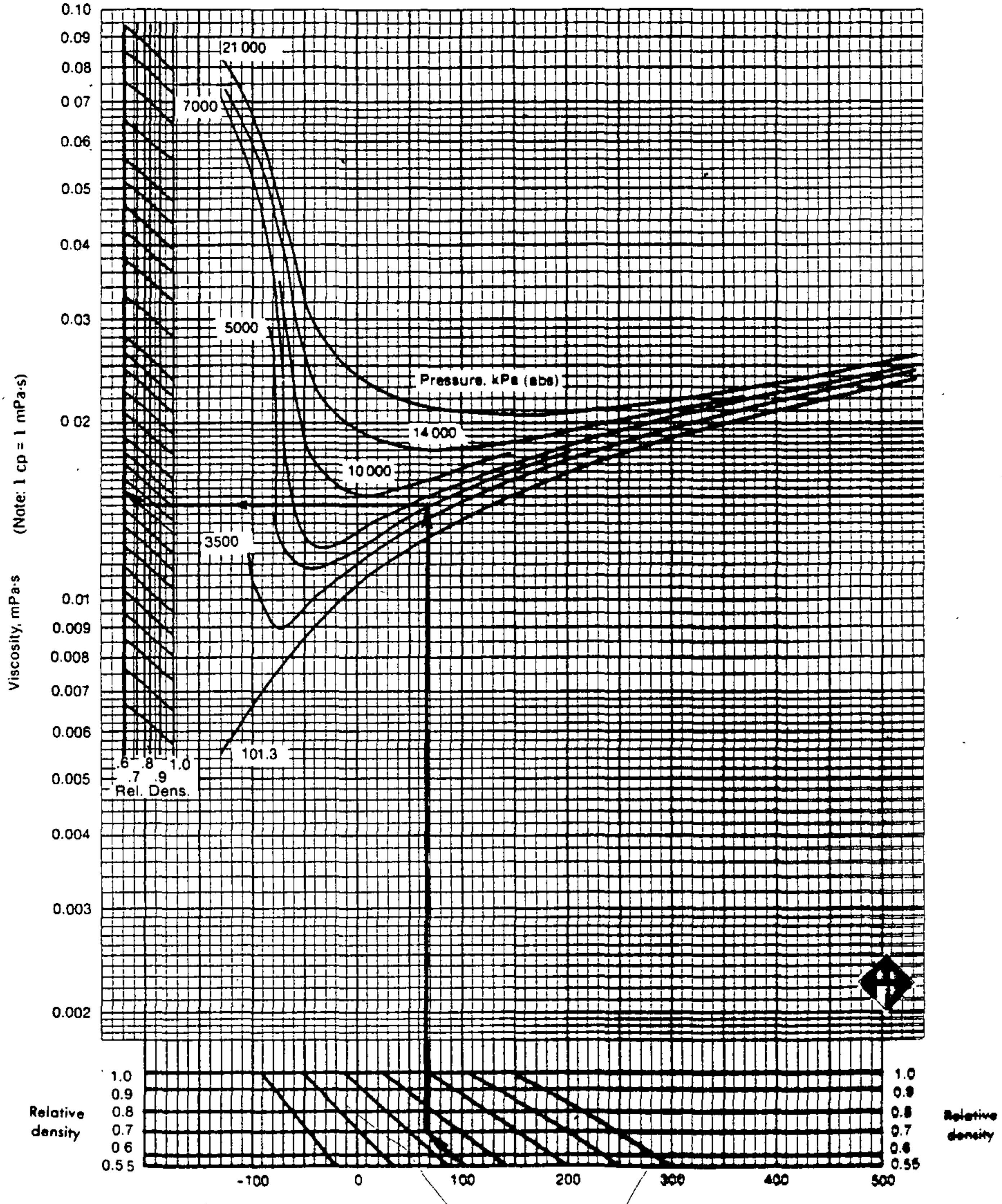
1. A.P.I. Research Project 44
2. Swift et al, AIChE Journal 6, No. 3, Sept. 1960
3. Parisot & Johnson, J. Chem. Eng. Data, 6, No. 2, Apr. 1960
4. Adapted from Heat Transfer Tables, American Locomotive Co., 1952

Olefins are approximately 15% less viscous than the corresponding normal paraffin hydrocarbons

IS

FIG. 16-24

Hydrocarbon gas viscosity



$$\sigma^{1/4} = \frac{P}{M}(d_L - d_v)$$

Where:

σ = Surface tension, dynes/cm

P = Parachor

M = Molecular mass

d_L = Liquid density, gm/cc, at the desired conditions

d_v = Vapor density, gm/cc, at the desired conditions

Note: Not valid within 40° of the critical temperature.

Whenever experimental surface tension data are available for the pure components in a mixture, the above equation can be used to estimate the parachor of each component. The parachor, a dimensionless number, of a pure component is essentially constant and is an additive property. The parachor of a mixture is the summation of the pure component parachors times their mole fractions in the mixture.

In the absence of experimental surface tension data for estimating the parachor, the group contribution values in the accompanying Fig. 16-30 may be used to calculate the parachors of pure components.

The parachor calculated from an equation derived from the Baker and Swerdloff plot for hydrocarbon mixtures seems to give fair estimates of surface tension when used in the Sudgen equation. The equation is:

$$P = 40 + 2.38\,(\text{M of liquid})$$

Fig. 16-31 relates parachor with molecular mass for paraffins and mixtures.

Surface tension for binaries of known composition at or near atmospheric pressure may be calculated using the procedure developed by Stackorsky (2):

$$\sigma_m = \frac{\sigma_1\ \sigma_2}{\sigma_1\ X_2 + \sigma_2\ X_1}$$

Where:

σ_1 = surface tension of component 1

σ_2 = surface tension of component 2

σ_m = surface tension of mixture

X_1 = mole fraction of component 1

X_2 = mole fraction of component 2

Surface tension for mixtures of known composition at high pressures may be calculated using the procedure developed by Weinaug and Katz (3):

$$\sigma_m^{1/4} = \Sigma P_i \left(X_i \frac{d_L}{M_L} - Y_i \frac{d_v}{M_v} \right)$$

Where:

σ_m = surface tension of the mixture, dynes/cm.

P_i = Parachor for component i

d_L = Liquid density of the mixture, gm/cc, at the desired conditions

d_v = Vapor density of the mixture, gm/cc, at the desired conditions

M_L = Liquid molecular mass of the mixture

M_v = Vapor molecular mass of the mixture

X_i = Liquid mole fraction of component i

Y_i = Vapor mole fraction of component i

For petroleum fractions, absorption oils and crude oils of unknown composition, the parachor may be estimated from the correlation of Baker and Swerdloff (4) for use in the above equation.

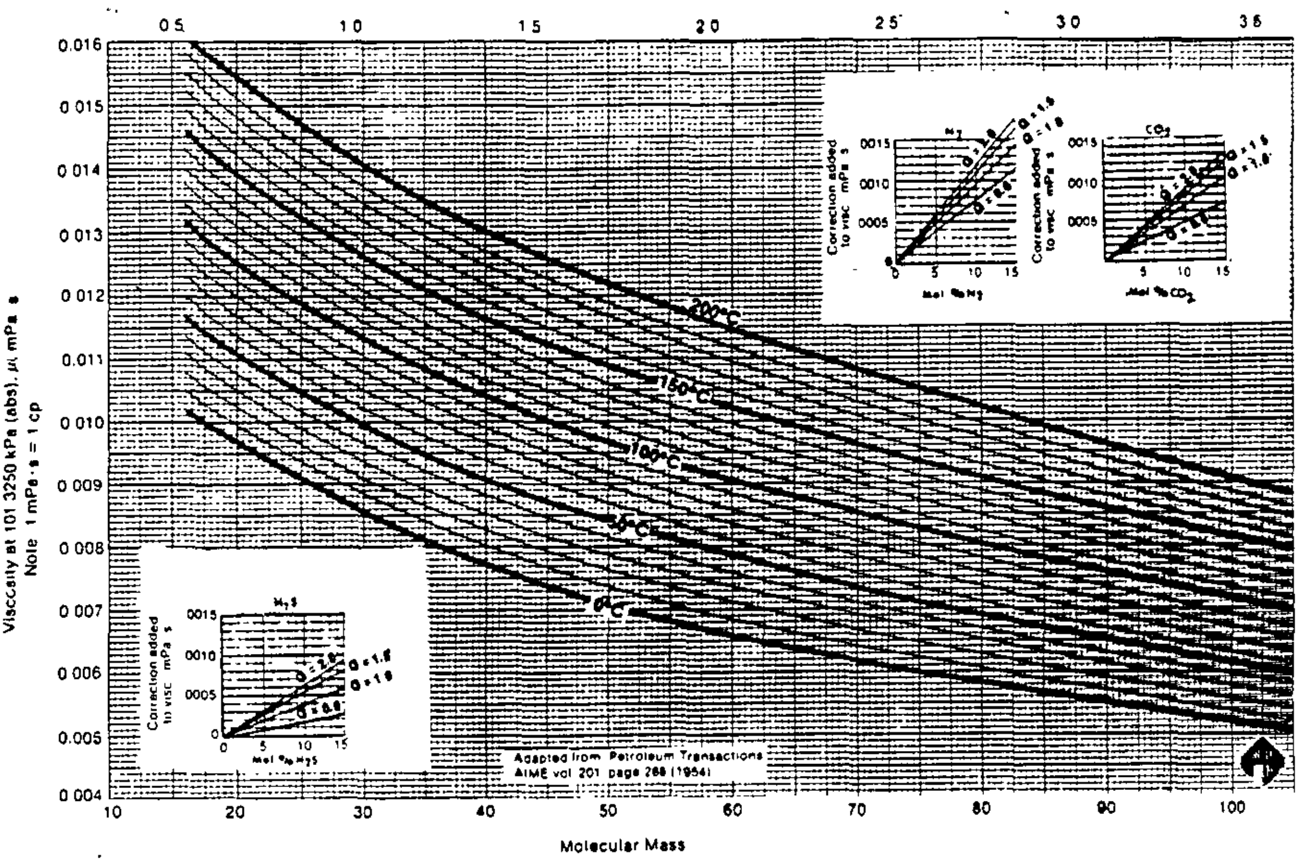
The presence of inert gases, such as N_2 and CO_2, in the liquid phase tends to lower the surface tension of the liquid. Where the concentration of inert gases in the liquid exceeds 1.0 mole %, estimated values of surface tension may be 5 to 20% higher than actual values for the mixture.

REFERENCES

1. Sudgen, S., "The variation of Surface Tension. VI. The Variation of Surface Tension With Temperature and Some Related Functions," J. Chem. Soc. 125, 32 (1924). Based on Macleod, Trans. Faraday Soc. 19, 38 (1923).
2. Stachorsky, K. M. "Surface Tensions of Liquid Mixtures," Z. Elektrochem. 34, 111 (1928).
3. Weinaug, C., Katz, D. L. "Surface Tension of Methane-Propane Mixtures", Ind. Eng. Chem. 35 239 (1943).
4. Baker, O., Swerdloff, W. "Calculations of Surface Tension-3: Calculations of Surface Tension Parachor Values", Oil Gas., J. Dec. 5, (1955).
5. "API Technical Data Book", Ch 10, Surface Tension.
6. J. R. Deam and R. N. Maddox — "Interfacial Tension in Hydrocarbon Systems," Proceedings of the 48th Annual Meeting of the Gas Processors Association, pp. 41-44, March, 1969 (Dallas).
7. J. R. Deam and R. N. Maddox — "Interfacial Tension in Hydrocarbon Systems," Proceedings of the 47th Annual Meeting of the Gas Processors Association, pp. 30-38, March, 1968 (New Orleans).
8. L. D. Bagzis and R. N. Maddox — "Calculating Surface Tension of Hydrocarbon Mixtures," Proceedings of the 49th Annual Meeting of the Gas Processors Association, pp. 41-45, March, 1970 (Denver).

FIG. 16-25

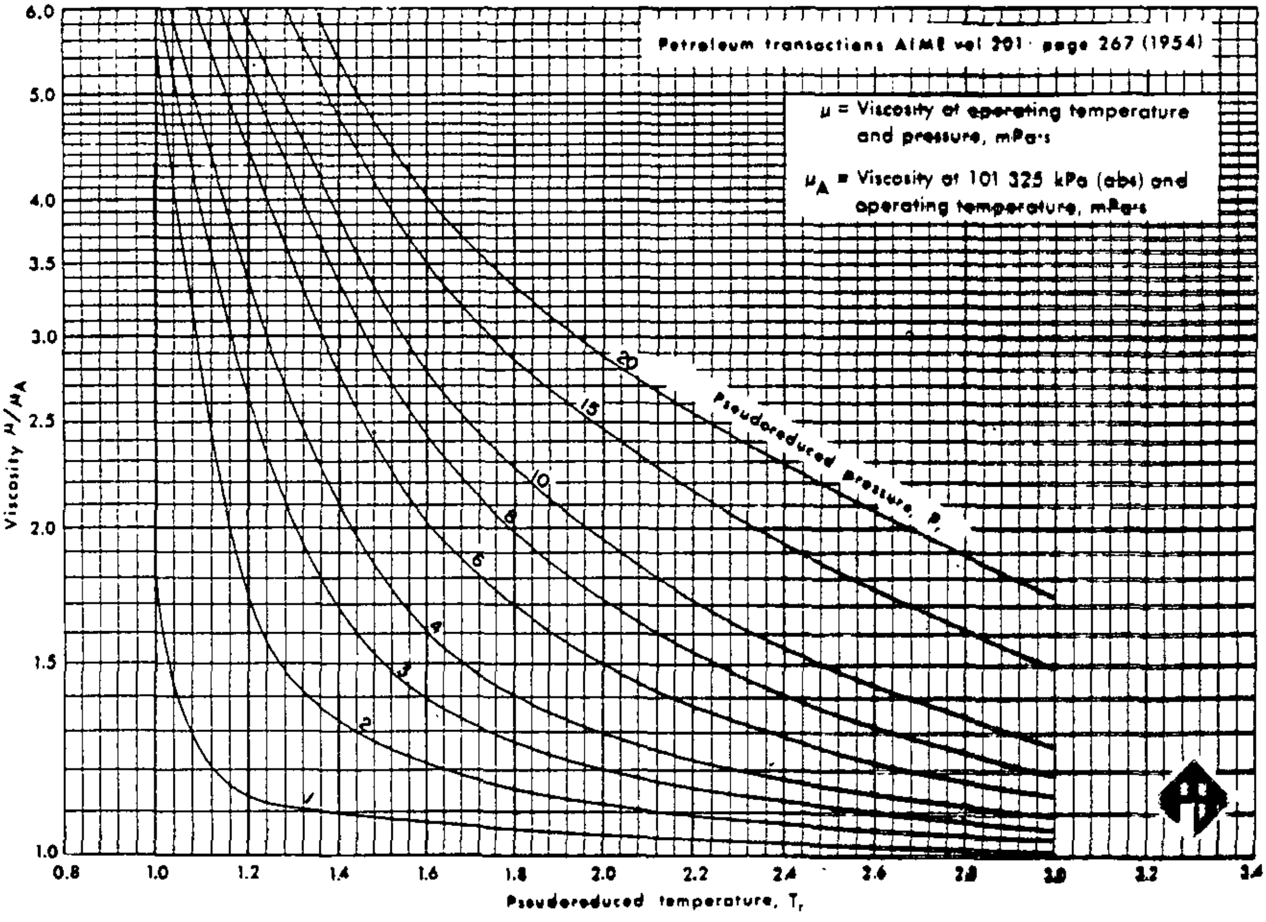
Viscosity of Paraffin Hydrocarbons
Gases at 101.3250 kPa (abs)



Adapted from Petroleum Transactions AIME vol 201 page 288 (1954)

FIG. 16-26

Viscosity ratio vs pseudo reduced temperature

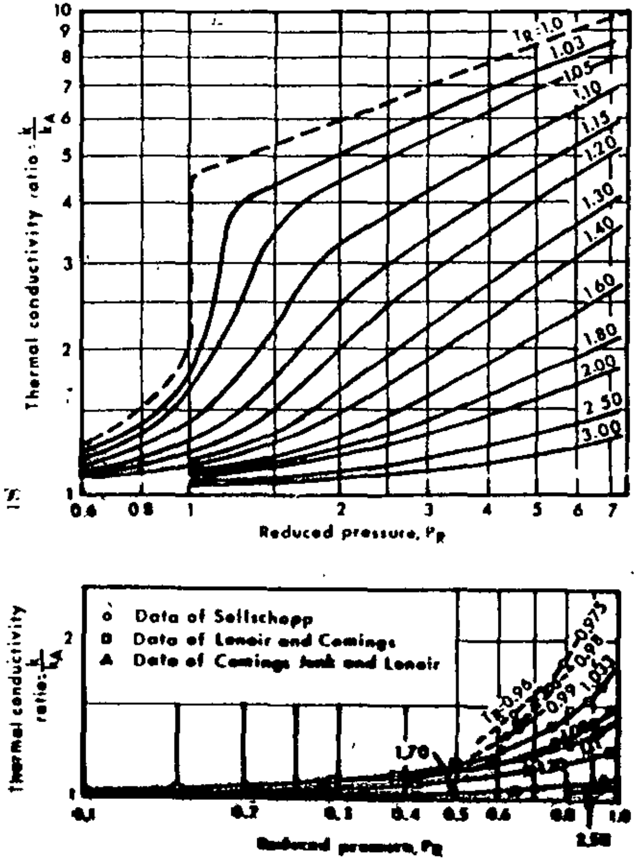


Petroleum transactions AIME vol 201 · page 267 (1954)

μ = Viscosity at operating temperature and pressure, mPa·s

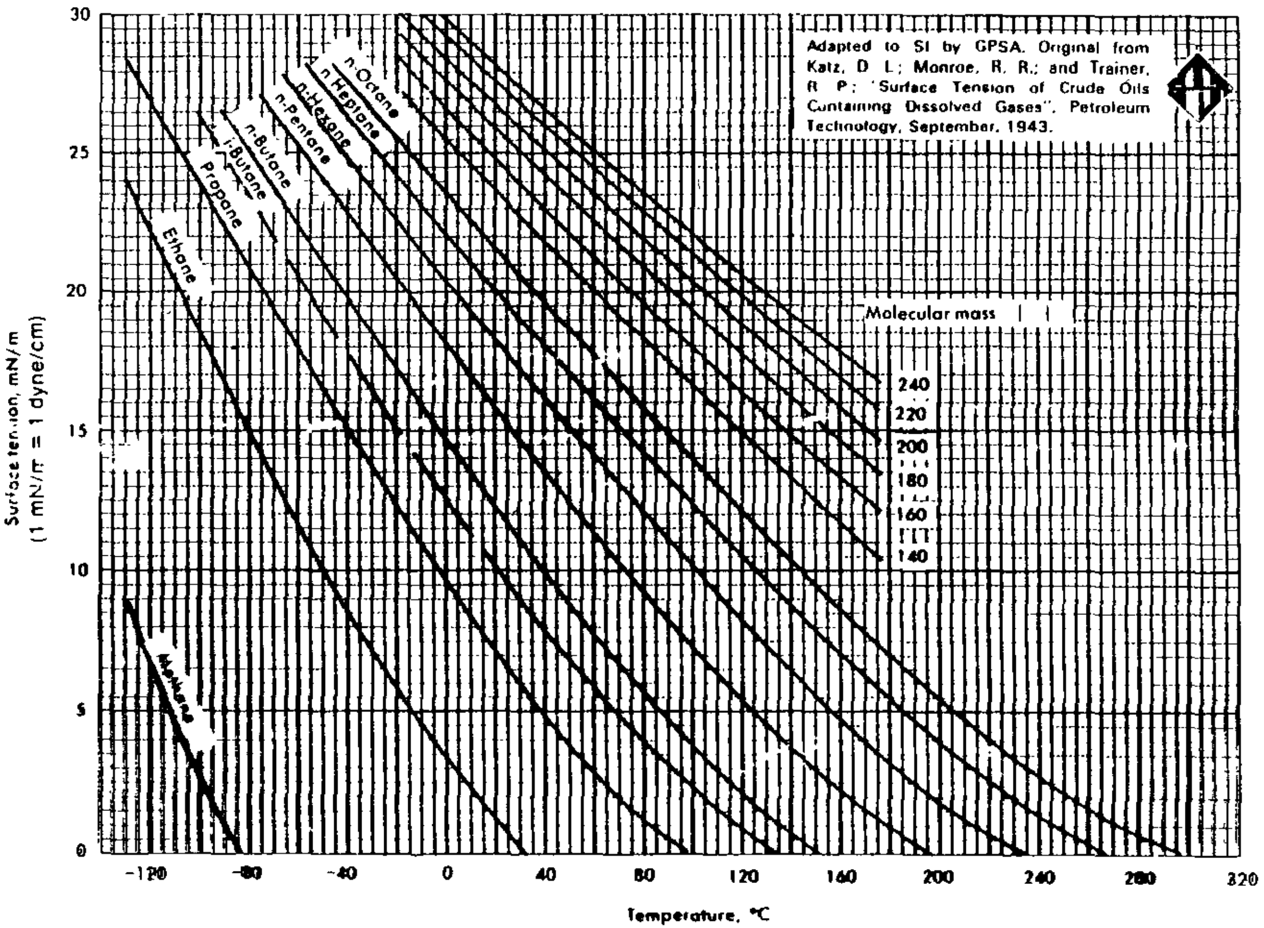
μ_A = Viscosity at 101 325 kPa (abs) and operating temperature, mPa·s

FIG. 16-28
Thermal conductivity ratio for gases



Measurement & correlation of thermal conductivity of gases of high pressure Lenoir, Junk and Comings.
Chem. Eng. Prog. vol. 49, no. 10 539 (1953)

FIG. 16-29
Surface tension of paraffin hydrocarbons



Adapted to SI by GPSA. Original from Katz, D. L.; Monroe, R. R.; and Trainer, R. P.; "Surface Tension of Crude Oils Containing Dissolved Gases", Petroleum Technology, September, 1943.

FIG. 16-30

Group contribution values for the calculation of parachors‡

Group	Increment
CH_2 in — $(CH_2)_N$,	
$N < 12$	40.0
$N > 12$	40.3
C	9.0
H	15.5
H in OH	10.0
H in HN	12.5
O	19.8
O_2 in esters	54.8
N	17.5
S	49.1
P	40.5
F	26.1
Cl	55.2
Br	68.0
I	90.3
Ethylenic bond	
Terminal*	19.1
2, 3—position	17.7
3, 4—position**	16.3
Triple bond	40.6
Carbonyl bond in ketones RCOR′	
Total C in—	
R + R′ = 3	22.3
4	20.0
5	18.5
6	17.3
7	17.3
8	15.1
9	14.1
10	13.0
11	12.6
Single bond	0.0
Semipolar bond	0.0
Singlet Linkage	−9.5
Hydrogen Bridge	−14.4
Chain Branching, per branch	−3.7
Secondary—secondary adjacency	−1.6
Secondary—tertiary adjacency	−2.0
Tertiary—tertiary adjacency	−4.5
Alkyl Groups	
1—Methyl ethyl	133.3
1—Methyl propyl	171.9
1—Methyl butyl	211.7
2—Methyl propyl	173.3
1—Ethyl propyl	209.5
1, 1—Dimethyl ethyl	170.4
1, 1—Dimethyl propyl	207.5
1, 2—Dimethyl propyl	207.9
1, 1, 2—Trimethyl propyl	243.5
Ring closure	
3-membered ring	12.5
4-membered ring	6.0
5-membered ring	3.0
6-membered ring	0.8
7-membered ring	4.0
Position differences in benzene	
Ortho-meta	1.8-3.4
Meta-para	0.2-0.5
Ortho-para	2.0-3.8

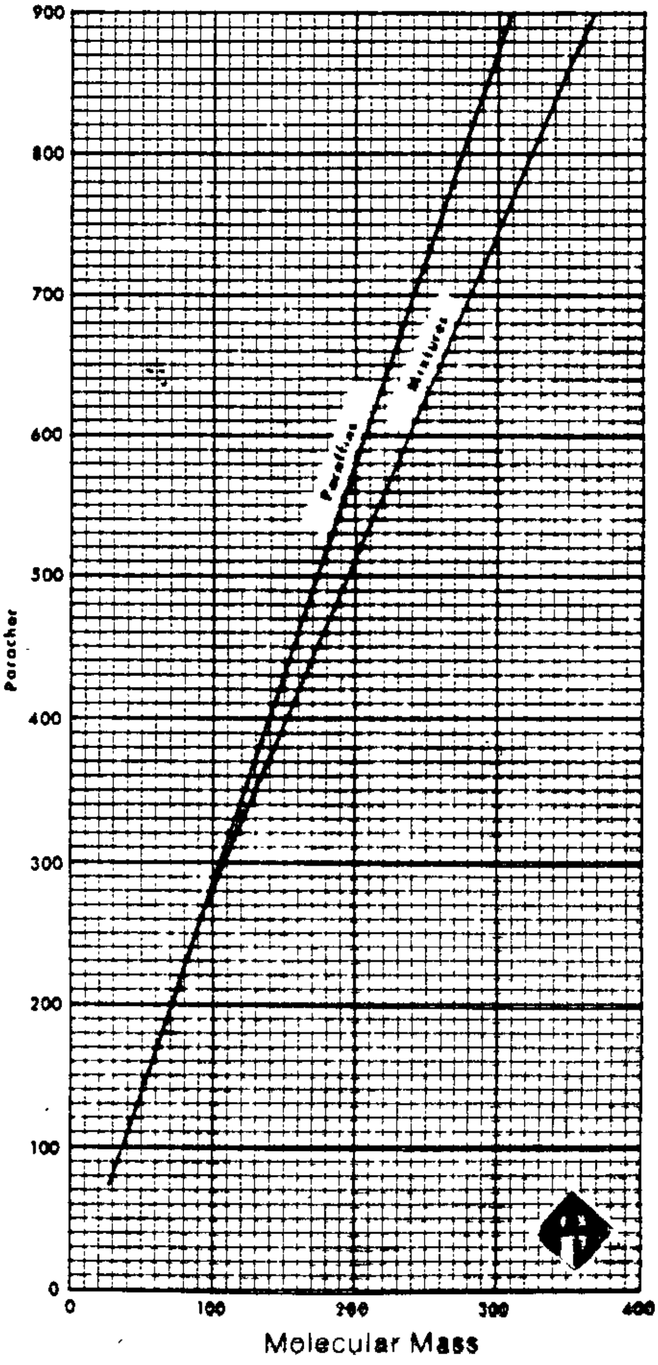
*Use this value for double bonds in cyclic compounds

**Use 16.3 for double bonds in the 3, 4 or higher positions

‡From O. R. Quale, Chem. Revs., 53 439 (1953)

FIG. 16-31

Parachors for paraffins and mixtures



FACULTAD DE INGENIERÍA UNAM
DIVISIÓN DE EDUCACIÓN CONTINUA

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INSTALACIONES DE GAS NATURAL

CLAVE CA- 231

TEMA

COMBUSTIÓN ESTEQUIOMÉTRICA Y AIRE PARA LA COMBUSTIÓN

DEL 26 AL 30 DE ABRIL

ING. ALFREDO SÁNCHEZ FLORES
PALACIO DE MINERÍA
ABRIL DE 2004

CAPITULO 2 Combustión estequiométrica y aire para la combustión

2.1 Definiciones

En cualquier instante y lugar el oxígeno se combina con otros elementos. Este es un proceso clásico de oxidación. Interesa estudiar aquí a fondo un proceso muy particular de oxidación; esto es, la combustión.

COMBUSTION

Se define como combustión a aquél proceso de oxidación rápida, en el cual el oxígeno reacciona con materiales combustibles para producir energía calorífica, generalmente en forma de gases de alta temperatura.

La gran mayoría de la energía calorífica utilizada por la humanidad, se produce por la ignición de combustibles sólidos, líquidos ó gaseosos con oxígeno contenido en el aire atmosférico, formando productos gaseosos durante el proceso. Los explosivos y ciertos combustibles no requieren aire para realizar la combustión, ya que el oxígeno necesario se encuentra químicamente ligado a ellos.

Combustión Teórica ó Estequiométrica

La combustión se denomina teórica o estequiométrica -conocida como completa- cuando todo el combustible se ha oxidado al máximo para producir CO_2, H_2O y SO_2.

Si la combustión es incompleta, los productos de la combustión poseen substancias todavía capaces de ser oxidados como cenizas, hollín ó gases combustibles como el CO, H_2, CH_4 y otros hidrocarburos. En este caso, no queda oxígeno libre. El propósito que se persigue en una buena combustión es evitar que ésta sea incompleta, ya que se relaciona a las pérdidas de combustible, energía y contaminación ambiental.

Combustión con Exceso de Oxígeno

La combustión real exige un exceso de oxígeno para llevar a cabo en forma completa la química de la combustión. Esto es, el combustible requiere una cantidad extra de oxígeno de la calculada en forma estequiométrica. En el uso cotidiano se suele manejar con el calificativo de "exceso de aire".

El exceso de aire se justifica por existir dificultad para lograr el contacto perfecto entre las moléculas de oxígeno, del aire, y los elementos constitutivos del combustible a ser oxidados. Se dice también que el exceso de aire sirve para incrementar la probabilidad de choque de ambos participantes.

Esto quiere decir que el exceso de aire asegura una combustión completa y, por ende, evita la generación de productos indeseables característicos de la combustión incompleta.

Más sin embargo, los exagerados excesos de aire en Generadores de Vapor motivan deterioros en las eficiencias Termodinámicas, sumados a otras consecuencias importantes de orden ecológico.

En términos reales, y estrictamente hablando, es obvio aclarar que no existen combustiones estequiométricas aun con excesos de aire apropiados. Siempre se presentan como productos de combustión algunos compuestos gaseosos semioxidados; claro está, en pequeñas proporciones. Véase Figura(2.1).

Oxígeno		Carbono		CO_2
				CO
				SO_x
				O_2
Nitrógeno	+	Hidrógeno	=	
		Azufre		NO_x
		Oxígeno		
Vapor de agua		Nitrógeno		H_2O
		Cenizas		Cenizas
		Agua		Desechos
				C_nH_m

Aire suministrado	+	Combustible	=	Productos

Figura 2.1

2.2 Ecuaciones Estequiométricas de combustión

De acuerdo a los conceptos de análisis químico es posible establecer las ecuaciones estequiométricas de mayor interés aplicado a un cierto combustible. En estas ecuaciones, el primer miembro contiene los reactantes, representados por el componente sujeto a oxidación más el oxidante, ambos dispuestos para la combustión, y el segundo miembro, los productos o gases generalmente, formados por la combustión más los poderes caloríficos.

Los principales componentes de todo combustible orgánico ó hidrocarburo son: carbono (C) e hidrógeno(H_2); además, el azufre (S) puede estar presente en pequeñas cantidades. Entonces, la mayor parte de los procesos de combustión se pueden circunscribir a las siguientes ecuaciones básicas:

$$C + O_2 \rightarrow CO_2 + 406,957 \text{ [kJ/kmol] ó } 33,913 \text{ [kJ/kg]} \qquad (2.1)$$

$$C + \tfrac{1}{2}O_2 \rightarrow CO + 124,013 \text{ [kJ/kmol] ó } 10,334 \text{ [kJ/kg]} \qquad (2.2)$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2 + 282,944 \text{ [kJ/kmol] ó } 10,105 \text{ [kJ/kg]} \qquad (2.3)$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow (H_2O)_{liq} + 286,796 \text{ [kJ/kmol] ó } 142,260 \text{ [kJ/kg]} \qquad (2.4)$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow (H_2O)_{vap} + 241,756 \text{ [kJ/kmol] ó } 119,919 \text{ [kJ/kg]} \qquad (2.5)$$

$$S + O_2 \rightarrow SO_2 + 296,677 \text{ [kJ/kmol] ó } 9,271 \text{ [kJ/kg]} \qquad (2.6)$$

en dichas ecuaciones:

O_2	representa 32 kg de oxígeno;
CO_2	representa 44 kg de bióxido de carbono;
H_2	representa 2 kg de hidrógeno y
S	representa 32 kg de azufre.

En los casos del carbono (C) y el azufre (S), que evidentemente son sólidos, se ocupan los pesos atómicos ya que el número de atomos en la molécula resulta incierto. Cuando se forma agua en la combustión, su estado final, ya sea líquido o vapor, se han indicado con un subíndice.

Debido a que un kilomol [kmol] (por ejemplo) de cualquier gas ocupa el mismo volumen a las mismas condiciones de temperatura y presión, el volumen de CO_2 producido por la combustión de carbono es igual al volumen del oxígeno consumido bajo las mismas condiciones. Si se desprecia el volumen de carbono sólido, entonces no ocurre variación en el volumen durante el proceso de combustión. Lo mismo pasa para otros combustibles sólidos como azufre, por ejemplo. Entonces, la combustión del carbono en monóxido de carbono (CO) da un incremento de volumen en 0.5; en cambio, la combustión del CO y H_2 experimentan un decremento en el volumen de 1.5 kmol de reactantes a 1 kmol de productos de combustión.

Si se analizan, para el caso de algunos gases, las ecuaciones:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2(H_2O)_{liq} + 889{,}276 \text{ [kJ/kmol] ó } 55{,}474 \text{ [kJ/kg]} \tag{2.7}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2(H_2O)_{liq} + 1\ 449{,}470 \text{ [kJ/kmol] ó } 51{,}711 \text{ [kJ/kg]} \tag{2.8}$$

$$C_2H_6 + 3\tfrac{1}{2}O_2 \rightarrow 2CO_2 + 3(H_2O)_{liq} + 1,\ 561{,}258 \text{ [kJ/kmol] ó } 51{,}955 \text{ [kJ/kg]} \tag{2.9}$$

$$H_2S + 1\tfrac{1}{2}O_2 \rightarrow SO_2 + (H_2O)_{liq} + 561{,}536 \text{ [kJ/kmol] ó } 16{,}536 \text{ [kJ/kg]} \tag{2.10}$$

Se puede observar que, por ejemplo, en los casos del metano (CH_4) y del etileno (C_2H_4) no existe cambio en el volumen después de la combustión. En el caso del etano y todos los hidrocarburos con más de cuatro átomos de hidrógeno, se presenta un incremento de volumen en sus productos.

Las cantidades indicadas en las ecuaciones anteriores consideran los reactantes (carburante y comburente) inicialmente a 0 °C y los productos de la combustión finalmente enfriados hasta 0 °C.

2.3 Oxígeno y aire necesario para la combustión y sus productos, caso combustibles sólidos y líquidos.

Generalmente en textos tradicional y en manuales de ingeniería se presentan ecuaciones para el cálculo del oxígeno y aire necesario para la combustión, cuya procedencia se ignora y hasta parecen fórmulas empíricas. En esta sección se deducirán las ecuaciones correspondientes, paso por paso, por los caminos másicos y molares.

2.3.1 Análisis másico

Para este análisis se requiere, obviamente, conocer la composición másica del combustible, en cuanto a carbono (C), hidrógeno (H_2) y azufre (S).

Tomando el caso de combustión completa, la ecuación para el carbono resulta:

$$C + O_2 \rightarrow CO_2 \tag{2.11}$$

Lo cual expresado en términos de sus masas moleculares queda:

$$12 \text{ kg de } C + (2x16) \text{ kg de } O_2 = 44 \text{ kg de } CO_2$$

INCREMENTO DE VOLUMEN

$$\Delta V = (22.41/12)[3h + 3/8\ o + 2/3\ w]\ [\mathrm{Nm^3/kg_c}] \qquad (2.33)$$

Cuando se quema 1 kg de combustible con la cantidad teórica de aire X_{min}, el nitrógeno aparece tanto en los reactantes como en los productos. Entonces, el volumen de los productos es:

$$V_{pmin} = X_{min} + \Delta V = X_{min} + (22.41/12)[3h + 3/8\ o + 2/3\ w][\mathrm{Nm^3/kg_c}] \qquad (2.34)$$

En la ecuación (2.34) puede notarse que el incremento de volumen durante la combustión depende exclusivamente de hidrógeno, oxígeno y de la humedad presentes en el combustible.

EXCESO DE AIRE

Si X es la cantidad práctica de aire para asegurar la combustión completa, se tiene:

$$X = \lambda X_{min} = (1+\delta)\, X_{min} \qquad (2.35)$$

donde:

λ es la relación de aire
δ es el coeficiente de exceso de aire o simplemente el exceso de aire.

entonces, el volumen total de los productos de combustión está dado por:

$$V_p = X + (22.41/12)[3h + 3/8\ o + 2/3\ w]\ [\mathrm{Nm^3/kg_c}] \qquad (2.36)$$

Puesto que el exceso de oxígeno y la totalidad del nitrógeno pasan por el proceso sin cambio alguno. Es obvio que en condiciones reales se propicia la formación de NO_x.

2.4 Oxígeno y aire necesario para la combustión completa y sus productos: gases combustibles gaseosos

2.4.1 Oxígeno y aire para la combustión con gases combustibles.

La composición de los combustibles gaseosos se expresa en fracciones molares (también llamadas volumétricas), como por ejemplo:

$$(r_{CO})_c + (r_{H2})_c + (r_{CH4})_c + (r_{C2H4})_c + (r_{O2})_c + (r_{N2})_c + (r_{CO2})_c = 1 \text{ ó } 100\% \qquad (2.37)$$

donde:

El subíndice "*c*" refiere al gas componente antes de la combustión.

Los componentes gaseosos de la ecuación (2.37) corresponden a un combustible hipótetico, los cuales se tomarán como ejemplos. Debe admitise que otros combustibles gaseosos pueden tener más o menos componentes.

Entonces, para la combustión completa de este gas combustible, dado por la ecuación (2.37) se requieren las cantidades de oxígeno ya presentadas en las ecuaciones (2.3), (2.5), (2.7) y (2.8), por orden de aparición. Los gases componentes O_2, N_2 y CO_2 no figuran, obviamente, en estos requerimientos de oxígeno.

Haciendo la aclaración que un [kmol] a las mismas condiciones de presión y temperatura ocupan el mismo volumen, las ecuaciones estequiomé-tricas resultan ser ecuaciones volumétricas. Si estos volúmenes se toman a condiciones normales, el O_{min} se calcula por:

$$O_{min} = 0.5(r_{CO})_c + 0.5(r_{H2})_c + 2(r_{CH4})_c + 3(r_{C2H4})_e - (r_{O2})_e \ [Nm^3/Nm^3c] \qquad (2.38)$$

O lo que es lo mismo, la relación estequiométrica gas combustible-oxígeno es para:

a) el CO de 1 a 0.5
b) el H_2 de 1 a 0.5
c) el CH_4 de 1 a 2.0
d) el c_2H_4 de 1 a 3.0

Entonces, el aire mínimo o estequiométrico se calcula por la relación siguiente:

$$X = O_{min}/0.21$$

$$X_{\min} = \frac{0.5(r_{CO})_c + 0.5(r_{H_2})_c + 2(r_{CH_4})_c + 3(r_{C_2H_4})_e - (r_{O_2})_e}{0.21} \quad \left[\frac{Nm^3}{Nm_e^3}\right] \qquad (2.39)$$

Recuérdese que (2.39) sólo es válido para el gas combustible adoptado como ejemplo.

También se aplica aquí la ecuación (2.35) para asegurar una combustión completa. El aire necesario se calcula por:

$$X = \lambda \left[\frac{0.5(r_{CO})_c + 0.5(r_{H_2})_c + 2(r_{CH_4})_c + 3(r_{C_2H_4})_c - (r_{O_2})_c}{0.21} \right] \left[\frac{Nm^3}{Nm^3_c} \right] \quad (2.40)$$

Aire práctico de la combustión

2.4.2 Productos de gases combustibles

Después de efectuado el proceso de combustión y de acuerdo a (2.40), donde $X = \lambda X_{min}$, se puede tomar en cuenta que:

a) El CO se transforma en CO_2 en proporción 1 a 1.

b) El H_2 se transforma en H_2O en proporción 1 a 1.

c) El CH_4 se transforma en CO_2 en proporción 1 a 1. Además, se produce H_2O en proporción 1 a 2.

d) El C_2H_4 se transforma en CO_2 en proporción 1 a 2. Además, se produce H_2O en proporción 1 a 2.

e) Los demás gases como el CO_2, O_2 y N_2 pasan idealmente sin alterarse. La verdad es que eventualmente pueden transformarse en NO_x.

En suma, los productos de la combustión de gases combustibles se componen de los siguientes volumenes parciales:

BIOXIDO DE CARBONO

$$(V_{CO_2})_p = (r_{CO})_c + (r_{CH_4})_c + 2(r_{C_2H_4})_c + (r_{CO_2})_c \quad (2.41)$$

VAPOR DE AGUA

$$(V_{H_2O})_v = (r_{H_2})_c + 2(r_{CH_4})_c + 2(r_{C_2H_4})_c \quad (2.42)$$

OXIGENO

$$(V_{O_2})_p = (\lambda - 1)O_{min} = \delta O_{min} = 0.21X - O_{min} \quad (2.43)$$

NITROGENO

$$(V_{N_2})_p = (r_{N_2})_e + 0.79X \tag{2.44}$$

Las expresiones anteriores se dan en [kmol] o en unidades volumétricas. Por kilogramo de combustible [Nm^3/kg_c].

Comparando los volumenes de los productos con el gas combustible sumado al del aire, existe un decremento igual a:

$$\Delta V_p = = 0.5[(r_{CO})_e + (r_{H_2})_n] \tag{2.45}$$

el cual se debe totalmente a la combustión del CO y del H_2, ya que el CH_4 y el C_2H_4 se queman sin cambio de volumen.

Como en los productos de combustión aparecen tantos kmoles de CO_2 como kmoles hay de carbono en un combustible dado, se cumple:

$$\sigma = \frac{O_{min}}{(V_{CO_2})_p} \tag{2.46}$$

donde:

O_{min} y $(VCO_2)_p$ se expresa en [$kmol/kg_e$] ó [Nm^3/kg_e]

Entonces, los coeficientes característicos para este combustible son:

$$\sigma = \frac{0.5(r_{CO})_c + 0.5(r_{H_2})_c + 2(r_{CH_4})_4 + 3(r_{C_2H_4})_e - (r_{O_2})_e}{(r_{CO})_c + (r_{CH_4})_c + 2(r_{C_2H_4})_c + (r_{CO_2})_e} \tag{2.47}$$

$$v = \frac{(V_{N_2})_c}{(V_{CO_2})_p}$$

(2.48)

$$v = \frac{(r_{N_2})_c}{(r_{CO})_c + (r_{CH_4})_c + 2(r_{C_2H_4})_e + (r_{CO_2})_e}$$

2.5 Relación entre la composición de los productos de la combustión y la cantidad de oxígeno o aire necesario

Puesto que los productos de la combustión se secan antes de realizar su análisis, el vapor de agua y el bióxido de azufre se condensan y no aparecen en el análisis. Entonces:

$$(r_{CO_2})_p + (r_{O_2})_p + (r_{N_2})_p = 1 \text{ ó } 100\% \qquad (2.49)$$

donde:

Cada término representa la fracción volumétrica o molar y el subíndice p se refiere a los productos.

De (2.43) y (2.46) se obtiene la relación oxígeno y bióxido de carbono en los productos como:

$$\frac{(V_{O_2})_p}{(V_{CO_2})_p} = \frac{(\lambda - 1)O_{min}}{\frac{O_{min}}{\sigma}} = (\lambda - 1)\sigma \qquad (2.50)$$

Con exceso de aire, la cantidad total de oxígeno suministrado es (λO_{min})kmol y el nitrógeno suministrado es $(0.79/0.21)\lambda O_{min}$. Usando la ecuación (2.49) se puede obtener el volumen de nitrógeno que es: $(0.79/0.21)\lambda\sigma(CO_2)_p$. El nitrógeno presente en el gas combustible también se puede expresar en términos del contenido de carbono por el símbolo v. Este nitrógeno debe pasar a los productos de la combustión de igual forma. Puesto que los productos contienen tantos kmoles de CO_2 como kmoles de C hay de combustibles, el nitrógeno del combustible que está en los productos es $v(VCO_2)_p$. Entonces, la relación del nitrógeno total al bióxido de carbono en los productos está dada por:

$$(V_{N_2})_p/(V_{CO_2})_p = [(0.79/0.21)\lambda\sigma] + v \qquad (2.51)$$

Si las ecuaciones (2.49), (2.50) y (2.51) se solucionan para $(r_{CO_2})_p$, $(r_{O_2})_p$ y $(V_{N_2})_p$ se obtiene:

$$(r_{CO_2})_p = \frac{0.21}{(\lambda - 0.21)\sigma + 0.21(v + 1)} \qquad (2.52a)$$

$$(r_{O_2})_p = \frac{0.21(\lambda - 1)\sigma}{(\lambda - 0.21)\sigma + 0.21(v + 1)} \qquad (2.52b)$$

$$(r_{N_2})_p = \frac{0.79\ \lambda\ \sigma + 0.21\ v}{(\lambda - 0.21)\sigma + 0.21(v + 1)} \tag{2.52c}$$

De la ecuación (2.49) y de estas tres ecuaciones se obtiene:

$$\lambda = \frac{0.21}{\sigma}\left[\frac{1}{(r_{CO_2})_p} + \sigma - 1 - v\right] \tag{2.53}$$

Como regla, si el contenido de nitrógeno se desconoce las últimas cuatro ecuaciones se reducen a:

$$(r_{CO_2})_p = \frac{0.21}{(\lambda - 0.21)\sigma + 0.21} \tag{2.54a}$$

$$(r_{O_2})_p = \frac{0.21(\lambda - 1)\sigma}{(\lambda - 0.21)\sigma + 0.21} \tag{2.54b}$$

$$(r_{N_2})_p = \frac{0.79\ \lambda\ \sigma}{(\lambda - 0.21)\sigma + 0.21} \tag{2.54c}$$

$$\lambda = \frac{0.21}{\sigma}\left[\frac{1}{(CO_2)_p} + \sigma - 1\right] \tag{2.55}$$

Por medio de estas ecuaciones se puede determinar el exceso de aire de la combustión si se conoce el contenido porcentual molar de CO_2 en los gases secos de combustión y los coeficientes σ y v.

Cuando en el combustible no hay nitrógeno, el coeficiente σ puede eliminarse de las dos primeras ecuaciones (2.54), y después de solucionar para λ se obtiene:

$$\lambda = \frac{1 - (r_{CO})_p - (r_{O_2})_p}{1 - (r_{CO})_p - \left(\frac{1}{0.21}\right)(r_{O_2})_p} \tag{2.56}$$

Esta ecuación no puede usarse en cálculos que requieren una aproximación en el análisis de los productos que no puede alcanzarse prácticamente.

2.6 Relaciones empíricas entre X_{min}, V_p y PCI.

En la práctica se puede demostrar que el consumo mínimo de aire y el volumen de productos de combustión pueden representarse como función lineal de los poderes caloríficos inferiores. Estas relaciones se enuncian por grupos afines de combustibles como sigue:

Combustibles sólidos: PCI < 23,300 kJ/kg$_c$:

$$X_{min} = \left[\frac{0.5619}{23300}\, PCI + 0.5 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.57a)}$$

$$V_{p_{min}} = \left[\frac{0.4932}{23300}\, PCI + 1.823 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.57a)}$$

Combustibles sólidos: PCI > 23,300 kJ/kg$_c$:

$$X_{min} = \left[\frac{0.5619}{23300}\, PCI + 0.5619 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.58a)}$$

$$V_{p_{min}} = \left[\frac{0.5556}{23300}\, PCI + 0.874 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.58b)}$$

Combustibles líquidos (para todo PCI):

$$X_{min} = \left[\frac{0.472}{23300}\, PCI + 2 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.59a)}$$

$$V_{p_{min}} = \left[\frac{0.618}{23300}\, PCI \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.59b)}$$

Gases combustible: PCI < 11,200 kJ/Nm^3:

$$X_{min} = \left[\frac{7.8}{16900}\, PCI \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.60a)}$$

$$V_{p_{min}} = \left[\frac{5.7}{16900}\, PCI \pm 1.11 \right] \qquad \left[\frac{Nm^3}{kg_c}\right] \qquad \textbf{(2.60b)}$$

Gases combustible: PCI > 11,200 kJ/Nm³:

$$X_{min} = \left[\frac{0.5619}{16900} PCI - 0.25 \right] \qquad \left[\frac{Nm^3}{kg_c} \right] \qquad (2.61a)$$

$$V_{p_{min}} = \left[\frac{12}{16900} PCI - 0.67 \right] \qquad \left[\frac{Nm^3}{kg_c} \right] \qquad (2.61b)$$

En el caso de combustibles sólidos y líquidos, el PCI se da por unidad de masa del combustible, mientras que en el caso de combustibles gaseosos el PCI se toma por unidad de volumen en condiciones normales.

Con ayuda de estas ecuaciones se puede determinar el volumen de los productos a partir del poder calorífico del combustible. Para obtener los productos reales de la combustión se puede usar la ecuación:

$$V_p = V_{pmin} + (\lambda - 1)X_{min}$$

Este método empírico simplifica considerablemente los cálculos de combustión. Los resultados son lo suficientemente aproximados para todos los fines prácticos.

3.2 Combustibles Gaseosos

En el desarrollo de este capítulo, se analizan los productos de combustión tanto del gas L.P. como los del gas natural, considerando una combustión ideal o completa, así como una combustión real aproximada.

3.2.1 Caso Gas L.P.

El gas L.P., tiene un mayor uso en aplicaciones domésticas, aunque algunas industrias lo utilizan como combustible para calderas y generadores de vapor. Se dice que su uso resulta atractivo debido a su alta eficiencia de combustión y su alto poder calorífico. Este gas se compone básicamente de gases como butano y propano, su composición exacta la proporciona la planta que lo destila.

La siguiente tabla proporciona un análisis cromatográfico de un gas L.P de la zona metropolitana de la Cd. de México.

COMPOSICION MASICA DEL GAS L.P.

Etano	CH_4	0.02%
Etano + etileno	C_2H_6	0.45%
Propano	C_3H_8	46.64%
Propileno	C_3H_6	0.05%
iso-Butano + n-Butano	C_4H_{10}	49.50%
1-Buteno	C_4H_8	0.37%
iso-Buteno	C_5H_{10}	0.09%
iso-Pentano	C_6H_2	2.88%

Obteniendo las reacciones de combustión de cada uno de sus componentes y calculando el O_{min} necesario para que se realice la combustión, resulta:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$16\ kg\ CH_4 + 64\ kg\ O_2 \rightarrow 44\ kg\ CO_2 + 36\ kg\ H_2O$$

$$1\ kg\ CH_4 + \frac{64}{16}\ kg\ O_2 \rightarrow \frac{44}{16}\ kg\ CO_2 + \frac{36}{16}\ kg\ H_2O$$

3.2.2 Caso Gas Natural

El Gas Natural es muy estimado en el ámbito de Calderas y Generadores de Vapor debido a que proporciona una correcta combustión al no poseer azufre ni cenizas. El motivo por le cual no se hace extensivo su uso es por que su oferta es muy limitada y se expende solamente en determinadas zonas del país.

El Gas Natural esta compuesto básicamente por Etano, Metano, Bióxido de Carbono y otros gases. Es obvio que su composición varia en función del yacimiento.

La siguiente proporciona las características del gas natural en su composición molar (o volumétrica) que fueron tomadas de un análisis cromatográfico según PEMEX.

COMPOSICION MOLAR DEL GAS NATURAL

Etano	CH_4	=	76.30
Bióxido de Carbono	CO_2	=	0.60
Etano + Etileno	C_2H_6	=	6.00
Metano	C_2H_4	=	2.30
Propano	C_3H_8	=	0.10
Propileno	C_3H_6	=	0.70
Hidrógeno	H_2	=	10.80
Nitrógeno	N_2	=	3.20

Las ecuaciones de reacción son:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + 3\tfrac{1}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

$$C_3H_6 + 4\tfrac{1}{2}O_2 \rightarrow 3CO_2 + 3H_2O$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

Masas moleculares de los componentes del Gas Natural en [kg/kmol] son:

CH_4 = 16
CO_2 = 44
C_2H_6 = 30
C_2H_4 = 28
C_3H_8 = 44
C_3H_6 = 42
H_2 = 2
N_2 = 28

Poo lo que la Masa molecular del Combustible [kg_c/kmol]:

0.763(16) = 12.208
0.006(44) = 0.264
0.060(30) = 1.800
0.023(28) = 0.644
0.001(44) = 0.044
0.007(42) = 0.294
0.108(2) = 0.216
0.032(28) = 0.896
$\sum$ riMi = Mc = 16.366 (masa molecular del combustible)

Entonces el valor de la densidad del combustible (ρ_c) se calcula por:

$$\rho_c = \frac{M_c}{22.41} = \frac{16.366}{22.41} = 0.738 \left[\frac{kg_c}{Nm_c^3}\right]$$

Ahora para encontrar el valor de los volumenes parciales de bióxido de carbono $(V_{CO_2})_p$ y el vapor de agua $(V_{H_2O})_p$, productos de combustión son:

$$(V_{CO_2})_p = 1(0.763)+2(0.06)+2(0.023)+3(0.001)+3(0.007)+0.006 =$$

$$(V_{CO_2})_p = 0.956 \left[\frac{Nm^3_{CO_2}}{Nm^3_c}\right]$$

$$(V_{H_2O})_p = 2(0.763)+3(0.06)+2(0.023)+4(0.001)+3(0.007)+1(0.108) =$$

$$(V_{H_2O})_p = 1.8850 \left[\frac{Nm^3_{H_2O}}{Nm^3_c}\right]$$

El oxígeno mínimo *(O_{min})* para la combustión es:

$$O_{min} = 2(0.763) + 3.5(0.06) + 3(0.023) + 5(0.001) + 4.5(0.007) + 0.5(0.108)$$

$$O_{min} = 1.8955 \left[\frac{Nm^3_{O_2}}{Nm^3_c}\right]$$

Por tanto, el aire estequiométrico *(X_{min})* resulta:

$$X_{min} = \frac{O_{min}}{0.21} = \frac{1.8955}{0.21} = 9.026 \left[\frac{Nm^3}{Nm^3_c}\right]$$

Considerando $\lambda = 5\%$ se obtiene:

$$(V_{O_2})_p = O_{min}(\lambda - 1) = 1.8955(1.05-1) = 0.0947 \left[\frac{Nm^3}{Nm^3_c}\right]$$

$$(V_{N_2})_p = r_{(N_2)_c} + 0.79(\lambda X_{min}) = 0.032 + 0.79\{9.026(1.05)\} = 7.5190 \left[\frac{\Lambda}{\Lambda}\right.$$

El volumen total un base humeda es igual a:

$$V_T = (V_{CO_2})_p + (V_{H_2O})_p + (V_{O_2})_p + (V_{N_2})_p$$

$$V_T = 0.959 + 1.885 + 0.0947 + 7.519 = 10.4577 \left[\frac{Nm^3}{Nm^3_c}\right]$$

Las fracciones volumétricas de los productos de la combustión estequiométricas en base humeda es igual a:

$$r_{(CO_2)} = \frac{(V_{CO_2})_p}{V_T} = \frac{0.9590}{10.4577} = 0.0917$$

$$r_{(H_2O)} = \frac{(V_{H_2O})_p}{V_T} = \frac{1.885}{10.4577} = 0.1802$$

El volumen total un base seca es igual a:

$$x_{(O_2)} = \frac{(V_{O_2})_p}{V_T} = \frac{0.0947}{10.4577} = 0.0090$$

$$x_{(N_2)} = \frac{(V_{N_2})_p}{V_T} = \frac{7.519}{10.4577} = 0.7189$$

$$V_T = (V_{CO_2})_p + (V_{O_2})_p + (V_{N_2})_p$$

$$V_T = 0.959 + 0.0947 + 7.519 = 8.5637 \left[\frac{Nm^3}{Nm^3_c}\right]$$

Las fracciones volumétricas de los productos de la combustión estequiométricas en base seca es igual a:

$$x_{(CO_2)} = \frac{(V_{CO_2})_p}{V_T} = \frac{0.9590}{8.5637} = 0.1119$$

$$x_{(O_2)} = \frac{(V_{O_2})_p}{V_T} = \frac{0.0947}{8.5637} = 0.0110$$

$$x_{(N_2)} = \frac{(V_{N_2})_p}{V_T} = \frac{7.510}{8.5637} = 0.8769$$

Por lo tanto los coeficientes característicos del Gas Natural son:

$$\sigma = \frac{O_{\min}}{V_{(CO_2)_p}} = \frac{1.8955}{0.9590} = 1.9765$$

$$\nu = \frac{V(N_2)_c}{V_{(CO_2)_p}} = \frac{0.032}{0.9590} = 0.0333$$

Aplicando las ecuaciones (2.52a, 2.52b y 2.52c) para un exceso de aire (λ) predeterminado se obtienen los volumenes parciales productos de una combustión estequiemétrica en base seca para el Gas Natural, se muestra en la Tabla 3.5

Exceso de Aire λ [%]	$(\Gamma_{CO_2})_p$	$(\Gamma_{O_2})_p$	$(\Gamma_{N_2})_p$
0	0.118081	0	0.881919
1	0.116783	0.002308	0.880909
10	0.10627	0.021004	0.872725
20	0.096608	0.038189	0.865203
30	0.088556	0.052509	0.858935
40	0.081743	0.064626	0.853632
50	0.075903	0.075011	0.849086

Tabla 3.5 Fracciones Volumétricas de los Gases de Combustión del Gas Natural

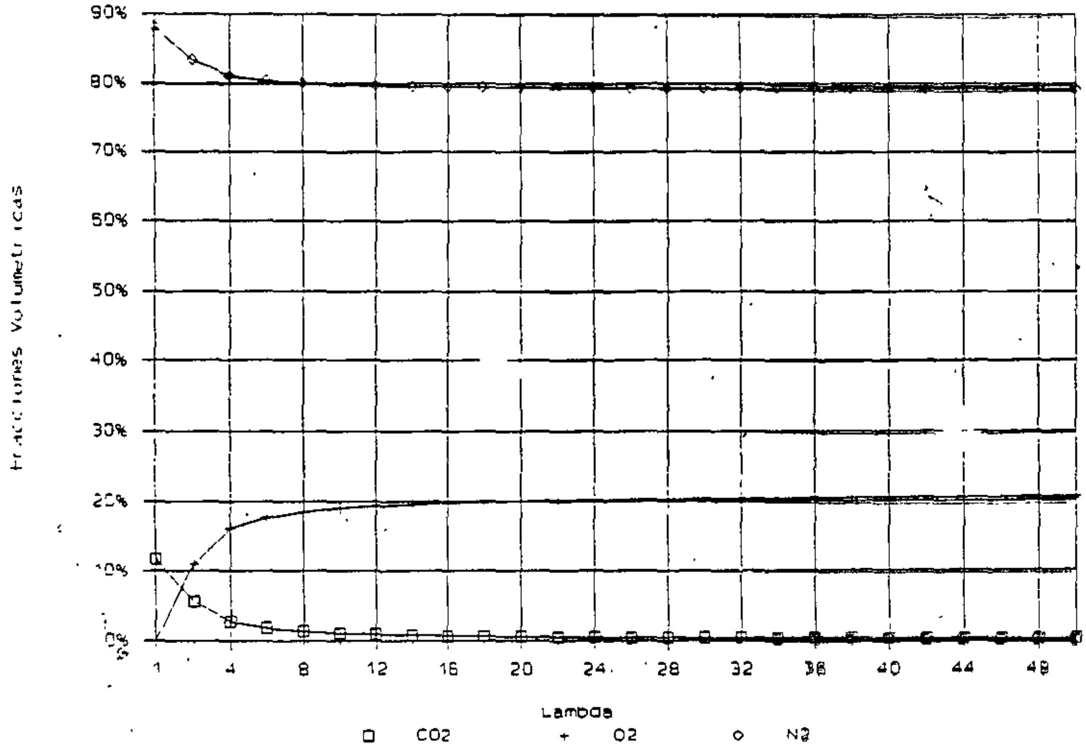


Figura 3.5 Gráfica Característica del Gas Natural

$$V'_{CO} = V_{CO} \times \frac{\rho^N_{CO}}{\rho^N_C} = 0.0075 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.2494 \left[\frac{kg_{CO}}{Nm^3_{CO}}\right]}{2.2489 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 0.0042 \left[\frac{kg_{CO}}{kg_c}\right]$$

$$V''_{O_2} = V'_{O_2} \times \frac{\rho^N_{O_2}}{\rho^N_C} = 1.1254 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.4279 \left[\frac{kg_{O_2}}{Nm^3_{O_2}}\right]}{2.2489 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 0.7149 \left[\frac{kg_{O_2}}{kg_c}\right]$$

$$V''_{N_2} = V'_{N_2} \times \frac{\rho^N_{N_2}}{\rho^N_C} = 25.4840 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.2494 \left[\frac{kg_{N_2}}{Nm^3_{N_2}}\right]}{2.2489 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 14.1579 \left[\frac{kg_{N_2}}{kg_c}\right]$$

$$V'_{NO_x} = V_{NO_x} \times \frac{\rho^N_{NO_x}}{\rho^N_C} = 0.00601 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.3386 \left[\frac{kg_{NO_x}}{Nm^3_{NO_x}}\right]}{2.2489 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 0.0036 \left[\frac{kg_{NO_x}}{kg_c}\right]$$

3.3.2.2 Productos de una combustión real aproximada para el Gas Natural

Caso A: Exceso de aire = λ = 5%

Composición de los gases secos

Los volumenes parciales son:

$$(V_{CO_2})_P = 0.9560 \left[\frac{Nm^3_{CO_2}}{Nm^3_C}\right]$$

$$(V_{O_2})_P = 0.0947 \left[\frac{Nm^3_{O_2}}{Nm^3_C}\right]$$

$$(V_{N_2})_p = 7.5190 \left[\frac{Nm^3_{O_2}}{Nm^3_c}\right]$$

Por lo que el volumen total (Base seca) es:

$$V_T = (V_{CO_2})_p + (V_{O_2})_p + (V_{N_2})_p$$

$$V_T = 0.9560 + 0.0947 + 7.5190 = 8.5637 \left[\frac{Nm^3}{Nm^3_c}\right]$$

Las fracciones volumetricas son iguales a:

$$x_{(CO_2)} = \frac{(V_{CO_2})_p}{V_T} = \frac{0.9590}{8.5637} = 0.1118$$

$$x_{(O_2)} = \frac{(V_{O_2})_p}{V_T} = \frac{0.0947}{8.5637} = 0.0110$$

$$x_{(N_2)} = \frac{(V_{N_2})_p}{V_T} = \frac{7.5190}{8.5637} = 0.8770$$

Por lo que la composición ideal es:

$$x_{CO_2} = 111\ 800\ ppm$$

$$x_{O_2} = 11\ 000\ ppm$$

$$x_{N_2} = 877\ 000\ ppm$$

Se considera que una parte de CO_2 se convierte a CO y que tanto N_2 como O_2 dará origen a una cantidad de NOx, de lo anterior se puede determinar una composición real aproximada, la que se muestra a continuación:

r'_{CO_2} = 111 550 ppm

r_{CO} = 250 ppm*

r'_{O_2} = 10 900 ppm

r'_{N_2} = 876 900 ppm

r_{NO_x} = 200 ppm*

*Según Norma ecológica

Recalculando los volúmenes parciales:

$$V'_{CO_2} = r'_{CO_2} \times V_T = (111\ 550 \times 10^{-6})(8.5727) = 0.9562 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V_{CO} = r_{CO} \times V_T = \ 50 \times 10^{-6})(8.5727) = 0.00214 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V'_{O_2} = r'_{O_2} \times V_T = (10\ 900 \times 10^{-6})(8.5727) = 0.0934 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V'_{N_2} = x'_{N_2} \times V_T = (879\ 900 \times 10^{-6})(8.57274) = 7.5174 \left[\frac{Nm^3}{Nm_C^3} \right]$$

$$V_{NO_x} = x_{NO_x} \times V_T = (200 \times 10^{-6})(8.5727) = 0.0017 \left[\frac{Nm^3}{Nm_C^3} \right]$$

Realizando un artificio matemático con la (ρ^N) del componente, así como con la (ρ_C^N) del combustible se deduce que:

$$V''_{CO_2} = V'_{CO_2} \times \frac{\rho_{CO_2}^N}{\rho_C^N} = 0.9562 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.9630 \left[\frac{kg_{CO_2}}{Nm_{CO_2}^3} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 2.5436 \left[\frac{kg_{CO_2}}{kg_C} \right]$$

$$V'_{CO} = V_{CO} \times \frac{\rho_{CO}^N}{\rho_C^N} = 0.00214 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.2494 \left[\frac{kg_{CO}}{Nm_{CO}^3} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 0.00362 \left[\frac{kg_{CO}}{kg_C} \right]$$

$$V''_{O_2} = V'_{O_2} \times \frac{\rho_{O_2}^N}{\rho_C^N} = 0.0934 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.4279 \left[\frac{kg_{O_2}}{Nm_{O_2}^3} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 0.1807 \left[\frac{kg_{O_2}}{kg_C} \right]$$

$$V''_{N_2} = V'_{N_2} \times \frac{\rho_{N_2}^N}{\rho_C^N} = 7.5174 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.2494 \left[\frac{kg_{N_2}}{Nm_{N_2}^3} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 12.7266 \left[\frac{kg_{N_2}}{kg_C} \right]$$

$$Y_{NO_x} = V_{NO_x} \times \frac{\rho^N_{NO_x}}{\rho^N_C} = 0.0017 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.3386 \left[\frac{kg_{NO_x}}{Nm^3_{NO_x}}\right]}{0.7380 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 0.003108 \left[\frac{kg_{NO_x}}{kg_C}\right]$$

Caso B: Exceso de aire = λ = 20%
Composición de los gases secos

Los volumenes parciales son:

$$(V_{CO_2})_p = 0.9590 \left[\frac{Nm^3_{CO_2}}{Nm^3_C}\right]$$

$$V_{O_2})_p = O_{min}(\lambda - 1) = 1.8955(1 - 1.20) = 0.3791 \left[\frac{Nm^3_{O_2}}{Nm^3_C}\right]$$

$$(V_{N_2})_p = (x_{N_2})_c + 0.79(X_{min} \cdot \lambda) = 0.032 + 0.79(9.026 \cdot 1.20) = 8.5886 \left[\frac{Nm^3_{N_2}}{Nm^3_C}\right]$$

Por lo que el volumen total (Base seca) es:

$$V_T = (V_{CO_2})_p + (V_{O_2})_p + (V_{N_2})_p$$

$$V_T = 0.9590 + 0.3791 + 8.5886 = 9.9267 \left[\frac{Nm^3}{Nm^3_C}\right]$$

Las fracciones volumetricas son iguales a:

$$x_{(CO_2)} = \frac{(V_{CO_2})_p}{V_T} = \frac{0.9590}{9.9267} = 0.0966$$

Por lo que la composición ideal es:

$$x_{(O_2)} = \frac{(V_{O_2})_p}{V_T} = \frac{0.3791}{9.9267} = 0.0381$$

$$x_{(N_2)} = \frac{(V_{N_2})_p}{V_T} = \frac{8.5886}{9.9267} = 0.8652$$

$x_{CO_2} = 96\ 600\ ppm$

$x_{O_2} = 38\ 100\ ppm$

$x_{N_2} = 865\ 200\ ppm$

Se considera que una parte de CO_2 se convierte a CO y que tanto N_2 como O_2 dará origen a una cantidad de *NOx*, de lo anterior se puede determinar una composición real aproximada, la que se muestra a continuación:

$x'_{CO_2} = 96\ 350\ ppm$

$x_{CO} = 250\ ppm^*$

$x'_{O_2} = 38\ 000\ ppm$

$x'_{N_2} = 865\ 100\ ppm$

$x_{NO_x} = 200\ ppm^*$

egún Norma ecológica

Recalculando los volúmenes parciales:

$$V'_{CO_2} = x'_{CO_2}\ x\ V_T = (96\ 350\ x\ 10^{-6})(9.9267) = 0.6564 \left[\frac{Nm^3}{Nm^3_c} \right]$$

$$V_{CO} = x_{CO} \times V_T = (250 \times 10^{-6})(9.9267) = 0.0024 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V'_{O_2} = x'_{O_2} \times V_T = (38\ 000 \times 10^{-6})(9.9267) = 0.3772 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V'_{N_2} = x'_{N_2} \times V_T = (865\ 100 \times 10^{-6})(9.9267) = 8.5875 \left[\frac{Nm^3}{Nm_c^3} \right]$$

$$V_{NO_x} = x_{NO_x} \times V_T = (200 \times 10^{-6})(9.9267) = 0.0019 \left[\frac{Nm^3}{Nm_c^3} \right]$$

Realizando un artificio matemático con la (ρ^N) del componente, así como con la (ρ_C^N) del combustible se deduce que:

$$V''_{CO_2} = V'_{CO_2} \times \frac{\rho^N_{CO_2}}{\rho^N_C} = 0.9564 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.9630 \left[\frac{kg_{CO_2}}{Nm^3_{CO_2}} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 2.5440 \left[\frac{kg_{CO_2}}{kg_c} \right]$$

$$V'_{CO} = V_{CO} \times \frac{\rho^N_{CO}}{\rho^N_C} = 0.0024 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.2494 \left[\frac{kg_{CO}}{Nm^3_{CO}} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 0.0024 \left[\frac{kg_{CO}}{kg_c} \right]$$

$$V''_{O_2} = V'_{O_2} \times \frac{\rho^N_{O_2}}{\rho^N_C} = 0.3772 \left[\frac{Nm^3}{Nm_C^3} \right] \left(\frac{1.4279 \left[\frac{kg_{O_2}}{Nm^3_{O_2}} \right]}{0.7380 \left[\frac{kg_C}{Nm_C^3} \right]} \right) = 0.7298 \left[\frac{kg_{O_2}}{kg_c} \right]$$

$$V'_{N_2} = V'_{N_2} \times \frac{\rho^N_{N_2}}{\rho^N_C} = 8.5875 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.2494 \left[\frac{kg_{N_2}}{Nm^3_{N_2}}\right]}{0.7380 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 14.5382 \left[\frac{kg_{N_2}}{kg_c}\right]$$

$$V'_{NO_x} = V_{NO_x} \times \frac{\rho^N_{NO_x}}{\rho^N_C} = 0.0019 \left[\frac{Nm^3}{Nm^3_C}\right] \left(\frac{1.3386 \left[\frac{kg_{NO_x}}{Nm^3_{NO_x}}\right]}{0.7380 \left[\frac{kg_C}{Nm^3_C}\right]} \right) = 0.0036 \left[\frac{kg_{NO_x}}{kg_c}\right]$$

A continuación se muestra un resumen de las combustiones reales del Gas L.P. y el Gas Natural, para lo cual se tomó encuenta la Norma Ecológica para el Valle de México [1], dichas combustiones se muestran en las Tablas 3.9 y 3.10

Tabla 3.9 Caso Gas L.P.

Producto de la Combustión	$\lambda = 5\%$		$\lambda = 20\%$	
	[kg/kg$_c$]	[ppm]	[kg/kg$_c$]	[ppm]
*CO_2	3.0174	132950	3.0157	115050
*CO	0.0036	250	0.0041	250
N_2	12.3625	855800	14.1296	846900
*NO_x	0.0030	200	0.0036	200
O_2	0.1766	10700	0.7131	37400

* Son considerados productos contaminantes

Tabla 3.10 **Caso Gas Natural**				
Producto de la Combustión	**$\lambda = 5\%$**		**$\lambda = 20\%$**	
	[kg/kg$_c$]	**[ppm]**	[kg/kg$_c$]	**[ppm]**
*CO_2	2.5436	111550	2.5440	**96350**
*CO	0.0036	**250**	0.0024	**250**
N_2	12.7266	**876900**	14.5382	865100
*NO_x	0.0031	**200**	0.0036	**200**
O_2	0.1807	10900	0.7298	38000

* Son considerados productos contaminantes

CURSOS ABIERTOS

INSTALACIÓN DE GAS NATURAL

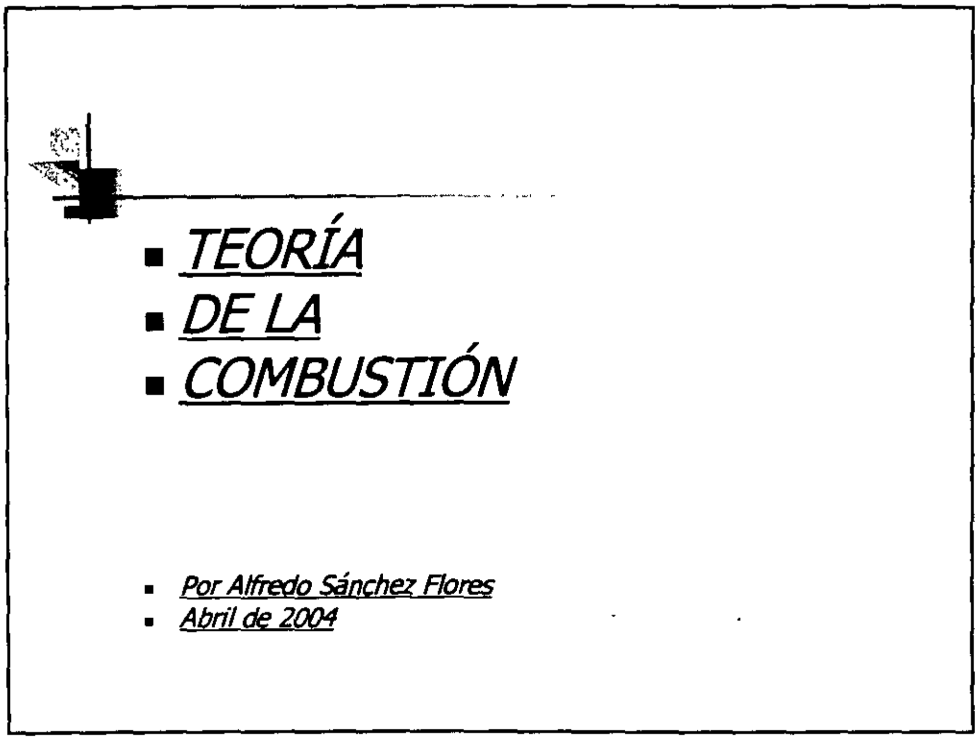
CLAVE CA-231

TEMA

TEORÍA DE LA COMBUSTIÓN

DEL 19 AL 30 DE ABRIL

ING. ALFREDO SÁNCHEZ FLORES
PALACIO DE MINERÍA
ABRIL DE 2004



- *TEORÍA*
- *DE LA*
- *COMBUSTIÓN*

- *Por Alfredo Sánchez Flores*
- *Abril de 2004*

Part 1. BASIC PRINCIPLES OF COMBUSTION SCIENCE

WHAT IS COMBUSTION?

Combustion, or **burning**, is a rapid combination of oxygen with a fuel, resulting in release of heat.

The oxygen comes from the air, which is about 21% oxygen and 78% nitrogen by volume. (See Table 1.1.)

Most fuels contain carbon, hydrogen, and sometimes sulfur. (See Table 1.4.) As a simplification, we might say that combustion consists of the following three processes:

carbon + oxygen ⟶ carbon dioxide + heat
hydrogen + oxygen ⟶ water vapor + heat
sulfur + oxygen ⟶ sulfur dioxide + heat

The three products of combustion listed above are called **chemical compounds**, and they are made up of molecules in which elements are combined in

Table 1.1. Composition of air[1]

% by Volume (mole) % by Weight	60 F db 0% rh[2]	60 F db 80% rh	60 F db 100% rh	90 F db 20% rh	90 F db 80% rh	90 F db 100% rh
	Dry Bulb Temperature (db) and Relative Humidity (rh)					
Oxygen, O_2	20.99 23.20	20.70 22.99	20.62 22.94	20.79 23.06	20.19 22.63	19.99 22.50
Nitrogen, N_2	78.03 75.46	76.94 74.81	76.67 74.63	77.29 75.01	75.06 73.61	74.32 73.18
Argon, Ar	0.94 1.30	0.93 1.29	0.92 1.28	0.93 1.29	0.90 1.27	0.90 1.26
Other[3]	0.04 0.04	0.04 0.04	0.04 0.04	0.04 0.04	0.04 0.04	0.04 0.04
Water, H_2O	0.00 0.00	1.40 0.87	1.75 1.10	0.95 0.59	3.81 2.46	4.70 3.02
Equiv. molecular weight	28.96	28.81	28.77	28.86	28.55	28.45
Density, lb/ft³	0.07632	0.07587	0.07581	0.07189	0.07111	0.07080
Density, kg/m³	1.222	1.216	1.214	1.152	1.139	1.134

[1] For easy computation, it is convenient to remember these ratios.
$Air/O_2 = 100/20.99 = 4.76$ by volume (mole). $Air/O_2 = 100/23.20 = 4.31$ by weight
$N_2/O_2 = 3.76$ by volume (mole); $N_2/O_2 = 3.31$ by weight

[2] From International Critical Tables, all other columns calculated from I.C.T. data and from Reference 1.1 at the end of Part 1.

[3] CO_2 (about 0.03%), H_2 (about 0.01%), Neon, Helium, Krypton, Xenon.

certain fixed proportions. For example, a molecule of carbon dioxide contains one atom of carbon plus two atoms of oxygen; a molecule of water vapor contains two atoms of hydrogen plus one atom of oxygen. (See Table 1.4.)

It is an established law of science that matter* is neither created nor destroyed in the process of combustion, and that the heat given off in any combustion process is merely excess energy which the new molecules are forced to liberate because of their internal make-up.

Let us now use equations to show how one carbon atom plus two oxygen atoms (one molecule) burn to form one carbon dioxide molecule and heat:

Fig. 1.2. $C + O_2 \longrightarrow CO_2$ + heat.

Likewise, when two hydrogen atoms burn, one molecule of water is formed.

Fig. 1.3. $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ + heat, or $2H_2 + O_2 \longrightarrow 2H_2O$ + heat.

The second of the above two forms is the more common way of writing this process, because oxygen usually comes in package units, or di-atomic molecules, containing two oxygen atoms. The amount of heat released in this case is twice as great as when only one oxygen atom and two hydrogen atoms are used.

---

* Matter is anything which has weight and occupies space. Energy does not have weight and does not occupy space.

PERFECT COMBUSTION

Perfect combustion is obtained by mixing and burning just exactly the right proportions of fuel and oxygen so that nothing is left over, as in Figures 1.2 and 1.3. This is like a situation which exists at the assembly line in an automobile factory. Each chassis needs four wheels, and this is the only proportion (4 to 1) that will go together properly. If the conveyor supplying the wheels moves too slowly, some chassis will go by incomplete. But if the wheel conveyor goes too fast, there will be some wheels left over.

Table 1.4. Elements and compounds commonly encountered in combustion*

Element (E) or Compound	Symbol	Relative (mol) Weight†	Normal State	Found in	lb/ft³ at stp	kg/m³ at stp	Gas Gravity
Air○	—	28.96	gas	—	0.0763	1.225	1.000
Butane, n-	$n\text{-}C_4H_{10}$	58.12	vapor or liquid	fuels	0.1582	2.593	2.067
Carbon (E)	C	12.01	solid	fuels,♦ flue gas♦	130	2300	—
Carbon dioxide	CO_2	44.01	gas	flue gas	0.1170	1.874	1.529
Carbon monoxide	CO	28.01	gas	fuels, flue gas♦	0.0740	1.185	0.967
Ethane	C_2H_6	30.07	gas	fuels	0.0803	1.366	1.049
Hydrogen (E)	H	1.01	—	—	—	—	—
Hydrogen	H_2	2.02	gas	fuels	0.00532	0.0898	0.0696
Hydrogen sulfide	H_2S	34.08	gas	fuels	0.0900	1.539	1.177
Methane	CH_4	16.04	gas	fuels	0.0424	0.676	0.554
Nitrogen (E)	N	14.01	—	—	—	—	—
Nitrogen	N_2	28.01	gas	air, fuels♠, flue gas	0.0744	1.191	0.972
Octane, n-	$n\text{-}C_8H_{18}$	114.23	liquid	fuels	—	—	—
Oxygen (E)	O	16.00	—	—	—	—	—
Oxygen	O_2	32.00	gas	air, fuels♠, flue gas	0.0846	1.354	1.105
Propane	C_3H_8	44.10	vapor or liquid	fuels	0.1196	1.916	1.567
Sulfur (E)	S	32.06	solid	fuels♠	119-130	1906-2081	—
Sulfur dioxide	SO_2	64.06	gas	fuels♠ flue gas	0.1733	2.776	2.264
Sulfur trioxide	SO_3	80.06	gas	flue gas	0.2109	3.378	2.765
Water	H_2O	18.02	liquid	fuels♠,	62.4	1000	—
Water	H_2O	18.02	vapor	flue gas	0.0476	0.761	0.622

* Parts of this table are derived from data from Reference 1.1—see list of references at the end of Part 1.

♠ Usually in minor amounts in fuels, a trace constituent

○ Air is neither an element nor a compound, but a mixture of both. See Table 1.1. Air is listed here only for comparison.

† If the element or compound is in the gaseous state, the density of the gas in lb/ft³ will be the relative (mol) weight divided by 379, the ft³/lb mol at 60 F and 14.696 psia, or 359 at 0 F. The density in kg/m³ will be the relative (mol) weight divided by 22.4 m³/kg mol at 0 Celsius and 760 mm Hg. Example: for N_2 or CO, 28 ÷ 379 = 0.0739 lb/ft³ at 60 F; 28 ÷ 359 = 0.0780 at 0 F; 28 ÷ 22.4 = 1.250 kg/m³ at 0 C.

♦ Not found in combustion products if a good burner is properly adjusted at stoichiometric or slightly less air/fuel ratio.

If too much oxygen (excess air) is supplied, we say that the mixture is lean and that the fire is oxidizing. This results in a flame that tends to be shorter and clearer. The excess oxygen plays no part in the process. For example, if four atoms of oxygen (instead of two) were mixed with an atom of carbon, two oxygen atoms would be left over. (This is like having six wheels for every chassis.)

Fig. 1.4. $C + 2O_2 \rightarrow CO_2 + O_2 +$ heat.

If too much fuel (or not enough oxygen) is supplied we say that the mixture is rich and that the fire is reducing. (This results in a flame that tends to be longer and sometimes smoky.) This is usually called incomplete combustion; that is, all of the fuel particles combine with some oxygen, but they cannot get enough oxygen to burn completely. (Like chassis with only three wheels.) For example, if we mix two atoms of carbon (instead of one) with two atoms of oxygen, the carbon atoms may share the available oxygen, but neither has enough to become carbon dioxide. Instead they may form carbon monoxide (CO), a compound which will burn to carbon dioxide if given more oxygen later.

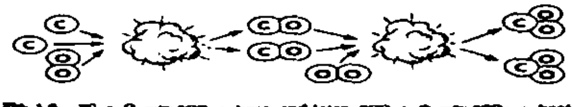


Fig. 1.5. $2C + O_2 \rightarrow 2CO +$ heat, and later, $2CO + O_2 \rightarrow 2CO_2 +$ heat.

Table 1.7 lists the proper proportions for perfect combustion of several typical fuels. The fuel and air must not only be properly proportional but also thoroughly mixed. Otherwise one part of the fire may be rich while the other part remains lean.

The **oxygen supply** for combustion usually comes from the air. Because air contains a large proportion of nitrogen, the required volume of air is much larger than the required volume of pure oxygen. (See Table 1.1.)

The nitrogen in the air does not take part in the combustion reaction—it just goes along for the ride. It does, however, absorb some of the heat with the result that the heat energy is *spread thinly* throughout a large quantity of nitrogen and the combustion products. This means that a much lower flame temperature results from using air instead of pure oxygen. The same phenomenon occurs when excess air is supplied, as in Figure 1.5. The effect of excess air on efficiency and flame temperature is covered in Figures 3.10 and 3.12 of Part 3.

Primary air is that air which is mixed with the fuel at (or in) the burner. **Secondary air** is usually that air brought in around the burner. **Tertiary air** is usually that air brought in downstream of secondary air or through other openings in the furnace.

COMBUSTION OF PRACTICAL FUELS

Carbon, hydrogen, and sulfur are seldom burned in their pure forms. Most fuels are mixtures of chemical compounds called **hydrocarbons** (combinations of hydrogen and carbon some of which are listed in Table 1.4). When these burn, the final products are carbon dioxide and water vapor unless there is a shortage of oxygen, in which case the products may contain carbon monoxide, hydrogen, unburned hydrocarbons, and free carbon.

Up to now, we have spoken only of the *final* products of combustion. Although these final products are usually limited to the same few compounds for all hydrocarbon fuels, they are not always produced by the same combustion process. Within different flames, many varied and unknown processes and intermediate products occur, even though the final products are the same.

Table 1.7. Proper combining proportions for perfect combustion
(See also Tables 1.10, 2.1, 2.12, 3.1)

Fuel	vol O_2 / vol fuel	vol air / vol fuel	wt O_2 / wt fuel	wt air / wt fuel	ft³ O_2 / lb fuel	ft³ air / lb fuel	m³ O_2 / kg fuel	m³ air / kg fuel
Acetylene, C_2H_2	2.50	11.9	3.08	13.3	36.5	174	2.28	10.8
Benzene, C_6H_6	7.50	35.7	3.08	13.3	36.5	174	2.28	10.8
Butane, C_4H_{10}	6.50	31.0	3.59	15.5	42.5	203	2.65	12.6
Carbon, C	—	—	2.67	11.5	31.6	150	1.87	8.90
Carbon monoxide, CO	0.50	2.38	0.571	2.46	6.76	32.3	0.422	2.01
Ethane, C_2H_6	3.50	16.7	3.73	16.1	44.2	210	2.76	13.1
Hydrogen, H_2	0.50	2.38	8.00	34.5	94.7	451	5.92	28.2
Hydrogen sulfide, H_2S	1.50	7.15	1.41	6.08	16.7	79.6	1.04	4.97
Methane, CH_4	2.00	9.53	4.00	17.2	47.4	226	2.96	14.1
Naphthalene, $C_{10}H_8$	—	—	3.00	12.9	35.5	169	2.22	10.6
Octane, C_8H_{18}	—	—	3.51	15.1	41.6	198	2.60	12.4
Propane, C_3H_8	5.00	23.8	3.64	15.7	43.1	205	2.69	12.8
Propylene, C_3H_6	4.50	21.4	3.43	14.8	40.6	194	2.54	12.1
Sulfur, S	—	—	1.00	4.31	11.8	56.4	0.74	3.52

The carbon and hydrogen form and reform into a succession of unstable aldehydes and other compounds which finally combine to form CO_2 and H_2O. The types of intermediate compounds formed, and their speed of formation, depend upon such factors as the temperature, pressure, amount of oxygen present, and degree of mixing.

Good combustion requires (a) proper proportioning of fuel and air, (b) thorough mixing of the fuel and air, and (c) initial and sustained ignition of the mixture. These, together with flame positioning, are the functions of a combustion system.

Proportioning. Basic proportioning requirements were discussed on previous pages. See also Part 3. Proportioning equipment is discussed in Volume II.

Mixing. Good mixing of the fuel and air is important so that the mixture will be uniform throughout--every particle of fuel must contact a particle of air. Most fuels actually turn into a gas before they burn. A highly turbulent scrubbing action aids this conversion to gas and the mixing of the gas with the air.

Liquid fuels are usually evaporated, and the resulting combustible vapors then burn as gases. **Atomization** of the liquid speeds evaporation because it produces millions of tiny liquid particles, thus providing a large amount of surface for evaporation. Heat from the adjacent flame will sometimes cause the fuel to crack, or decompose, before it can evaporate. This cracking usually produces a lighter hydrocarbon (which burns like a gas) and a heavier hydrocarbon (which may burn like solid carbon, producing a very luminous yellow flame).

When solid carbon is burned the process is further complicated by the fact that each atom of oxygen must contact the carbon surface, form CO gas, and then move out of the way so that more oxygen may move in. Thus combustion of solid fuels consists of a mass transport phenomenon (of oxygen to the surface and CO away from the surface), plus mixing, plus chemical combination. If solid fuels are to be burned at high rates comparable to those attainable with gaseous and liquid fuels, they must be pulverized to increase the surface area for mass transfer. (This may be compared with the situation existing in a bus station with only one loading platform. No matter how many buses are waiting outside or how many people are waiting inside, the maximum rate with which the people can be taken away depends upon how fast one bus can pull up to the platform and how quickly it can pull away to let in the next bus. Pulverizing a solid fuel or atomizing a liquid fuel is like adding more loading platforms.)

Ignition. Chemical combination of fuels and air will occur at room temperature, but only very slowly. If a pile of coal is located in a confined place, the small amount of heat liberated by this slow oxidation will gradually build up.

thus raising the temperature of the coal pile. As the temperature gradually rises, the rate of oxidation increases and the temperature rises some more. This goes on until a full-fledged fire is in progress. This is known as **spontaneous ignition**. It can happen only in very confined places where the heat is allowed to collect in the combustible material and in the adjacent stagnant air.

When we wish to ignite a fuel-air mixture, we cannot usually arrange to collect heat in a confined space. (Even if we could, this process would be too slow to be practical.) Instead it is necessary to apply a lot of heat to a very localized area. For example: a match will not light a log, but it will start a twig. This is because the log has so much mass that it conducts heat away from the match flame so fast that no part of the log gets hot enough to burn. The twig, however, has much of its surface exposed to the match flame, but little mass to absorb the heat; so localized hot spots develop and burst into flame.

Ignition is usually accomplished by speeding the oxidation reaction by addition of an external heat source until the reaction itself releases heat faster than heat is lost to the surroundings--until it continuously ignites itself without the external heat source. The lowest temperature at which this is possible is the **minimum ignition temperature** of the fuel-air mixture. It can be lowered by increasing the pressure on a mixture. Table 1.10 lists some approximate ignition temperatures. Ignition devices are discussed in Volume II.

A cold blast of air or contact with a cold wall may quench parts of a flame, cooling it below the ignition temperature; so some of the fuel goes unburned.

Flame Stabilizing, which can make the difference between useful and useless combustion, is usually a function of burner nozzle/tile configuration. A flame holder positions the area of flame initiation by providing (a) ignition temperature, (b) localized fuel-air mixture within the flammability limits, and (c) feed-speed equal to the flame speed. Practical industrial burners must provide flame stability over a wide range of firing rates and fuel/air ratios.

Heat Available from Fuels. Heat quantities are measured in *Btu, kilocalories, watt-seconds,* or *joules.* See Table C.6 and Glossary.

Experimental measurements have been made to determine the heat released by perfect combustion of various fuels. If a certain fuel is mixed with proper amount of air and placed in a closed chamber where the heat given off by combustion can be collected and measured, the total amount of heat collected will depend on the final temperature of the products of combustion. For example, one pound of light oil releases about 18 500 Btu *(4662 kcal, 19.5 MJ)* if the products are cooled to 60 F *(15.6 C)*, but releases only about 16 300 *(4108 kcal, 17.2 MJ)* if cooled to 500 F *(260 C)*. When a perfect mixture of a fuel and air, originally at 60 F *(15.6 C)* is ignited and then cooled to 60 F *(15.6 C)* the total heat released is termed the **higher heating value** or **gross heating value** of the fuel. The term **lower heating value** or **net heating value** is seldom used in this

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country, but this quantity is equal to the gross heating value minus the heat released by condensation of the water vapor in the combustion products. Values of gross and net heating values for various fuels are listed in Table 1.8. The products are seldom cooled to 60 F (15.6 C) in practical combustion applications, so the gross heating value is seldom attained. The so-called **available heat** is a much more useful figure. Values of available heats are listed in Part 3

Flame Temperatures. The heat released by the chemical combination of a fuel with air (a) heats up the combustion products and the incoming fuel-air mixture, (b) radiates to the surroundings, or (c) is carried away by direct contact with the surroundings. Naturally, the flame temperature is highest when

Table 1.8. Gross and net heating (calorific) values of simple fuels*

Gross heating value *Net heating value*	Heating value per unit volume Btu/ft³	 kcal/m³	 MJ/m³	Heating value per unit weight Btu/lb	 kcal/kg	 MJ/kg
Acetylene, C_2H_2†	1477 *1426*	13140 12690	55.01 53.11	21502 *20769*	11946 11539	50.014 48.309
Butane, n-C_4H_{10}† (100.0) (31.80)	3271 *3018*	29110 *26860*	121.9 112.4	21321 *19678*	11845 10933	49.593 45.771
Carbon, C	— —	— —	— —	14093 *14093*	7830 *7830*	32.780 32.780
Carbon monoxide, CO	321 *321*	2856 2856	12.0 12.0	4347 *4347*	2415 *2415*	10.11 10.11
Ethane, C_2H_6 (210.7) (37.48)	1773 *1622*	15780 14430	66.04 60.41	22323 *20418*	12402 11344	51.923 47.492
Hydrogen, H_2	325 *275*	2892 2450	12.11 10.2	61095 *51623*	33944 28681	142.11 120.08
Hydrogen sulfide, H_2S†	646 *595*	5749 5300	24.06 *22.2*	7097 *6537*	3943 3632	16.51 15.21
Methane, CH_4 (219.7) (60.1)	1012 *911*	9005 8110	37.69 33.9	23875 *21495*	13265 11942	55.533 49.997
Methanol, CH_3OH	782 *681*	— —	— —	9760 *8480*	5360 4707	— —
Octane, C_8H_{18}† (131.0) (10.80)	6260 *5806*	55710 51670	233.3 216.3	20977 *19292*	11654 10718	48.371 44.871
Propane, C_3H_8† (183.0) (36.41)	2524 *2322*	22460 20660	94.01 86.49	21689 *19937*	12050 11077	50.402 46.373
Sulfur, S	— —	— —	— —	3980 *3980*	2211 2211	9.257 9.257

* Derived from Reference 1.1 at the end of Part 1

† Heating values may be somewhat less for commercial forms of these compounds

‡ From Reference 1.k at the end of Part 1

the losses to the surroundings are smallest. Addition of excess air or excess fuel only provides more material to absorb the heat of combustion so the flame temperature cannot go as high as with a perfect fuel-air mixture, just as a furnace which will heat a small house to 68 F *(20 C)* might heat a large house to only 60 F *(15.6 C)*.

Under certain conditions, particularly high temperatures, a phenomenon known as **dissociation** occurs. Dissociation is simply reverse combustion; that is, it is the breaking down of the combustion products into combustibles and oxygen again. This process *absorbs* the heat which was originally liberated by combustion. For example,

$$\text{Heat} + CO_2 \longrightarrow CO + \tfrac{1}{2}O_2 \qquad \text{and} \qquad \text{Heat} + H_2O \longrightarrow H_2 + \tfrac{1}{2}O_2$$

The higher the temperature, the greater is this tendency to dissociate. So, the hotter the flame, the greater is the amount of heat re-absorbed by this reversing process, and the rising flame temperature comes to a halt at some equilibrium temperature in the range of 3400 F to 3800 F *(1870 C to 2090 C)* for most fuels. This equilibrium temperature has been calculated for many common fuels and is listed as **calculated flame temperature** in Table 1.10. It is *theoretical* because no account has been taken of losses to the surroundings. For this reason, actual flame temperatures are always lower than the listed figures. The data in Table 1.10 are for perfect combustion only.

A simplified formula for **theoretical adiabatic flame temperature** is

$$\frac{\text{net heating value of the fuel} - \text{effect of dissociation}}{(\text{weight of combustion products}) \times (\text{specific heat of combustion products})}$$

With large amounts of excess air, this is often called **hot mix temperature.**

The **actual flame temperature** is the theoretical flame temperature minus the temperature drop caused by heat transferred to the load and surroundings before the heat release process is completed.

The **furnace temperature** can equal the theoretical flame temperature only if the flame transfers no heat to its surrounding, i.e. if the furnace wall is a perfect insulator (not available) and if there is no load in the furnace (furnace is useless).

In most cases, special refractory materials are needed and a special furnace design required (to avoid localized overheating of the load), to take advantage of temperatures such as listed in Table 1.9.

Unless the fuel and air are so poorly mixed that incomplete combustion results, theoretical flame temperature is not a function of burner design. However, the actual flame temperature is intentionally lowered by increasing the heat transferred from the flame in burners designed for excess air, luminous flames, or delayed mixing.

Table 1.9. Comparison of some flame temperatures (See also Table 1.10)

Observed flame temperature F	Observed flame temperature C	Theoretical flame temperature F	Theoretical flame temperature C	Fuel	Air (or O_2) temp., F/C	Equivalence ratio
		5630	3110	Acetylene in O_2	(60/16)	—
		5385	2974	Hydrogen in O_2	(60/16)	—
		5120	2827	Natural gas in O_2	(60/16)	—
4207	2319	4770	2632	Acetylene	60/16	1.00
3812	2100	4475*	2468	Carbon monoxide	60/16	1.00
4190	2310			Gasoline		
		4100	2260	Natural gas	1400/760	1.00
		4070	2243	Natural gas	1400/760	1.11 (rich)
3713	2045	4010*	2210	Hydrogen	60/16	1.00
		4000	2204	Natural gas	1100/593	1.00
		3920	2160	Natural gas	900/482	1.00
		3800	2093	Natural gas	600/316	1.00
3189†	1755†	3610	1988	Coke oven gas	60/16	1.00
3416	1880	3562	1961	Natural gas	60/16	1.00
				Methane‡	60/16	1.00
		3460	1904	Methanol	60/16	1.00
		3400	1871	Natural gas	60/16	1.18 (rich)
		3300	1816	Natural gas	60/16	0.88 (lean)
		3010	1654	Producer gas	60/16	1.00
		3000	1649	Natural gas	60/16	1.40 (rich)
		2898	1592	Natural gas	60/16	0.70 (lean)
		2650	1454	Blast furnace gas	60/16	1.00

* Not corrected for dissociation

† In an actual production furnace firing refractories

‡ Methane, ethane, propane, butane have theoretical flame temperatures in the 3484 F to 3583 F (1918 C to 1972 C) range; observed flame temperatures in 3416 F to 3497 F (1880 C to 1924 C) range

A small amount of excess air or excess fuel can greatly reduce the flame temperature. In Table 1.9, 16.2% excess air *(0.86 equivalence ratio)* lowers the flame temperature by 282 degrees. If high flame and furnace temperature is desired, accurate fuel/air ratio control is most critical.

Flame Speeds. A flame is merely an envelope or zone within which the combustion reaction is occurring at such a rate as to produce visible radiation. The flame front is the 3-dimensional contour along which combustion starts, the dividing line between the fuel-air mixture and the combustion products.

In stable burner flames, the flame front appears to be stationary. This is because the flame is moving toward the burner with the same speed that the fuel-air mixture is coming out of the burner. (This may be compared with a fish swimming upstream at 5 miles per hour in a 5 mph current.)

If the fuel-air mixture is fed into the burner at too fast a rate, the flame may **blow off** (like a 5 mph fish being washed downstream by a 6 mph current). Most burners, however, allow a considerable range of feed rates by proper design of the burner nozzle.

If the fuel-air mixture is fed into the burner at too slow a rate, the flame may **flashback** into the burner (like a 5 mph fish making headway in a 3 mph stream). The flame may flashback as far as the mixing point, or it may be *quenched* by the cool burner wall.

Flame velocity depends on such factors as pressure, temperature, fuel, primary fuel/air ratio, turbulence (mixing), and cooling effects of surroundings, and it cannot be reliably predicted except in very specific cases. Table 1.10 indicates some typical flame velocities measured on simple Bunsen-type gas burners. Note that these are *maximum* flame velocities for the given fuels, and that they are for the listed fuel-air mixtures only. Preheating of the gas-air mixture results in a considerable increase in flame velocity. For other terms and related properties, see ***Flame velocity*** in the Glossary.

Flammability Limits. Not all mixtures of a fuel with air or oxygen will burn continuously in self-sustained combustion. Table 1.10 shows limiting lean (lower limit) mixtures and rich (upper limit) mixtures beyond which practical combustion is impossible. A common example of this is the *flooding* of an automobile engine—an excess of fuel produces a mixture too rich to burn (above the upper limit of flammability).

Even within the flammability limits, there are certain practical limitations to the fuel-air mixtures that may be used. One of these is the unsafe combustible gases or poisonous CO produced by a rich fire. Another limit is the temperature or atmosphere required for certain processes.

Table 1.10. Combustion characteristics of fuels* (See also Tables 1.7, 1.8, 2.1, 2.12, 3.1, and Appendix, Vol. II)

Fuel	Minimum ignition temp, °F/°C§		Calculated flame temperature,† °F/°C		Flammability limits, % fuel gas by volume◊				Maximum flame velocity, fps and m/s		% Theoretical air for max. flame velocity
					in air		in O_2				
	in air	in O_2	in air	in O_2	lower	upper	lower	upper	in air	in O_2	
Acetylene, C_2H_2	581/305	—	4770/2632	5630/3110	2.5	81.0	—	—	8.75/2.67	27.8/11.3^{l}	83
Blast furnace gas	—	—	2650/1454	—	35.0^{h}	73.5	—	—	—	—	—
Butane, commercial	896/480	—	3583/1973	—	1.86	8.41	—	—	2.85/0.87	—	—
Butane, n-C_4H_{10}	761/405	541/283	3583/1973	—	1.86	8.41	1.8	49	1.3/0.40	11.9/3.63^{l}	97
Carbon monoxide, CO	1128/609	1090/588^{l}	3542/1950	—	12.5^{l}	74.2^{l}	16	94	1.7/0.52	—	55
Carbureted water gas	—	—	3700/2038	5050/2788	6.4	37.7	—	—	2.15/0.66	—	90
Coke oven gas	—	—	3610/1988	—	4.4^{l}	34.0^{l}	—	—	2.30/0.70	—	90
Ethane, C_2H_6	882/472	—	3540/1949	—	3.0	12.5	3	66	1.56/0.48	—	98
Gasoline	536/280	—	—	—	1.4	7.6	—	—	—	—	—
Hydrogen, H_2	1062/572	1040/560^{l}	4010/2045	5385/2974	4.0	74.2	4	94	9.3/2.83	36.8/11.2	57
Hydrogen sulfide, H_2S	558/292	—	—	—	4.3	45.5	—	—	—	—	—
Mapp gas, C_3H_4	850/455	—	—	5301/2927	3.4	10.8	—	—	—	15.4/4.69	—
Methane, CH_4	1170/632	1033/556	3484/1918	—	5.0	15.0	5.1	61	1.48/0.45	14.76/4.50	90
Methanol, CH_3OH‡	725/385	—	3460/1904	—	6.7	36.0	—	—	—	1.6/0.49	—
Natural gas	—	—	3525/1941	4790/2643	4.3	15.0	—	—	1.00/0.30	15.2/4.63	100
Producer gas	—	—	3010/1654	—	17.0^{l}	73.7	—	—	0.85/0.26	—	90
Propane, C_3H_8	871/466^{l}	874/468^{l}	3573/1967	5130/2832	2.1	10.1	2.3	55	1.52/0.46	12.2/3.72	94
Propane, commercial	932/500	—	3573/1967	—	2.37	9.50	—	—	2.78/0.85	—	—
Propylene, C_3H_6	—	—	—	5130/2833	2.4	10.3	2.1	53	—	—	—
Town gas (Br. coal)^{d}	700/370	—	3710/2045	—	4.8	31.0	—	—	—	—	—

* For combustion with air at standard temperature and pressure. Unless otherwise noted, data is from Reference 1 c.

† Flame temperatures are theoretical—calculated for stoichiometric ratio, dissociation considered.

‡ From private communications.

§ See also "autoignition temperature" in the Glossary and in Reference 1 j at the end of Part 1.

◊ In a "fuel-air mix." Example for methane, LEL = 5% or 95 volumes air/5 volumes gas = 19:1 air/gas ratio. From p3, stoichiometric ratio is 9.53:1. Therefore excess air is 19 − 9.53 = 9.47 cf air/cf gas or 9.47/9.53 × 100 = 99.4% excess air.

Small letters refer to references at end of Part 1.

Table 1.11. Combustion reaction times and intensities*

Fuel	Combustion situation	Reaction time at normal pressure, seconds	Combustion intensity Btu/hr ft³ atm	 kcal/h m³ atm
All	drying and baking ovens		10[illegible]	10[illegible]
Coal	domestic		10[illegible]-10[illegible]	10[illegible]-10[illegible]
"	industrial stokers and pulverized fuel burners	1	10[illegible]-10[illegible]	10[illegible]-10[illegible]
"	possible limit in explosion flames	0.1		
"	fluid bed, cyclone		10[illegible]	10[illegible]
Solid fuel	rocket		10[illegible]-10[illegible]	10[illegible]-10[illegible]
Heavy oils	(carbon forming)	0.1		
" "	air and steam atomizer		10[illegible]-10[illegible]	10[illegible]-10[illegible]
Medium oils	pressure jet and air atomized		10[illegible]-10[illegible]	10[illegible]-10[illegible]
Light oils	domestic		10[illegible]-10[illegible]	10[illegible]-10[illegible]
" "	large drops	0.01		
" "	small drops	0.001		
" "	industrial furnaces		10[illegible]	10[illegible]
" "	gas turbines with pressure jet burners		10[illegible]-10[illegible]	10[illegible]-10[illegible]
" "	ram jets		10[illegible]-10[illegible]	10[illegible]-10[illegible]
Liquid	rockets		10[illegible]	10[illegible]
Gas	nozzle-mix turbulent (turbulent diffusion)		10[illegible]-10[illegible]	10[illegible]-10[illegible]
"	pre-mixed industrial flames	0.001	10[illegible]-10[illegible]	10[illegible]-10[illegible]
"	[illegible] torus, PSU countervortex burner		10[illegible]	10[illegible]
"	detonation or shock combustion	0.00001		

* Derived from pages 389-391 of Prof. Robert H. Essenhigh's paper in Reference 1.b listed at the end of Part 1.

† Furnace volume used in intensity evaluation.

‡ Flame volume used in intensity evaluation.

Flammability limits, also known as **explosive limits** (LEL and UEL), are expressed as volume percentages of fuel in a fuel-air mixture.

Combustion intensity. Interrelated with flame temperature and flame velocity are **reaction time** and **combustion intensity**, which are approximately the inverse of one another. Combustion intensity, like flame velocity, increases with the absolute pressure. Table 1.11 makes *generalized* comparisons of reaction times and combustion intensities for several combustion situations with solid, liquid, and gaseous fuels.

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Part 2. INDUSTRIAL PROCESS FUELS

CHEMICAL CONSTITUENTS OF FUELS

The physical properties of gaseous, liquid, and solid natural and man-made fuels are discussed later in Part 2. The chemical analyses of typical fuels from each of these categories are listed in Table 2.1. The chemical elements of most importance to the combustion engineer are carbon, hydrogen, and sulfur. Nitrogen, carbon dioxide, oxygen, water, and ash usually appear in minor amounts and contribute nothing but handling problems, and sometimes pollution problems.

Carbon is a major constituent of most fuels. The term available carbon is used to describe carbon which is not chemically combined with oxygen in any way. Unless otherwise specified the term carbon as used in this handbook will mean available carbon. Complete combustion of one pound of carbon yields a gross heat of 14 500 Btu.

$$\text{[2/1]}\qquad 1\ \text{lb C} + 2\tfrac{2}{3}\ \text{lb O}_2 \longrightarrow 3\tfrac{2}{3}\ \text{lb CO}_2 + 14\,500\ \text{Btu}$$

$$\text{or } 1\ \text{kg C} + 2\tfrac{2}{3}\ \text{kg O}_2 \longrightarrow 3\tfrac{2}{3}\ \text{kg CO}_2 + 8\,056\ \text{kcal or } 33.73\ \text{MJ}$$

Incomplete combustion (producing carbon monoxide instead of carbon dioxide) would yield only 4 350 Btu (per pound of carbon).

$$\text{[2/2]}\qquad 1\ \text{lb C} + 1\tfrac{1}{3}\ \text{lb O}_2 \longrightarrow 2\tfrac{1}{3}\ \text{lb CO} + 4\,350\ \text{Btu}$$

$$\text{or } 1\ \text{kg C} + 1\tfrac{1}{3}\ \text{kg O}_2 \longrightarrow 2\tfrac{1}{3}\ \text{kg CO} + 2\,417\ \text{kcal or } 10.12\ \text{MJ}$$

Further addition of oxygen and re-ignition would yield 14 500 minus 4 350 or 10 150 Btu (per pound of the original carbon).

$$\text{[2/3]}\qquad 2\tfrac{1}{3}\ \text{lb CO} + 1\tfrac{1}{3}\ \text{lb O}_2 \longrightarrow 3\tfrac{2}{3}\ \text{lb CO}_2 + 10\,150\ \text{Btu}$$

$$\text{or } 2\tfrac{1}{3}\ \text{kg CO} + 1\tfrac{1}{3}\ \text{kg O}_2 \longrightarrow 3\tfrac{2}{3}\ \text{kg CO}_2 + 5\,639\ \text{kcal or } 23.61\ \text{MJ}$$

Carbon in the form of a solid fuel is difficult to ignite and, as explained in Part 1, is slow to burn unless finely pulverized. In liquid or gaseous fuels, carbon appears in hydrocarbon compounds or carbon monoxide. If not burned properly, the hydrocarbon compounds may "crack" producing soot. Despite these disadvantages, carbon is one of man's primary sources of heat; so combustion engineers try to overcome these difficulties. In the case of solid fuels, rapid efficient combustion is often best accomplished by burning in a fluidized bed or in pulverized form in suspension. The soot problem with gaseous and liquid fuels is minimised by design of the burners and combustion chamber to provide adequate air and turbulence, and to avoid excessive heating of the fuel prior to its contact with the air.

Table 2.1a. Comparative data (by weight) for some typical fuels

FUELS — see also Tables 2.1b, 2.11, 2.12

			Constituents						
Analysis, in % by weight			C. available/total	H. available	S	O	N	Ash	Moisture
Blast furnace gas	[illegible]	1.02	5.0/15.8	0.1	[5]	27.3	56.8	[5]	[5]
Coke oven gas	1.81	0.40	41.1/48.3	22.7	[5]	18.0	13.0	[5]	[5]
Producer gas[1]	4.94	0.86	8.4/17.1	1.7	[5]	23.3	57.8	[5]	[5]
Natural gas[2]	3.08	0.60	69.4/69.4	22.5	[11]	0	8.1	0	0
Propane, natural[13]	4.43	1.55[8]	81.8/81.8	18.4	0	0	0	0	0
Butane, refinery[13]	5.10	2.00[8]	83.0/83.0	16.4	0	0	0	0	0
Methanol	1.60	0.791	18.8/37.5	12.5	—	50.0	—	—	—
Gasoline, motor[6]	5.04	0.733	85.5/85.5	14.4	0.1	0	0	0	0
#1 Distillate oil, 6.79#/USgal	6.51	0.814	86.6/86.6	13.3	0.14	—	—	—	—
#2 Distillate oil, 7.21#/USgal	6.98	0.865	87.3/87.3	12.5	0.31	—	—	—	—
#4 Fuel oil, 7.59#/USgal	7.45	0.910	88.4/88.4	11.6	1.88	—	—	0.018	0.2[12]
#5 Residual oil, 7.93#/USgal	8.29	0.951	88.7/88.7	10.7	0.57[7]	—	—	0.02	0.4[12]
#6 Residual oil, 8.45#/USgal	9.49	1.013	88.3/88.3	8.3	0.85[7]	0.7	0.3	0.04	0.2[12]
Wood, non-resinous	5.26	4-8	/37.8	7.2	0	53.8	0.1	1.0	[9]
Coal, bituminous	10.0	6-9	/80.1	5.0	1.0	5.2	0	7.2	3.1
Coal, anthracite	23.6	7-9	/80.6	2.4	1.1	5.9	0	9.5	5.2[12]
Coke	106	4-5	/85.0	0.8	1.0	1.2	1.3	10.7	0.8

[1] From a Wellman-Galusha producer using bituminous coal.

[2] Birmingham, AL.

[3] Multiply this figure by 0.0765 to obtain lb/ft³, by 1.226 to obtain kg/m³

[4] Multiply this figure by 62.43 to obtain lb/ft³, by 8.34 to obtain pounds/gallon, by 1000 to obtain kg/m³

[5] Varies with type of coal or coke used, equipment and process.

[6] From page 209 of Reference 2.i. See list of references at end of Part 2.

[7] Sulfur content may vary from 0.4 to 3.5%, depending on source, refining, and blending

[8] In the liquid state, specific gravity relative to water is 0.508 for propane, 0.582 for butane.

[9] Seasoned

[10] Multiply gross Btu/scf air by 8.90 to obtain gross kcal/m³ of standard air

[11] Sulfur content may be 1 to 2 percent at the gas well but this is usually reduced to less than 8 ppm by weight before distribution.

[12] See bottom sediment and water Table 2.11

[13] Typical liquid propane weighs 4.24#/USgal; typical liquid butane, 4.84#/USgal. See Table 2.12a and Reference 1.g at end of Part 1.

Table 2.1b. Comparative data (by weight) for some typical fuels

[illegible]—see also Tables 2.11, 2.12

	Heating value				Gross	Wt air	Weight of combustion products per wt of fuel (and ft³/gal)				Ultimate
	Btu/lb (and Btu/gal)		kcal/kg (and kcal/L)		Btu per scf	req'd per unit wt fuel					vol % CO_2 in dry
	Gross	Net	Gross	Net	air*	(and scf/gal)	CO_2	H_2O	N_2	Total	flue gas
Blast furnace gas	1 179	1 079	655	599	135.3	0.57	0.58	0.01	1.08	1.67	25.5
Coke oven gas	18 595	16 634	10 331	9 242	104.4	13.63	1.51	1.81	8.61	11.93	10.8
Producer gas	2 614	2 450	1 452	1 366	129.2	1.55	0.61	0.15	1.72	2.48	18.4
Natural gas	21 830	19 695	12 129	10 943	106.1	15.73	2.35	2.21	12.17	16.73	11.7
Propane, natural	21 573	19 886	11 985	11 049	107.5	15.65	3.01	1.62	12.01	16.64	13.8
	(91 500)	(84 345)	(6094)	(5617)		(850.8)	(108.11)	(144.30)	(682.06)	(934.57)	
Butane, refinery	20 810	19 183	11 562	10 658	106.1	15.00	3.04	1.53	11.82	16.39	14.3
	(102 600)	(94 578)	(6833)	(6299)		(949.0)	(124.27)	(146.92)	(747.18)	(1018.4)	
Methanol	9 797	8 706	5 444	4 838	115.4	6.47	1.38	1.13	4.97	7.48	15.0
	(64 630)	(57 430)	(4304)	(3825)		(559.5)	(78.4)	(156.8)	(445.3)	(681.1)	
Gasoline, motor	20 190	18 790	11 218	10 440	104.6	14.80	3.14	1.30	11.36	15.80	15.0
	(123 361)	(114 807)	(8216)	(7646)		(1183)	(165.1)	(166.8)	(940.3)	(1272)	
#1 Distillate oil	19 423	18 211	10 791	10 118	102.1	14.55	3.17	1.20	11.10	15.48	15.4
	(133 890)	(123 630)	(8794)	(8235)		(1207)	(185.7)	(171.0)	(1020)	(1377)	
#2 Distillate oil	18 993	17 855	10 553	9 920	101.2	14.35	3.20	1.12	10.95	15.27	15.7
	(137 080)	(128 869)	(9134)	(8587)		(1154)	(190.1)	(170.6)	(1070)	(1440)	
#4 Fuel oil	18 844	17 790	10 470	9 884	103.0	13.95	3.16	1.04	10.68	14.92	15.8
	(143 010)	(135 013)	(9524)	(8992)		(1388)	(205.7)	(165.1)	(1097)	(1472)	
#5 Residual oil	18 909	17 929	10 505	9 961	104.2	13.88	3.24	0.97	10.59	14.81	16.3
	(148 880)	(142 190)	(9907)	(9470)		(1439)	(221.0)	(161.4)	(1137)	(1520)	
#6 Residual oil	18 126	17 277	10 071	9 599	103.2	13.44	3.25	0.84	10.25	14.36	16.7
	(151 120)	(145 947)	(10 198)	(9720)		(1484)	(236.4)	(149.0)	(1172)	(1558)	
Wood, non-resinous	8 300		4 611		98.4	4.80	1.99	0.65	3.47	6.11	20.1
Coal, bituminous	14 000		7 778		99.3	10.81	2.94	0.49	8.28	11.71	18.5
Coal, anthracite	12 680		7 045		97.8	9.92	2.98	0.22	7.58	10.78	19.9
Coke	12 690		7 051		98.2	10.09	3.12	0.07	7.75	10.94	20.4

Footnotes are on Table 2.1a

Hydrogen has a heating value that is very high when compared with that of carbon (Table 1.6). However, hydrogen is a very light weight gas; so the heating value of one cubic foot of hydrogen is low in comparison with other gaseous fuels. Hydrogen has a higher flame speed than most gaseous fuels, which partially makes up for its low heat content (on a flame volume basis). The term **available hydrogen** refers to hydrogen which is not already combined with oxygen. Unless otherwise specified, the term **hydrogen** as used in this handbook will mean available hydrogen.

Sulfur is of concern because of its corrosive and pollution effects. In metallurgical and ceramic furnaces it may seriously effect the quality of the product. In boilers, the sulfur dioxide and water vapor in the combustion products may unite to form acids that can be highly corrosive to the breeching. The presence of some gaseous sulfur compounds may lower the dew point of water vapor in the flue gases, further aggravating corrosion problems.

Generalized Comparison of Fuels. Most fuels consist of carbon and hydrogen combined in various *proportions*. Table 2.1 facilitates a generalized comparison of fuels by studying the C/H ratios and the analyses by weight. The C/H ratio is based on available C and available H except for the last four (solid) fuels. The analyses do not always add up to 100% because some fuels contain CO_2.

It is a rule of thumb among combustion engineers that **one cubic foot of air releases 100 Btu of heat**. The 100 Btu here mentioned is gross heat. Thus one cubic foot of gas with a gross heating value of 1000 Btu requires 10 ft³ of air to burn completely, and one gallon of oil with a gross heating value of 140 000 Btu requires 1400 ft³ of air to burn. Table 2.1b indicates that this rule of thumb is *approximately* correct. It is common practice to determine the air requirement for a commercial fuel from this rule of thumb and the measured heating value rather than by calculation from the chemical analysis. In metric units the rule would be 890 kcal/m³ air or 3.725 MJ/m³ air.

For gaseous fuels, the following empirical formulas are somewhat more accurate.

[2/4a] For fuels having more than 400 gross Btu/ft³ (3560 kcal/m³, 14.92 MJ/m³),

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{gross heating value, Btu/ft}^3}{100} - 0.5, \text{ or } \frac{\text{kcal/m}^3}{890} - 0.5 \text{ or } \frac{\text{MJ/m}^3}{3.73} - 0.5$$

[2/4b] for producer gas,ᵃ

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{net heating value, Btu/ft}^3}{130} \text{ or } \frac{\text{kcal/m}^3}{1150} \text{ or } \frac{\text{MJ/m}^3}{4.81}$$

Small letters refer to references at end of Part 2.

[2/40] for blast furnace gas.[a]

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{net heating value, Btu/ft}^3}{141} \text{ or } \frac{\text{kcal/m}^3}{1260} \text{ or } \frac{\text{MJ/m}^3}{5.27}.$$

PROPERTIES OF SOLID FUELS

The designer and the user of fuel handling equipment and furnaces for solid fuels must pay careful attention to a great many properties of the fuel. Among these are calorific value, volatile matter content, ash content, moisture content, ash fusion temperature, grindability, and agglomerating characteristics. For further details about these factors, readers should consult references that specialize in solid fuels.

The above warnings are doubly important when dealing with by-product and waste materials as fuels. It is best to construct some sort of pilot plant to test the burning characteristics of an actual sample of the waste. A competent testing organization should be employed to analyse the waste material and evaluate the properties mentioned above. It must be realized that the analysis and properties of wastes will vary from one source to the next and from time to time for the same source. Because information on waste materials is so difficult to find, Table 2.2 is offered as a rough guide—for preliminary evaluations only.

PROPERTIES OF LIQUID FUELS

Chemical Analysis. Most liquid fuels are petroleum derivatives consisting of mixtures of hydrocarbon compounds. Chemical analysis of the compounds which comprise these mixtures is very difficult; so it is common practice to make an *ultimate* chemical analysis or several physical measurements instead. An ultimate chemical analysis lists the percentages (by weight) of the various chemical elements in the fuel. See Table 2.1a. From a theoretical point of view, a knowledge of percent carbon and hydrogen is useful in determining combustion air requirements and flue gas analysis. See Table 2.1b. The type or grade of an oil cannot be determined from the ultimate analysis alone. Most fuel oils contain 83 to 88% carbon and 6 to 12% hydrogen by weight.

Because all fuel oils are so similar in chemical analysis, and because the physical properties have far greater effect on the operation of fuel burning equipment, the physical properties are much more commonly measured and specified by oil producers. The physical measurements of most significance to the combustion engineer are discussed in the following paragraphs.

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[a] Small letters refer to references at end of Part 2.

Table 2.2. Approximate properties of some by-product and waste fuels. Different moisture contents may change these values considerably. Data courtesy of Reference 2.b and 2.e.

By-product or waste	% Ash/ Moisture	Density		Gross Heat Value	
		lb/ft³	kg/m³	Btu/lb	kcal/kg
Animal fats		50-60	801-961	17 000	9 445
Benzene, Benzol	0.5/0	55	881	18 210	10 120
Brown paper	1.0/6	7	112	7 250	4 028
Citrus rinds	0.75/75	40	641	1 700	945
Coated milk cartons	1.0/3.5	5	80	11 330	6 295
Coffee grounds	2/20	25-30	400-481	10 000	5 556
Corn cobs	3/5	10-15	160-240	8 000	4 445
Corrugated boxes	5/5	7	112	7 040	3 911
Cotton seed hulls	2/10	25-30	400-481	8 600	4 778
Latex	0/0	45	721	10 000	5 556
Leather	2.1/7.0	20	320	7 250	4 028
Linoleum		90	1442	11 000	6 112
Lubricants, spent				12 000	6 667
Magazines	22.5/5	35	561	5 250	2 917
Naphtha	0/0	41	641	15 000	8 335
Newspapers	1.5/6	7	112	7 975	4 431
Paint				8 000	4 445
Paper, sulfite (44% C 6% H)	1/6			7 590	4 217
Polyethylene	0/0	40-60	641-961	20 000	11 112
Polyurethane (foamed)	0/0	2	32	13 000	7 223
Rags (silk and wool)	2/5	10-15	160-240	8 500	4 723
Rags (cotton and linen)	2/5	10-15	160-240	7 200	4 000
Refinery gas				21 800	12 112
Rice hulls				5 900	3 278
Rubber waste	20-30/	62-125	993-2000	10 000	5 556
Sludge, industrial				3 800	2 111
Solvents, dirty				13 000	7 223
Toluene, Toluol	0.5/0	53.6	859	18 440	10 247
Waste, Type 0, trash (highly combustible paper, cardboard, wood boxes, sweepings; up to 10% plastics and rubber)	5/10	8-10	128-160	8 500	4 723
Waste, Type 1, rubbish (combustible paper, cardboard, wood, foliage sweepings; up to 20% food waste no plastic/rubber)	10/25	8-10	128-160	6 500	3 611
Waste, Type 2, refuse (even mix of rubbish and garbage)	7/50	15-20	240-320	4 300	2 389
Waste, Type 3, garbage (animal and vegetable food wastes)	5/70	30-35	481-561	2 500	1 389
Waste, Type 4 pathological (human and animal remains)	5/85	45-55	721-881	1 000	556
Waste, Type 6 compact (documents rubber, plastic, wood)		35-50	561-801	7 400	4 107
Wood bark	5/10	12-20	192-320	9 000	5 000
Wood sawdust and shavings	3/10	10-12	160-192	8 500	4 723

Gravity. This property of liquid fuels is similar to density and specific weight. It is specified by a number of different scales of units, the most common of which are degrees API (American Petroleum Institute) and weight relative to water when both the oil and the water are at 60 F (abbreviated "sp gr 60/60 F" or simply "sg"). The API scale replaces the similar Baumé scale (abbreviated °Bé) originally introduced because it gave a linear scale on a hydrometer, an instrument used for measuring specific gravity. At 60 F (15.6 C), the specific weight of water is 62.3 lb/ft³, 8.34 lb/US gallon, or 1000 kg/m³; the specific gravity of water is 1.0, the API gravity of water is 10.0°. The relationships between these various units are given by the following formulas:

[2/5] $$\text{sp gr 60/60 F} = \frac{141.5}{°\text{API} + 131.5}$$ where °API is measured at 60 F (15.6 C)

[2/6] $$\text{sp gr 60/60 F} = \frac{140}{°\text{Bé} + 130}$$ where °Bé is measured at 60 F (15.6 C)

[2/7] $$\text{sp gr 60/60 F} = \frac{\text{lb/ft}^3}{62.3}$$ where lb/ft³ is measured at 60 F (15.6 C)

[2/8] $$\text{sp gr 60/60 F} = \frac{\text{lb/gal}}{8.34}$$ where lb/gal is measured at 60 F (15.6 C)

Table 2.3 facilitates conversions between some of these scales, and lists other properties calculated from gravity.

The specific gravities of liquid fuels change with their temperature due to thermal expansion (as temperature increases) and contraction (as temperature decreases). Whenever a specific gravity is specified (in any scale) the temperature at which it was measured should also be specified. If no temperature is given, it is assumed to be 60 F. Table 2.4 lists the coefficients of thermal expansion for petroleum oils, and Table 2.3 lists the change in API gravity per degree Fahrenheit change above or below 60 F. (Note: API gravity rises as temperature rises, and falls as temperature falls.)

Example 2-1. An oil has a gravity of 40°API at 60 F. What is the gravity of this oil when heated to 100 F?

From Table 2.3 or formulas 2/5 and 2/8, 40°API is equivalent to 6.88 lb/gal. The coefficient of expansion can only be applied to volumes; so it is necessary to find the reciprocal of specific gravity which is specific volume, $\frac{1}{6.88\ \text{lb/gal}} = 0.145$ gal/lb.

Now applying the coefficient from Table 2.4, 0.145 gal/lb × 0.00050/°F × (100 − 60)°F = 0.0029 gallons expansion per lb. The new volume per pound is therefore 0.145 + 0.0029 = 0.148 gal/lb. Again taking the reciprocal, $\frac{1}{0.148\ \text{gal/lb}} = 6.76$ lb/gal.

From Table 2.3 or formulas 2/8 and 2/5, this is equivalent to 42.9°API.

Table 2.3. Gravities and related properties of liquid petroleum products
(See Examples 2-1, 2-2, 2-3, and formulas 2/5 through 2/15)

typical oil	°API	sp gr 60F/60F (15.6C/15.6C)	lb/gal	kg/m³	gross Btu*/gal	gross kcal*/L	% H, wt*	net Btu*/gal	net kcal*/L	sp ht @40F	sp ht @300F	Temp corr °API/°F*	ft³ 60F air/gal	ult % CO₂
	0	1.076	8.969	1075	160 426	10 681	8.359	153 664	10 231	0.391	0.504	0.045	1581	—
	2	1.060	8.834	1059	159 038	10 589	8.601	152 183	10 133	0.394	0.508	—	—	—
	4	1.044	8.704	1043	157 692	10 499	8.836	150 752	10 037	0.397	0.512	—	—	18.0
	6	1.029	8.577	1028	156 384	10 412	9.064	149 368	9 945	0.400	0.516	0.048	1529	17.6
	8	1.014	8.454	1013	155 115	10 328	9.285	148 028	9 856	0.403	0.519	0.050	1513	17.1
	10	1.000†	8.337†	1000†	153 881	10 246	10.00	146 351	9 744	0.406	0.523	0.051	1509	16.7
#6 oil	12	0.986	8.219	985.0	152 681	10 166	10.21	145 100	9 661	0.409	0.527	0.052	1494	16.4
	14	0.973	8.106	971.5	151 515	10 088	10.41	143 888	9 580	0.412	0.530	0.054	1478	16.1
	16	0.959	7.996	958.3	150 380	10 012	10.61	142 712	9 502	0.415	0.534	0.056	1463	15.8
	18	0.946	7.889	945.5	149 275	9 939	10.80	141 572	9 426	0.417	0.538	0.058	1448	15.5
#5	20	0.934	7.785	933.0	148 200	9 867	10.99	140 466	9 353	0.420	0.541	0.060	1433	15.2
	22	0.922	7.683	920.9	147 153	9 798	11.37	139 251	9 272	0.423	0.545	0.061	1423	14.9
	24	0.910	7.585	909.0	146 132	9 730	11.55	138 210	9 202	0.426	0.548	0.063	1409	14.7
#4	26	0.898	7.488	897.5	145 138	9 664	11.72	137 198	9 135	0.428	0.552	0.065	1395	14.5
	28	0.887	7.394	886.2	144 168	9 599	11.89	136 214	9 069	0.431	0.555	0.067	1381	14.3
	30	0.876	7.303	875.2	143 223	9 536	12.06	135 258	9 006	0.434	0.559	0.069	1368	14.0
#2	32	0.865	7.213	864.5	142 300	9 475	12.47	134 163	8 933	0.436	0.562	0.072	1360	13.8
	34	0.855	7.126	854.1	141 400	9 415	12.63	133 259	8 873	0.439	0.566	0.074	1347	13.6
	36	0.845	7.041	843.9	140 521	9 356	12.78	132 380	8 814	0.442	0.569	0.076	1334	13.4
	38	0.835	6.958	833.9	139 664	9 299	12.93	131 524	8 757	0.444	0.572	0.079	1321	13.3
#1	40	0.825	6.877	824.2	138 826	9 243	13.07	130 689	8 702	0.447	0.576	0.082	1309	13.1
	42	0.816	6.798	814.7	138 007	9 189	—	—	—	0.450	0.579	0.085	—	13.0
	44	0.806	6.720	805.4	137 207	9 136	—	—	—	0.452	0.582	0.088	—	12.8

* For gravity measured at 60 F (15.6 C) only

† Same as H₂O

Table 2.4. Coefficients of thermal expansion for petroleum oils
(See Examples 2-1 and 2-2)

°API at 60 F (15.6 C)	Specific gravity (60/60 F) (15.6/15.6 C)	Specific volume, gallons per lb	Specific volume, litres/kg	Coefficient (per F)	Coefficient (per C)
Below 14.9	Above 0.9665	Below 0.124	Below 1.035	0.000 35	0.000 63
15.0 - 34.9	0.8504 - 0.9659	0.1411 - 0.1243	1.178 - 1.036	0.000 40	0.000 72
35.0 - 50.9	0.7758 - 0.8504	0.1547 - 0.1411	1.291 - 1.179	0.000 50	0.000 90
51.0 - 63.9	0.7242 - 0.7753	0.1657 - 0.1547	1.383 - 1.291	0.000 60	0.001 08
64.0 - 78.9	0.6725 - 0.7238	0.1784 - 0.1658	1.489 - 1.384	0.000 70	0.001 26
79.0 - 88.9	0.6420 - 0.6722	0.1869 - 0.1785	1.560 - 1.490	0.000 80	0.001 44
89.0 - 93.9	0.6278 - 0.6417	0.1911 - 0.1870	1.595 - 1.561	0.000 85	0.001 53
94.0 - 100.0	0.6112 - 0.6276	0.1963 - 0.1912	1.638 - 1.596	0.000 90	0.001 62

Example 2-2. An oil with a specific gravity (at 60/60 F) of 0.91, and with a gross heating value of 146 000 Btu/gal at 60 F, is to be heated to 168 F. Find the specific gravity, lb/gal, and Btu/gal at 168 F.

First, find the lb/gal and specific weight (density) at 60 F. From Table 2.3 or formula 2/6, lb/gal = 7.585. The density of water at 60 F is 62.35 lb/ft³ and specific gravity is 0.91 relative to water; so, by formula 2/7, the density of the oil at 60 F is 0.91 × 62.35 = 56.74 lb/ft³. Taking the reciprocal of this, the specific volume at 60 F is 0.0176 ft³/lb. Applying the appropriate coefficient from Table 2.4, the expansion is 0.0176 ft³/lb × 0.00040/°F × (168 − 60)°F = 0.00076 ft³/lb, and the specific volume at 168 F will be 0.0176 + 0.00076 = 0.01836 ft³/lb. The density will be the reciprocal, $\frac{1}{0.01836\ \text{ft}^3/\text{lb}}$ = 54.47 lb/ft³ at 168 F. The specific gravity at 168 F will be $\frac{54.47\ \text{lb/ft}^3}{62.35\ \text{lb/ft}^3}$ = 0.8736.

By Table 2.3 or formula 2/6, this is equivalent to 7.28 lb/gal at 168 F, whereas the oil weighed 7.59 lb/gal at 60 F. The heating value of a gallon of 168 F oil is therefore reduced

to $\frac{146\,000\ \text{Btu}}{60\ \text{F gal}} \times \frac{7.283\ \text{lb}/168\ \text{F gal}}{7.585\ \text{lb}/60\ \text{F gal}} = 140\,187\ \text{Btu/gal}$

Fortunately the simple measurement of specific gravity is the key to a number of other important properties of petroleum oils. Relationships between some of these other properties and the specific gravity (abbreviated sp gr) are given in formulas 2/9 through 2/15. These relationships are empirical generalizations and should therefore be resorted to only when more specific data are not available. Different crude sources and refining methods may cause deviations from the values obtained by these formulas.

[2/9] gross heating value, GHV[1], in Btu/lb = 17 887 + (57.5 × °API) − (102.2 × %S)

$$\text{or GHV}^1\text{, in kcal/kg} = 5\,736 + \frac{4521}{\text{sp gr}} - 56.8 \times \%S$$

---

[1] Constant volume combustion. See also the footnote on p 34.

[2/10] $$\%\ \text{hydrogen, by weight} = F - \frac{2122.5}{°\text{API} + 131.5}$$

where F = 24.50 for 0 ≤ °API ≤ 9 (1.076 ≥ sp gr ≥ 1.007)
F = 25.00 for 9 < °API ≤ 20 (1.007 > sp gr ≥ 0.934)
F = 25.20 for 20 < °API ≤ 30 (0.934 > sp gr ≥ 0.876)
F = 25.45 for 30 < °API ≤ 40 (0.876 > sp gr ≥ 0.825)

[2/11] net heating value, NHV[1], in Btu/lb = GHV in Btu/lb − 91.23 × %H
or NHV[1], in kcal/kg = GHV in kcal/kg − 50.70 × %H

[2/12] $$\text{specific heat, c (in Btu/lb °F or kcal/kg °C)} = \frac{0.388 + [0.00045 \times (\text{temp, F})]}{\sqrt{\text{sp gr}}}$$

[2/13] $$\text{latent heat of vaporization, in Btu/lb} = \frac{110.9 - [0.09 \times (\text{temp, F})]}{\text{sp gr}}$$

$$\text{or, in kcal/kg} = \frac{60.02 - [0.09 \times (\text{temp, C})]}{\text{sp gr}}$$

[2/14] ft³ air reqd/gal = (28.1 × (sp gr) × %H) + (1430 × (sp gr))
or m³ air reqd/kg = (0.186 × %H) + 9.43

[2/15] temp correction, add °API/°F
= (°API + 131) × (coefficient of thermal expansion/°F, from Table 2.4)

$$\text{or sp gr at } T_2 = \frac{\text{sp gr at } T_1}{1 + (T_2 - T_1) \times (\text{coeff. of th. exp. from Table 2.4})}$$

All of the above formulas are for pure hydrocarbon fuels containing no impurities. Most commercial fuels contain such a small percentage of impurities, however, that the above relationships may be safely applied. Table 2.3 lists some values calculated by formulas 2/9 through 2/15.

Formula 2/12 above is a generalization for the specific heat of all oils. A more specific expression could be written for oils from a limited area. Table 2.5 lists the heat contents (in Btu/gallon) for oils at various temperatures and gravities.

Example 2-3. A fuel oil has an API gravity of 24 degrees measured at 60 F. Determine the number of pounds per gallon at 60 F and at 200 F. Also find the net Btu/gallon and the cubic feet of air required per gallon at 60 F and at 200 F.

Using Table 2.3, read the following information: 7.586 lb/gal, 0.063°API per °F, 1409 ft³ air/gal, and 138 210 net Btu/gal. All this information applies at 60 F only.

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[1] Constant pressure combustion—the type encountered in industrial heating, but since the heating value for constant volume combustion, as in a gasoline engine, is much more easily measured, it is used more widely. The difference between these two values is very small, and is usually neglected. See Part 1 for an explanation of differences between gross and net heating values.

The "temperature correction" means that an oil whose API gravity is 24° at 60 F increases in API gravity by 0.063° for every degree Fahrenheit rise above 60 F. At 200 F, the API gravity will therefore be 24 + [0.063 × (200 − 60)] = 24 + 8.8 = 32.8°API.

Interpolating in Table 2.2 at 32.8°API, this is found to be equivalent to 7.178 lb/gal. To determine the net Btu/gal and the air required per gallon of 200 F oil, it is necessary to make the following corrections:

$$138\,210 \text{ net Btu/gal} \times \frac{7.178 \text{ lb/gal (at 200 F)}}{7.585 \text{ lb/gal (at 60 F)}} = 130\,794 \text{ net Btu/gal of 200 F oil,}$$

$$1\,434 \text{ ft}^3 \text{ air/gal} \times \quad \text{(same factor)} \quad = \quad 1\,357 \text{ ft}^3 \text{ air/gal of 200 F oil}$$

Both of the above calculations apply to gallons of oil measured at 200 F. These corrections are unnecessary if the oil is metered at 60 F. For correction of air volumes for temperature, see column 4 of Table A.2 in the Appendix. The heating value and air requirement at elevated temperature cannot be read directly opposite the gravity at the elevated temperature in Table 2.3 because the 60 F gravity is the key to the oil composition, and composition does not change with temperature as gravity does.

Example 2-4. A #6 fuel oil of 15°API gravity is to be heated (for pumping) from 32 to 138 F in a tank suction heater using 10 psig dry saturated steam, and from 120 to 295 F (for atomization) by electric booster heaters at the furnaces. (Heat loss from the insulated pipes causes the temperature to drop from 138 to 120 F between the tank and furnaces.)

(a) If the flow through the tank heater is 150 gph, how much steam will be condensed?

Interpolating in the second column of Table 2.5, $\frac{138 - 120}{140 - 120} \times (378 - 305) + 305 = 371$ Btu/gal (which checks Table 2.10b)

From Table A.4a, the latent heat of 10 psig steam is 952.7 Btu/lb; so the steam consumption will be 371 Btu/gal × 150 gal/hr ÷ 952.7 Btu/lb = 58.4 lb/hr.

(b) If the maximum flow to a furnace is 12 gph, what kW heater capacity is required, assuming 10% loss (90% efficiency)?

From Table 2.5, the heat content of the liquid oil at 120 F, is 305 Btu/gal; at 295 F, is 996 Btu/gal (which checks Table 2.10b). Applying the conversion factor, 1kW hr = 3413 Btu, from Table C.6 in the Appendix, the kW requirement is then

$$\frac{(996 - 305) \text{ Btu output/gal} \times 12 \text{ gal/hr}}{3413 \text{ Btu/kW hr} \times 0.90 \text{ output/input}} = 2.70 \text{ kW input.}$$

Viscosity. The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity is the opposite of fluidity. A high viscosity oil approaches the solid state and will not flow easily, whereas a low viscosity oil flows readily. The higher the viscosity of an oil, the higher are the costs of pumping it, and the more difficult it is to atomize.

Viscosity is measured by timing the flow by force of gravity of a test sample through a capillary restriction at a controlled temperature. Since the rate of flow depends upon the density of the oil as well as the viscosity, these measurements are termed **kinematic viscosity**. The **absolute viscosity** is obtained by multiplying the kinematic viscosity by the density of the fluid. A great many

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different sets of viscosity units are in use. Table 2.6 is a list of conversion factors for various viscosity scales used for fuel oils. Figure 2.7 shows a graphical comparison of some of these scales.

As the temperature of an oil is raised, its viscosity is reduced and it flows more readily. Hence heavy oils are often heated before being pumped into

Table 2.5. Heat contents of various oils* (See Example 2-4)

Heat content in Btu/gallon of liquid → vaporized →	Gravity, °API at 60 F (15.6 C)							
	10	15	20	25	30	35	40	45
	Specific gravity, 60 F/60 F							
Temperature, F	1.0000	0.9659	0.9340	0.9042	0.8762	0.8498	0.8251	0.8017
32	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
60	95	93	92	90	89	87	86	85
								988
100	237	233	229	226	222	219	215	
							1068	1052
120	310	305	300	295	290	286	281	
							1116	1112
140	384	378	371	366	360	355	349	
							1169	1164
160	460	453	445	438	431	425	418	
					1235		1232	1217
180	538	529	520	511	503	496	488	
					1293		1278	1272
200	617	607	598	587	577	569	560	
			1371		1352		1335	1327
220	697	686	674	663	652	643	633	
			1434		1412		1392	1384
240	779	766	753	741	729	718	707	
			1499		1474		1453	1443
260	862	848	833	820	807	795	783	
			1563		1537		1518	1502
300	1034	1017	999	984	968	954	939	
			1689		1665		1639	1626
400	1489	1463	1439	1416	1393	1372	1352	1333
		2088	2064	2041	2018	1997	1977	1958
500	1981	1947	1914	1884	1854	1826	1799	1774
		2497	2464	2434	2404	2376	2349	2324
600	2511	2467	2426	2387	2350	2314	2281	2248
		2943	2901	2863	2825	2789	2756	2729
700	3078	3025	2974	2927	2881	2837	2796	2756
	3478	3425	3374	3327	3281	3237	3196	3156
800	3683	3619	3559	3502	3447	3395	3345	3297
	4006	3944	3884	3827	3772	3720	3670	3623

* See Reference 2.c in the list of references at the end of Part 2

delivery lines. Figure 2.8 shows how temperature affects the viscosity of some typical fuel oils. Figure 2.8 is plotted on special graph paper prepared by the American Society for Testing and Materials. If the viscosity of a particular oil is known at two different temperatures, a straight line may be drawn between these known points on this special graph paper to obtain the viscosity-temperature characteristics of that oil. Table 2.10a gives some useful viscosity and temperature information for typical oils.

Example 2-5. The oil of Example 2-2 is to be heated to 168 F to reduce its viscosity to 100 SSU. Find its absolute viscosity in centipoises and in pounds mass/hr ft at 168 F.

From Figure 2.7 or formula 2/31, 100 SSU is found equivalent to 20.65 centistokes. In Example 2-2, the specific gravity of the oil at 168 F was 0.873. Applying formula 2/16, the absolute viscosity in centipoises is 20.65 × 0.873 = 18.03 cp.

The absolute viscosity in lb/hr ft can be calculated by formula 2/22: 18.03 cp ÷ 0.413 = 43.7 lb/hr ft. Another method is by formula 2/28 and formula 2/17: 20.65 cs ÷ 25.81 = 0.800 ft^2/hr; then 0.800 ft^2/hr × 54.47 lb/ft^3, the specific weight from Example 2-2, = 43.6 lb/hr ft.

Certain ranges of viscosity have been found best for pumping and for atomization of fuel oils. These ranges are shown as shaded areas on Figure 2.8. Table 2.10a provides a convenient way to find the oil temperature required to attain these viscosities. The effect of viscosity on oil atomization is an important consideration for clean, complete combustion. Good combustion depends on properly atomized oil intimately mixed with air. With low pressure air atomizing burners, an oil viscosity higher than the 70 to 100 SSU range tends to produce oil droplets too large for intimate air and oil mixing and that encourages carbon formation in burner blocks and furnaces. Since the heavy oils tend to carbonize more readily than light oils, good atomization is doubly important for these more viscous oils. Another important consideration is the fact that viscosity variations affect fluid flow through orifices or valves in such a way as to upset controlled air/oil ratios. The degree of oil preheating must be determined by the viscosity required for reliable control and clean combustion. See Tables 2.10a and 2.10b.

Example 2-6. The viscosity of an oil has been measured as 75 SSF at 122 F and 1530 SSU at 100 F.

(a) If this oil is to be burned in a burner whose atomizer requires 100 SSU, to what temperature must it be heated?

Following the horizontal arrows on Figure 2.8, locate the two test measurement points. A line drawn between these points (diagonal dashed arrows) represents the loci of viscosity-temperature conditions for this particular oil. Extending the line until it intersects the horizontal 100 SSU line, read 209 F as the oil temperature required for atomizing.

(b) What temperature range is recommended for this oil for easy pumping? The diagonal dashed arrows on Figure 2.8, from Example 2-6a, intersect the upper and lower extremes of the "easy pumping" viscosity band at 72 F and 93 F, so the thermostat for the heater at the tank should be set in this range.

Table 2.9. Formulas for conversion of viscosity units (See Example 2-5)

[2/16] abs visc in cp = kin visc in cs × specific gravity
[2/17] abs visc in #m/sec ft = kin visc in ft^2/sec × mass density in #m/ft^3
[2/18] abs visc in #f sec/ft^2 = kin visc in ft^2/sec × (mass density in #m/ft^3) ÷ 32.17

[2/19] 1 #f sec/ft^2 = 32.17 #m/sec ft
[2/20] 1 poise = 100 cp = 1 dyne·s/cm^2† = 1 g/s·cm
[2/21] 1 #m/sec ft = 1488 cp = 1.488 Pa·s
[2/22] 1 #m/hr ft = 0.413 cp = 1.488 kgm/hr·m
[2/23] 1 #m/sec in. = 17 860 cp = 178.6 poise
[2/24] 1 #f sec/ft^2 = 47 880 cp = 0.4882 kgf·s/m^2
[2/25] 1 #f hr/ft^2 = 172 300 000 cp = 0.4882 kgf·hr/m^2
[2/26] 1 #f sec/in.^{2} = 6 890 000 cp = 1 Reyn

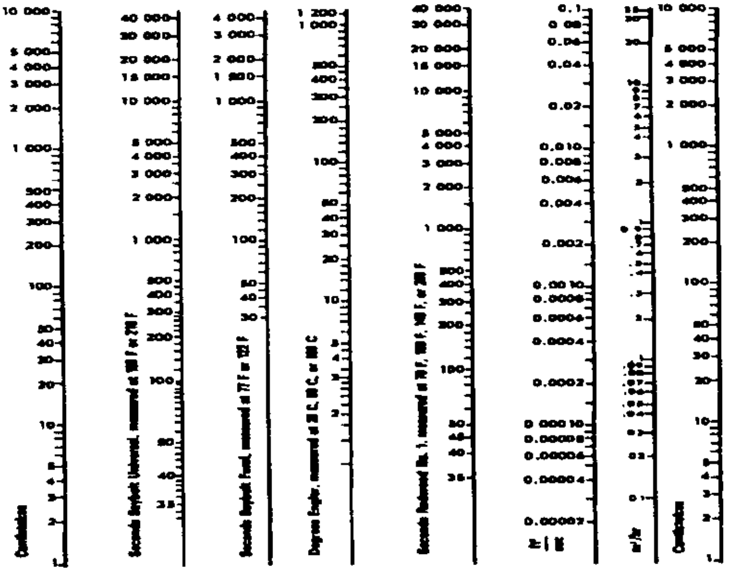
[2/27] 1 ft^2/sec = 92 900 cs = 0.0929 m^2/s
[2/28] 1 ft^2/hr = 25.81 cs = 0.0929 m^2/hr
[2/29] 1 in.^{2}/sec = 645.2 cs = 0.000 645 m^2/s
[2/30] 1 stoke = 100 cs = 0.000 1 m^2/s
[2/31] kin visc in centistokes = (0.226 × SSU) − (195/SSU), for SSU 32 to 100
[2/32] kin visc in centistokes = (0.220 × SSU) − (135/SSU), for SSU > 100
[2/33] kin visc in centistokes = (2.24 × SSF) − (184/SSF), for SSF 25 to 40
[2/34] kin visc in centistokes = (2.16 × SSF) − (60/SSF), for > 40
[2/35] kin visc in centistokes = (0.26 × SR1) − (179/SR1), for SR1 34 to 100
[2/36] kin visc in centistokes = (0.247 × SR1) − (50/SR1), for SR1 > 100
[2/37] kin visc in centistokes = (8.0 × °E) − (8.64/°E), for °E 1.35 to 3.2
[2/38] kin visc in centistokes = (7.6 × °E) − (4.0/°E), for °E > 3.2

abs visc is absolute viscosity, μ; kin visc is kinematic viscosity, ν
cp is centipoise (abs visc); cs is centistokes (kin visc)
specific gravity is relative to water, = (mass density in #m/ft^3) ÷ 62.35
#m is pounds mass; #f is pounds force
kgm = kilograms mass; kgf = kilograms force
SSU is kinematic viscosity in seconds, Saybolt Universal
SSF is kinematic viscosity in seconds, Saybolt Furol
SR1 is kinematic viscosity in seconds, Redwood No. 1 (or Redwood Standard)
°E is kinematic viscosity in degrees Engler; 1 °E = 51.28 seconds Engler

At 60 F & 14.7 psia 15.6 C & 760 mm Hg	Water*	Air	Nat'l Gas
	μ = 1.124 cp	μ = 0.0180 cp	μ = 0.011 cp
	= 2.72 #m/hr·ft	= 0.0436 #m/hr ft	= 0.0266 #m/hr ft
	= 2.349 × 10^{-5} #f·s/ft^2	= 3.763 × 10^{-7} #f·s/ft^2	= 2.30 × 10^{-7} #f·s/ft^2
	ν = 1.130 cs	ν = 14.69 cs	ν = 14.81 cs
	= 32 SSU	= 1.469 × 10^{-5} m^2/s	= 1.49 × 10^{-5} m^2/s
	= 0.04378 ft^2/hr	= 0.5691 ft^2/hr	= 0.578 ft^2/hr

* Approximate viscosity of water at 70 F (21 C) is 1 cp and 1 cs.
† A dot between symbols means "times" or "multiply by".

Figure 2.7. Alignment chart for comparing viscosity scales at the same temperature. Use a straightedge to read horizontally across all scales—far left and far right scales are identical. See Example 2-6 and Table 2.6.



Distillation Test. This test evaluates the distillation range of a fuel as to initial boiling point (temperature), end point, and some intermediate points, such as the 10% and 90% points. (The 10% point is the temperature at which 10% of the initial volume has distilled off.) The test is run with specified standard equipment and technique, to obtain comparable and reproducible results. Only light oils are subjected to this test because heavy oils crack before they reach their boiling points. Low initial and 10% points indicate a possibility of vapor lock in heaters. High 90% and end points suggest the possibility of residues and droplet deposits. Table 2.10b lists distillation ranges of some typical fuels.

Figure 2.8. Viscosity-temperature relations for typical fuel oils. The diagonal lines are examples, not standards, for the designated grades of fuel oils. Source of the crude determines the slope of the line. This ASTM chart may be used for plotting properties of other fuel oils. See Example 2-8.

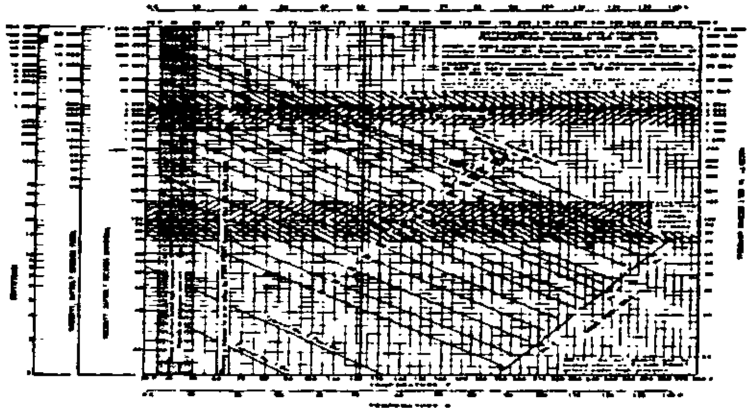


Table 2.8. Analyses and characteristics of selected fuel oils*

	Source	Ultimate analysis (weight) %C	%H	%N	%S	%ash	%O†	ppm ‡>10	%wt Asphaltine	%wt C residue	°API at 60 F	Flash pt, F	HV, Btu/pound gross	net	Pour pt, F	Viscosity, SSU at 140 F	at 210 F
Distillates	Alaska	86.00	13.07	0.007	0.31	<0.001	0.62	–	–	–	33.1	–	–	–	–	33.0	30.5
	California	86.0	13.32	0.003	0.27	<0.001	0.36	–	–	–	32.6	–	19 330	–	–	38.0	30.5
	West Texas	88.09	9.70	0.025	1.08	<0.001	0.24	–	–	–	18.3	–	–	–	–	32.0	30.0
Residuals	Alaska	86.04	11.38	0.51	1.63	0.004	0.41	30 Ni 67 V	3.8	11.9	15.8	223	18 470	17 300	38	1071	194
	California	86.05	10.46	0.86	0.97	0.30	0.85	‡	8.82	15.2	12.6	180	18 230	17 300	42	720	200
	DFM (whole)	86.18	11.80	0.26	0.34	0.003	1.67	–	0.025	4.1	31.1	182	19 430	18 240	40	38.1	38.7
	Gulf of Mexico	84.62	10.77	0.78	2.44	0.027	1.70	–	7.02	16.0	13.2	188	18 300	17 280	40	830	181
	Indo/Malaysian	85.51	11.83	0.24	0.27	0.026	1.04	101 V	0.74	3.00	21.8	270	18 670	17 000	61	190	66
	Middle East Δ	86.70	11.65	0.10	0.67	0.012	0.41	–	3.24	6.8	18.8	300	18 670	17 000	46	400	131.8
	Pennsylvania ⌐	84.82	11.23	0.34	2.30	0.087	1.3	65 Ni 42 V	4.04	12.4	15.4	275	18 520	17 500	46	1040	200
	Venezuela	85.26	10.88	0.40	2.22	0.001	1.10	32 Ni 335 V	8.4	8.0	14.1	210	18 420	17 400	50	702	108.7
	Venezuela desulfurized	85.00	12.00	0.24	0.83	0.023	0.83	101 V	2.80	5.1	23.3	176	18 420	17 300	40	113.2	58.5

* Largely from Reference 13 at the end of Part 2

† By difference.

‡ 91 Ca, 77 F_e, 68 Ni, 68 V

Δ Exxon.

⌐ Amerada Hess.

Table 2.10a. Viscosity-temperature information for selected fuel oils. The far right-hand columns list temperatures required to reduce the oil viscosity to levels often required for easy pumping (2000 SSU), and for atomization (100 SSU).

Fuel oil designation	Viscosity at 100 F, 38 C: SSU	cs	Required oil temperature, F, C — Kinematic Viscosity 2000 SSU 440 cs: F	C	100 SSU 20.7 cs: F	C
6 max	10 000 SSU	2200 cs	130 F	50 C	265 F	128 C
6 min	1 000	220	82	28	196	91
5 max	700	165	72	22	182	83
5 min	150	32.1	20	-7	122	50
4 max	100	20.7	2	-17	100	38
4 min	46	6.0	-70	-50	27	-3
2 max	38	3.6	—		2	-17

Table 2.10b. Heating requirements for products derived from petroleum (See also Table 2.8 and Example 2-4)

Commercial fuels	Specific gravity at 60/60 F (15.6 C)	Distillation range F/C⁴	Vapor pressure psia/mm Hg	Latent Btu/gal² to vaporize	Btu/gal² to heat from 32 F (0 C) to: Pumping temp¹	Atomizing temp³	Vapor
No. 6 oil	0.965	600-1000/300-500	0.054/2.8	764	171	996	3618⁴
No. 5 oil	0.945	800-1000/300-500	0.004/0.2	746	133	835	2858⁴
No. 4 oil	0.902	325-1000/150-600	0.232/12	737	—	733	2723⁴
No. 2 oil	0.849	375-750/190-400	0.019/1	743	—	—	2704⁴
Kerosene[f]	0.780	356-481/180-285	0.039/2	750	-	—	1303⁴
Gasoline[f]	0.723	35-300/37-185	0.135/7	772	—	—	1215⁴
Methanol[f]	0.796	148/64	4.63/239	3140	—	—	3400
Butane[d]	0.582	31/-0	31/1604	808	—	—	978⁵
Propane[d]	0.508	-44/-42	124/6415	785	—	—	983⁵

¹ At the atomizing temperature or 60 F, whichever is lower. Based on a sample with the lowest boiling point from column 3.

² To convert Btu/US gallon to kcal/litre, multiply by 0.466. To convert Btu/US gallon to Btu/pound, divide by 8.335 × sp gr from column 2. To convert Btu/US gallon to kcal/kg, divide by 15.00 × sp gr from column 2.

³ See Table 2.10a.

⁴ Calculated for boiling at mid-point of distillation range from column 3.

⁵ Includes latent heat plus sensible heat of the vapor heated from boiling point to 60 F (15.6 C).

Small letters refer to references at end of Part 2.

Flash and Fire Points. As fuel oil is heated, vapor collects above the liquid surface. If it becomes sufficiently concentrated, exposure to an open flame will result in a flash. The lowest temperature at which this occurs is called the *flash point*, determined by the closed cup (Pensky-Martens) test or the open cup (Cleveland) test. The open cup test readings are 20 to 30 degrees F higher than the closed cup readings for the same oils. The *fire point* determined with the above-mentioned open cup tester, is the temperature at which a flame is sustained for at least five seconds.

The flash and fire points indicate the extent of fractionation. They are of interest from the standpoints of safety and lighting characteristics. Although somewhat arbitrary, they serve to indicate the relative storage hazard of various fuels.

Carbon Residue. When an oil is evaporated, some free carbon may be left, sometimes formed by cracking during the evaporation process. The amount of carbon remaining indicates to some extent the tendency of the oil to carbonize under vaporizing conditions.

Carbon residue is measured by the Conradson test with an open flame or the Ramsbottom test heating through a molten bath. Results are not identical. Formulas are available, however, for converting the results from one test to the equivalent value of the other test. The tests are arbitrary, their value lies in showing the relative soot-forming potentials of oils. The carbon-forming possibilities should not be judged entirely from these tests, because carbonization is also influenced by burner design and operation.

Ash, %, is determined by burning off all the combustible material from a known weight of oil. The mineral matter remaining is the ash and usually consists of a minute quantity of mud or sand. Ash is not usually a problem in burners, but it can foul heat transfer surfaces, or melt and attack refractories.

Water and Sediment (bottom sediment and water, bsw) are determined by centrifuging 50 millilitres of fuel oil mixed with 50 millilitres of 90% benzol at 1400 to 1500 rpm and 120 F. The water and sediment are thrown to the bottom and measured. Any appreciable amount of water will cause discontinuous oil flames. Sediment tends to clog burners and control equipment.

Pour Point. If a sample of oil is gradually cooled, a temperature will ultimately be reached at which the oil will not flow—the *pour point*, mainly dependent on the amount and type of wax contained in the oil.

Standards. Table 2.11 compares some commercial and military standards for fuel oils, specified in terms of the above-mentioned physical properties. Some oil suppliers have established grades other than those listed.

Table 2.11. Comparison of various fuel oil specifications. Local legal limits may supersede these specifications.

		Flash point, F (C)	Pour point F (C)	Water and sediment, % by volume	Carbon residue on 10% bottoms, %	Ash, % by weight	Distillation temperatures, F (C)			Kinematic viscosity								Gravity, deg API	Sulfur, %
							10% point	90% point		Saybolt universal at 100 F (38 C)		Saybolt furol at 122 F (50 C)		Centistokes at 100 F (38 C)		Centistokes at 122 F (50 C)			
		min	max	max	max	max	max	min	max	min	max	min	max	min	max	min	max	min	max
ASTM¹ grades	No. 1	100 (38)	0 (-18)	trace	0.15	-	420 (216)	—	550 (288)	—	-	—	—	1.4	2.2	—	—	35	0.5
	No. 2	100 (38)	20 (-7)	0.05	0.35	—	-	540 (282)	640 (338)	32.6	37.93	—	—	2.0	3.6	—		30	0.5
	No. 4	130 (55)	20 (-7)	0.50	—	0.10	—	—	-	45	125	-	—	5.8	26.4	—	—	—	—
	No. 5 (light)	130 (55)		1.00	—	0.10	—	—		150	300	—	-	32	65	-		—	—
	No. 5 (heavy)	130 (55)		1.00	-	0.10	—			350	750	23	40	75	162	42	81	—	—
	No. 6	150 (65)	—	2.00	-	—	-	—	-	900	9000	45	300	[illegible]	[illegible]	92	638	—	—
Pacific grades ([illegible])	PS 100	110	—	0.05	-	—	420 (216)	450 (232)	550 (288)	-			—	—	—	—	—	—	—
	PS 200	150 (65)	—	0.5	—	—	-	400 (204)	-	[illegible]	55		—	—	—	-	—	—	—
	PS 300	150 (65)	—	1.0	-		-	—	—	—	—	27	40	-	—	—	—		—
	PS 400	150 (65)	—	2.0	-						—	90	-	—	—	—		·	-
Military grades ([illegible])	[illegible]	—	-	—	-	-		470 (243)			—	—	—	—	—	—	-	[illegible]	0.4
	[illegible]	140 (60)	—	—		-	400 (204)	600 (327)²	-	-	—	—	—	—	—	—	·	[illegible]	0.4

[illegible]

¹ [illegible]

² [illegible]

³ [illegible]

PROPERTIES OF GASEOUS FUELS

Gaseous fuels may be analysed volumetrically in terms of the chemical compounds they contain. Other important properties of gaseous fuels are discussed below.

Gas Gravity (specific gravity) is a convenient measure of the density of a gas relative to that of air (0.0763 lb/ft³ or 1.225 kg/m³ at stp):

$$[2/39] \quad \text{gas gravity} = \frac{\text{gas density}}{\text{air density}} = \frac{\text{gas density, lb/ft}^3}{0.0763} = \frac{\text{gas density, kg/m}^3}{1.222}$$

Heating Value. Although the heating value can be calculated from the gas analysis, it is frequently measured by means of a steady flow constant pressure calorimeter in which the gas is burned in a water-jacketed combustion chamber. The temperature rise of the water is a measure of the calorific value of the fuel. (Part 1 and the Glossary explain gross and net heating values.)

Heating values are expressed in Btu/ft³ under specified conditions of moisture content, pressure, and temperature. The conditions are not too well standardised. Some gas companies correct all consumption figures to 6 osi gauge pressure, saturated, for billing. Tables A.2a and A.3 in the Appendix contain volume correction factors for temperature and pressure.

Example 2-7. A gas meter in the supply line to a furnace reads 1 219 507 ft³ at 7 am and 1 224 443 ft³ at 11 am, same day, at 16 osi and 80 F. If the gas is Pittsburgh natural gas, what was the average hourly Btu input during this period?

1 224 443 − 1 219 507 = 4936 ft³ in 4 hours, or 4936/4 = 1234 ft³/hr. From Table A.3 in the Appendix the factor for correcting to standard pressure is 1.0765; from Table A.2a, column 2, the factor for correcting to 60 F is 0.9634. Thus the gas consumption at stp is 1234 × 1.0765 × 0.9634 = 1280 ft³/hr. From Table 2.12b, the gross heating value of Pittsburgh natural gas is 1129 Btu/ft³ at stp. The average input rate is 1280 ft³/hr × 1129 Btu/ft³ = 1 445 000 Btu/hr.

Condensible Hydrocarbon Content. The terms wet and dry indicate whether natural gases contain more or less than 0.1 gallon of condensible hydrocarbons (usually natural gasoline) per 1000 ft³ of gas.

Sulfur Content. The terms sweet and sour indicate a small or large proportion of hydrogen sulfide or other sulfur compounds.

Gaseous Fuels Data. Tables 2.12a, b, and c list properties of gaseous fuels. Example 2-8 illustrates conversion of combustion product data to another form.

Table 2.12a. Analyses of typical gaseous fuels

Type of Gas	Analysis % by Volume (mol %)								
	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO	H_2	CO_2	O_2	N_2
Acetylene, commercial			(97.1% C_2H_2, 2.5% C_3H_6O)					0.084	0.28
Blast furnace, B	—	—	—	—	22.7	2.2	19.3	0.7	55.0
Blast furnace, U	—	—	—	—	27.5	1.0	11.5	—	60.0
Butane, commercial, natural gas	—	—	6.0	70.7 n- 23.3 iso-	—	—	—	—	—
Butane, commercial, refinery gas	—	—	5.0	50.1 n- 16.5 iso-			(28.3% C_4H_8)		
Coke oven, B	28.5	3.4	0.2	—	4.2	50.8	0.8	1.6	10.5
Coke oven, U	29	3.3	(0.8 H_2S)		5.5	55.4	1.4	0.4	4.3
Digester (Sewage), Bergen, NJ	68.0	0.06	—	—	—	—	30.4	0.10	0.87
Digester (Sewage), Decatur, IL	68.0	—	—	—	—	2.0	22.0	—	8.0
Landfill, Capistrano, '81	63.4	(other hydrocarbons 0.17)			0.005	0.008	34.3	0.06	0.3
Mapp	—	—	16.0	10.0		(66.0% C_3H_4, 8.0% C_3H_6)			
Natural, Alaska	99.6	—	—	—	—	—	—	—	0.4
Natural, Algeria LNG, Canvey	87.20	8.61	2.74	1.07	—	—	—	—	0.36
Natural, Gaz de Lacq	97.38	2.17	0.10	0.05	—	—	—	—	0.30
Natural, Groningen, Netherlands	81.30	2.90	0.36	0.14	—	—	0.87	—	14.40
Natural, Kuwait, Burgan	86.7	8.5	1.7	0.5 n- 0.2 iso-	—	—	1.8	—	0.6
Natural, Libya LNG	70.0	15.0	10.0	3.5	—	—	—	—	0.90
Natural, North Sea, Bacton	93.63	3.26	0.69	0.27	—	—	0.13	—	1.78
Natural, Birmingham, AL	90.0	5.0	—	—	—	—	—	—	5.0
Natural, East OH	94.1	3.01	0.42	0.28	—	0.01	0.71	0.01	1.41
Natural, Kansas City, MO	84.1	6.7	—	—	—	—	0.8	—	8.4
Natural, Pittsburgh, PA	83.4	15.8	—	—	—	—	—	—	0.8
Producer, Koppers-Totzek¹		(0.02 COS, 0.29 H_2S)			55.7	32.9	7.0	—	1.1
Producer, Lurgi¹, commercial	5.6	(0.6 H_2O, 0.1 H_2S)			14.1	20.9	12.5	—	46.0
Producer, Lurgi¹, sub-bit	10.2	(0.4 C_nH_m, 0.3 H_2S)			17.1	40.2	31.4	—	—
Producer, IGT¹, lignite	28.3	(1.1 C_nH_m, 0.4 H_2S)			19.5	24.5	24.6	—	0.6
Producer, BCR¹ West KY	15.6	(1.4 H_2S)			44.0	24.4	14.0	—	0.6
Producer, W-G, bituminous²	2.7	—	—	—	28.6	15.0	3.4	0.0	50.3
Producer, Winkler¹	1	—	—	—	10	12	22	—	55
Propane, commercial, natural gas	—	2.2	97.3	0.5	—	—	—	—	—
Propane, commercial, refinery gas	—	2.0	72.9	0.8			(24.3% C_3H_6)		
Sasol, South Africa	26.0	—	—	—	22.0	48.0	1.0		
SNG, no methanation	79.3	—	—	—	1.2	19.0	0.5	—	—

¹ O₂-blown
² air-blown
³ Illinois coal

Table 2.12b. Properties of gaseous fuels from Table 2.12a (See Example 2-7)

Type of Gas	Gas Gravity	Calorific Value at stp Btu/ft³ Gross	Calorific Value at stp Btu/ft³ Net	Calorific Value at stp kcal/m³ Gross	Calorific Value at stp kcal/m³ Net	Gross Btu/ft³ of Std. Air	Gross kcal/m³ of Std. Air
Acetylene, commercial	0.92	1482	1444	13 200	12 830	122.0	1084
Blast furnace B	1.00	81	80	720	711	142.8	1280
Blast furnace U	1.02	92	92	810	815	135.2	1201
Butane, commercial, natural gas	1.95	3210	2961	28 540	26 325	105.1	935.1
Butane, commercial, refinery gas	1.97	3170	2965	28 200	26 400	108.6	966.0
Coke oven B	0.41	530	475	4 713	4 229	116.3	1035
Coke oven U	0.38	554	497	4 929	4 421	115.3	1026
Digester (Sewage), Bergen, NJ	0.83	598	544	5 322	4 841	106.1	944.2
Digester (Sewage), Decatur, IL	0.77	655	612	5 786	5 021	106.2	944.7
Landfill, Cagnetta '81	0.88	540	495	4 804	4 404	105	934
Mapp	1.48	2 406	2 243	21 052	19 960	111.4	990.8
Natural, Alaska	0.56	1006	917	8 976	8 160	106.0	943.7
Natural, Algeria LNG, Canvey	0.64	1139	1036	10 133	9 245	106.8	941.5
Natural, Gaz de Lacq	0.57	1028	936	9 154	8 330	105.9	942.5
Natural, Groningen, Netherlands	0.64	887	807	7 894	7 181	105.9	942.3
Natural, Kuwait, Burgan	0.84	1084	997	9 730	8 873	106.8	941.5
Natural, Libya LNG	0.79	1 340	1 217	11 923	10 819	105.6	940.0
Natural, North Sea, Bacton	0.59	1032	939	9 187	8 356	105.9	942.2
Natural, Birmingham, AL	0.60	1000	910	8 897	8 096	105.9	942.4
Natural, East OH	0.58	1027	938	9 140	8 348	105.0	942.3
Natural, Kansas City, MO	0.63	970	883	8 630	7 858	106.0	942.1
Natural, Pittsburgh, PA	0.63	1123	1025	9 986	9 116	108.8	941.4
Producer, Koppers-Totzek	0.71	290	275	2 581	2 447	131.3	1168
Producer, Lurgi, commercial	0.80	173	158	1 538	1 406	123.6	1100
Producer, Lurgi, sub-bit	0.74	304	275	2 705	2 447	122	1087
Producer, IGT, lignite	0.79	499	457	4 442	4 066	112.8	1003
Producer, BCR, West KY	0.77	390	362	3 485	3 221	120.4	1071
Producer, W-G, bituminous	0.84	168	159	1 499	1 415	126.6	1153
Producer, Wishler	0.99	117	111	1 041	988	168.8	1470
Propane, commercial, natural gas	1.52	2400	2316	22 296	20 605	108.1	935.1
Propane, commercial, refinery gas	1.50	2402	2265	21 082	20 167	106.0	942.7
Sasol, South Africa	0.41	511	463	4 544	4 117	118.7	1056
SNG, no methanation	0.47	899	787	7 721	7 003	107.8	958.7

See footnotes on page 38

Table 2.12c. Properties of gaseous fuels from Tables 2.12a, b (See Example 2-8)*

Type of Gas	Wobbe Index	vol air/vol fuel	Stoichiometric products of combustion %CO₂ dry	Stoichiometric products of combustion %H₂O wet	Stoichiometric products of combustion %N₂ wet	Stoichiometric products of combustion total vol/vol fuel	Flame temperature*, F O₂, lit. data[b]	Flame temperature*, F Air, lit. data[c]	Flame temperature*, F Air, theo calc[d]
Acetylene, commercial	1530	12.14	17.4	8.3	74.8	12.86	5640	4770	3886
Blast furnace B	78.8	0.68	29.7	1.6	68.2	1.44	—	—	2497
Blast furnace U	91.0	0.88	25.5	0.7	74.0	1.54	—	2650	2550
Butane, commercial, natural gas	2287	30.6	14.0	14.9	73.2	33.10	—	—	3543
Butane, commercial, refinery gas	2261	30.0	14.5	14.4	73.4	32.54	—	—	3565
Coke oven B	830	4.80	9.91	22.3	70.0	5.30	—	—	3625
Coke oven U	920	4.81	9.86	22.5	68.7	5.51	—	—	3642
Digester (Sewage), Bergen, NJ	619	5.84	18.1	17.8	67.2	6.63	—	—	3385
Digester (Sewage), Decatur, IL	759.5	6.35	14.7	18.4	66.7	7.52	—	—	3388
Landfill, Cagnetta '81	552.7	5.16	17.6	17.2	67.9	6.10	—	—	3276
Mapp	1987	21.25	15.6	11.9	74.4	22.56	5301	—	3732
Natural, Alaska	1352	9.52	11.7	18.9	71.8	10.52	—	—	3472
Natural, Algeria LNG, Canvey	1423	10.75	12.1	18.3	71.8	11.85	—	—	3483
Natural, Gaz de Lacq	1365	9.71	11.2	18.8	71.6	10.77	—	—	3474
Natural, Groningen, Netherlands	1107	8.30	11.7	18.4	72.0	9.45	—	—	3448
Natural, Kuwait, Burgan	1204	10.33	12.2	18.1	71.7	10.40	—	—	3476
Natural, Libya LNG	1529	12.00	12.5	17.4	72.2	13.90	—	—	3497
Natural, North Sea, Bacton	1345	9.74	11.8	18.7	71.7	10.77	—	—	3473
Natural, Birmingham, AL	1291	9.44	11.7	18.6	71.8	10.47	5120	3565	3466
Natural, East OH	1336	9.70	11.9	18.7	71.7	10.72	—	—	3472
Natural, Kansas City, MO	1222	9.16	11.8	18.5	71.9	10.19	—	3535	3461
Natural, Pittsburgh, PA	1446	10.62	12.0	18.3	71.9	11.70	5150	3562	3474
Producer, Koppers-Totzek	341	2.21	27.2	12.1	61.6	2.75	—	3723	3808
Producer, Lurgi, commercial	193.8	1.40	17.7	12.6	67.7	2.22	—	2987	2977
Producer, Lurgi, sub-bit	354	2.49	23.4	19.6	61.5	3.30	—	3348	3317
Producer, IGT, lignite	562	4.42	18.7	17.5	67.0	5.24	—	3635	3405
Producer, BCR, West KY	444	3.23	22.3	14.7	64.0	3.88	—	3878	3314
Producer, W-G, bituminous	183.6	1.40	18.3	9.8	73.5	2.08	—	3214	3167
Producer, Wishler	118.2	0.82	24.1	9.3	66.9	1.51	—	2815	3016
Propane, commercial, natural gas	2029	23.8	11.7	15.5	73.0	25.77	—	—	3532
Propane, commercial, refinery gas	2006	23.2	14.0	6.9	73.2	25.10	—	—	3560
Sasol, South Africa	794.4	4.30	12.8	21.0	66.6	4.94	—	4457	3504
SNG, no methanation	1364	8.00	11.1	18.8	71.1	8.98	—	—	3485

*Theoretical (calculated) flame temperatures, dissociation considered. See Figure 1.9 for some measured flame temperatures.

[b] With 100% Oxygen, from data in technical literature; mostly Reference 2.a listed at the end of Part 2.

[c] With air, from data in technical literature; mostly Reference 2.a listed at the end of Part 2.

[d] With air. Although these temperatures are lower than those reported in the literature, they are all computed on the same basis, so they offer a comparison of the relative flame temperatures of various fuels.

[e] ultimate

Example 2-8. Find the actual analysis of flue products for Birmingham natural gas from data in Table 2.12c.

$$\text{Volume of nitrogen} = \frac{71.8\%}{100} \times 10.47 = 7.52 \text{ ft}^3\ N_2/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of water vapor} = \frac{18.6\%}{100} \times 10.47 = 1.95 \text{ ft}^3\ H_2O/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of dry flue gases} = 10.47 - 1.95 = 8.52 \text{ ft}^3/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of carbon dioxide} = \frac{11.7\%}{100} \times 8.52 = 1.00 \text{ ft}^3\ CO_2/\text{ft}^3 \text{ fuel}$$

Check: Total volume = 7.52 ft³ N_2 + 1.95 ft³ H_2O + 1.00 ft³ CO_2 = 10.47

INTERCHANGEABILITY OF FUELS

Fuel supply shortages and price fluctuations may make it necessary to substitute one fuel for another, preferably without major changes in combustion chambers, burners, piping, or controls. Five aspects that must be considered are: 1) equal heat input rate, 2) fluid handling capability of flues, burners, piping, valves, controls, 3) burner stability, 4) heat release pattern, 5) furnace atmosphere.

Gas to Gas. The **Wobbe index**, formula 2/40b, is used to evaluate interchangeability with respect to items 1) and 2). If the substitute gas has the same Wobbe index as the gas being replaced, no change of valve settings should be necessary when changing fuels.

If the substitute fuel, which may be a fuel-air mixture, has higher gravity than the gas it replaces, fewer cubic feet will flow through the piping, valves, or orifices with the same pressure drop. See formula 5/1a. To compensate for this, the replacement mixture must have enough higher heating value to carry the same original amount of heat to the burner. Conversely, if the substitute has a lower gravity, it must also have lower heating value if the valve settings are to remain unchanged. This means that:

$$[2/40a] \quad \sqrt{\frac{G_o}{G_m}} \text{ must} = \frac{cfh_m}{cfh_o} \quad \text{or} \quad \sqrt{\frac{G_o}{G_m}} = \frac{H_o}{H_m}$$

where G = gravity relative to air as 1.0, H = calorific value, o = original gas, p = pure substitute, a = air, m = substitute mix consisting of p and a. Rearranging 2/40a gives the definition of Wobbe index:

$$[2/40b] \quad \text{Wobbe index} = \frac{H_o}{\sqrt{G_o}} = \frac{H_m}{\sqrt{G_m}}$$

For mixtures, when one ingredient is air,

$$[2/40c] \quad G_m = \left(\frac{\%p}{100} \times G_p\right) + \left(\frac{\%a}{100} \times G_a\right),$$

$$\text{but } G_a = 1.0 \text{ and } \%a = 100 - \%p; \text{ so } G_m = 1 + \frac{\%p}{100}(G_p - 1)$$

$$[2/40d] \quad H_m = \left(\frac{\%p}{100} \times H_p\right) + \left(\frac{\%a}{100} \times H_a\right), \text{ but } H_a = 0; \text{ so } H_m = \frac{\%p}{100}(H_p)$$

Combining the above formulas, the % of pure substitute in a mixture with air that will be interchangeable with the original gas both heat-release-wise and flow-wise is:

$$[2/41] \quad \%p = \frac{200}{1 - G_p + \sqrt{(G_p - 1)^2 + 4\, G_o\left(\frac{H_p}{H_o}\right)^2}}$$

Example 2-9. If propane is to be substituted for natural gas during curtailments, the different calorific value and gas gravity (density) would necessitate readjustment of the gas limiting orifice valve (see Volume II) when the propane is turned on, and again when resuming with natural gas. For one or a few burners, it may be practical to install duplicate gas trains in parallel. The limiting orifice valve in one gas train would be adjusted for correct air/natural gas ratio; the other for correct air/propane ratio. If fuel changes are frequent or if many burners are involved, a propane-air mix, having the same Wobbe index as the natural gas, can be substituted at the same pressure without readjusting valves.

A 1025 Btu/ft³ natural gas (gas gravity = 0.592) is to be replaced with a propane-air mix using 2615 Btu/ft³ propane (gas gravity = 1.552). Use formula 2/41 to find the % propane to be used in the propane-air mix.

$$\%p = \frac{200}{1 - 1.552 + \sqrt{0.3047 + 4(0.592)\left(\frac{2615}{1025}\right)^2}} = 58.6.$$

In the table below, the bold figures are given data. The other figures are derived by substituting given data in the formulas indicated in brackets.

	original	pure substitute	air	mix substitute, (2/41) 58.6% propane
H	**1025 Btu/ft³**	**2615 Btu/ft³**	0	(2/40d) 1532 Btu/ft³
G	**0.592**	**1.552**	1.0	(2/40c) 1.324
Wobbe	(2/40b) 1332	(2/40b) 2099	0	(2/40b) 1332

Liquefied petroleum gases (propane, butane, and mixes of propane and butane) are delivered and stored as liquids in pressurized vessels. For most industrial rates of consumption, a vaporizer is necessary. The volume of gas available from a gallon of liquid is 36.82 ft³/gal for commercial propane, and 31.46 ft³/gal for commercial butane, when both liquid and gas are measured at 60 F (15.6 C) and the gas is also at 30"Hg. A gas-air mixing station is necessary to automatically maintain the proper ratio of gas to air at all demand rates. See Volume II. For safety in handling, the gas-air mixture should be above the upper limit of flammability, i.e. too rich to burn, until it is further diluted with the normal amount of combustion air at the burners.

Table 2.13. Typical propane-air mixtures usable as substitutes for fuels from Table 2.12, based on refinery propane (H_p = 2504 Btu/ft³, G_p = 1.77)

Original Fuel				Mix Substitute			
Description	H_o	G_o	Wobbe$_o$	%p	H_m	G_m	Wobbe$_m$
Producer, Lurgi	173	0.80	193.4	7.96	199.3	1.061	193.4
Producer, K-T	290	0.71	344.0	14.49	362.9	1.112	344.0
Coke Oven, U	554	0.36	923.3	42.46	1063.7	1.327	923.3
Natl, Kans C. MO	970	0.63	1222.1	58.83	1473.1	1.453	1222.1
Natl, Birm AL	1000	0.60	1291.0	62.80	1572.4	1.484	1291.0
LNG, Algeria	1139	0.64	1423.8	70.65	1769.1	1.544	1423.8

Warning: Fuel specs change with locale and time; so these figures should be used only as a guide. Use formulas 2/40 and 2/41 for specific cases.

Burner stability is a function of flame velocity and flammability limits. Although some theoretical methods have been proposed for evaluating flame stability when interchanging fuels, it is advisable to actually try the substitute gas in the burner types to be used at all expected firing rates and gas/air ratios. Premix burners are generally more sensitive, stability-wise, than are most modern nozzle-mix burners. There is usually no stability problem with gaseous fossil fuels (methane, ethane, propane, butane and mixtures thereof) but these fuels sometimes contain soot-forming unsaturates such as propylene and butylene.

Heat release pattern depends on the flame's shape, intensity and luminosity. Natural gas is relatively slow burning; so most substitute fuels will tend to burn with shorter, more intense flames. The effect of such a change can only be evaluated by trial for each process for which a substitute fuel is proposed.

Furnace atmosphere may be seriously affected if the substitute fuel contains a higher concentration of an impurity such as sulfur. Some processes, particularly heat treat atmosphere generators, are sensitive to the changing carbon/hydrogen ratio, which may involve dew point control.

Gas to Oil. The only way to substitute oil burning through existing gas burners is with an external vaporizing system added to premix gas burners. If the input per burner can be at least 250 000 Btu/hr (17.5 kcal/s), it is usually less expensive to replace each gas burner with a dual-fuel burner (a combination gas burner and oil burner built into a common housing). Either of these conversion systems (vaporizer or dual-fuel burners) require more first cost than gas-to-gas

substitution, but may save on operating (fuel) cost. Selection of the conversion equipment takes care of the first three of the five aspects listed in the introduction to this section on interchangeability.

The fourth aspect, **heat release pattern**, is different for oils because their flames are more luminous. (However, there are a few burners designed to produce blue oil flames, and long luminous flame burners make yellow gas flames.) Because atomization and vaporization time is usually required after the oil leaves the burner nozzle, oil flames often require somewhat more combustion space. If combustion space is very confined or if a lot of flame radiation may be detrimental to the process, conversion to oil might require a combustion chamber revision; but this is not a problem in most conventional general-purpose furnaces because they are designed conservatively.

The fifth aspect, **furnace atmosphere**, was of great concern to the forging industry when converting to cheap natural gas in the 1950's, but serious effects upon scale formation could not be proved except in a handful of very critical cases. As with gas-for-gas substitutions, the effects of changes in sulfur or C/H ratio must be evaluated for each specific fuel and process.

COMPARATIVE COSTS OF FUELS

The most common way to compare fuels is by their heating values, and since gross heating values are more readily available, these figures are usually used. However, this comparison may be misleading for a number of reasons which are discussed in the following paragraphs.

The full gross heating value of a fuel is not available in practical combustion equipment because the exit gas temperature is not low enough to permit condensation of the moisture in the products of combustion. For this reason, a comparison of net heating values is much more desirable, if it is possible to do so. Gross and net heating values are not proportional throughout the range of commercially available fuels. Net heating values are readily calculated from the analysis of a gaseous or solid fuel, but the values obtained from formula 2/11 for liquid fuels may be subject to question because of the variation in refining methods.

Combustion efficiencies are not the same with all fuels. For example, fuels of higher hydrogen content produce combustion gases that have high specific heats*; thus the flue gas loss (stack loss) tends to be greater. Generally, gaseous or liquid fuels can be burned more efficiently than solid fuels, because less heat consuming excess air is needed to assure complete combustion. The ash in solid fuels is also cause for loss because it carries heat away from the furnace when it is removed and because some unburned fuel may be removed with the ash.

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* That is, for the same temperature rise, these gases absorb more Btu of heat than do other gases.

Operating costs usually vary widely with different fuels. The costs of handling solid fuels and the resulting ash may be considerable. Liquid fuels must be stored, pumped, and sometimes heated.

Equipment costs, for control, safety, handling, storage, combustion, and pollution abatement are generally less with lighter and cleaner fuels. Combustion chamber linings and breechings may have to be replaced more frequently with some fuels. Determination of the relative operating and equipment costs is a special problem in each individual case.

The figures in Example 2-10 should not be interpreted as typical. They are simply "made up" to illustrate the *method* for cost evaluation. Differing local costs and application requirements could result in entirely different conclusions on other jobs.

Example 2-10. For an existing system using natural gas only, compare the total annual costs of three possible standby systems—propane-air at $3.50 per million Btu, #2 oil at $2.50 per million Btu, and #6 oil at $2.00 per million Btu. Average consumption rate is 14 000 000 Btu/hr. Assume that the system will be on standby fuel about 3000 hours per year.

14 million Btu/hr × 3000 hr/yr = 42 000 million Btu/yr. Annual fuel cost with propane = 42 000 million Btu/yr × $3.50/million Btu = $147,000/yr; with #2 oil, 42 000 × $2.50 = $105,000/yr; with #6 oil, 42 000 × $2.00 = $84,000/yr.

By obtaining equipment and installation cost estimates the following type of cost comparison table might be developed

		Standby fuel		
	Estimated costs	**Propane-air**	**#2 Fuel oil**	**#6 Fuel oil**
Equipment & installation	Tanks, grading, insulation	$ 35,000[1]	$ 14,000[2]	$ 21,500[3]
	Piping	4,000	1,500	4,000
	Vaporizer and mixing station	15,000	0	0
	Pumps and heating system	0	2,000	6,000
	Burners and controls	0	3,000	4,000
	Subtotal, first cost	$ 54,000	$ 20,500	$ 36,500
Operating annual	Annual, 3-yr payout	18,000	6,833	12,167
	Elec. power, supervision, maintenance	3,000	4,000	6,500
	Fuel	147,000	105,000	84,000
	TOTAL ANNUAL COST	$168,000	$115,833	$102,667

WARNING. These figures should not be interpreted as typical. They are simply "made up" to illustrate the *method* for cost evaluation. Differing local costs and application requirements could result in entirely different conclusions on other jobs.

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[1] 30 000 gallon tank, 65' × 9' diameter. 10 to 14 days storage capacity.

[2] 20 000 gallon vertical or horizontal above-ground steel tank. If below ground, cost would be about $10,500—no dike or unloading pump required.

[3] 20 000 gallon horizontal heated and insulated steel tank

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Part 3. COMBUSTION ANALYSIS

It is frequently necessary to predict: the air requirement for burning a fuel, the products of combustion of that fuel, and the losses accompanying its combustion. The tabulated data on typical fuels in Part 2 supplies information of this sort for specific fuels. If none of the fuels listed in Part 2 approximates the particular fuel under consideration, the methods outlined in this Part 3 should be used.

This chapter also discusses the significance of experimental flue gas analyses and means of minimizing the various combustion losses to improve efficiency.

Throughout this handbook, volumes of air and gases are assumed measured at "stp", standard temperature (60 F, 15.6 C) and standard pressure (14.696 psia, 760 mm Hg), unless otherwise specified. It is common practice to refer to air at stp as "standard air."

COMBUSTION AIR REQUIREMENTS

Gaseous Fuels. The amount of air required for perfect combustion of one cubic foot of any gaseous fuel is given by the formula:

$$[3/1]\quad \frac{\text{volume of air}}{\text{volume of fuel}} = [(\%CH_4 \times 0.0956) + (\%C_2H_6 \times 0.1673) + (\%C_3H_8 \times 0.239) + (\%C_4H_{10} \times 0.311) + (\%H_2 \times 0.0239) + (\%CO \times 0.0239) - (\%O_2 \times 0.0478)] \times [1 + \%XSA/100]$$

where all percentages are by volume. Non-combustibles have no effect on the amount of air required for combustion. In formula 3/1, the air and gas volumes must be measured at the same temperature and pressure. If there is some difference between the air and gas temperature or pressure, correction can be made by use of the following formulas.

$$[3/2]\quad \text{volume at } t_2 = \text{volume at } t_1 \times \left(\frac{t_2\,F + 460}{t_1\,F + 460}\right), \text{ or } = \text{volume at } t_1 \times \left(\frac{t_2\,C + 273}{t_1\,C + 273}\right)$$

$$[3/3]\quad \text{vol at } p_2 = \text{vol at } p_1 \times \left(\frac{p_1 \text{ in psi} + 14.7}{p_2 \text{ in psi} + 14.7}\right), \text{ or } = \text{vol at } p_1 \times \left(\frac{p_1 \text{ in mm Hg} + 760}{p_2 \text{ in mm Hg} + 760}\right)$$

Tables A.2 and A.3 in the Appendix list volume correction factors calculated from the above formulas. Tables 1.7, 2.1, 2.3, 2.12 and 3.1 list the combustion air requirements of several chemical compounds and fuels.

Table 3.1. Combustion characteristics of chemical compounds

Fuel	Gas gravity*	Specific Volume ft³/lb	Specific Volume m³/kg	Gross Btu/ft³ of stand. air	Gross kcal/m³ of stand. air	Ult. % CO_2†	Products of perfect combustion per unit of fuel									
							CO_2		H_2O		N_2		SO_2		Total	
							wt‡	vol△	wt‡	vol△	wt‡	vol△	wt‡	vol△	wt‡	vol△
Acetylene C_2H_2	0.907	14.4	0.899	128.1	1139	17.3	3.38	2.00	0.692	1.00	10.22	9.41	0	0	14.30	12.4
Benzene C_6H_6	2.00	4.86	0.303	105.1	935.0	17.5	3.38	6.00	0.692	3.00	10.16	28.2	0	0	14.25	37.2
Butane C_4H_{10}	2.06	6.34	0.400	105.3	[illegible]	14.1	3.03	4.00	1.55	5.00	11.87	24.4	0	0	16.45	33.4
Carbon C	—	—	—	91.7	816.3	20.0	3.67	—	0	0	8.83	—	0	—	12.5	—
Carbon Monoxide CO	0.966	13.5	0.846	134.0	1200	34.7	1.57	1.00	0	0	1.90	1.88	0	0	3.48	2.88
Ethane C_2H_6	1.05	12.6	0.788	106.2	944.8	13.2	2.93	2.00	1.80	3.00	12.29	13.2	0	0	17.02	18.2
Hydrogen H_2	0.0690	189	11.82	136.5	1215	0	0	0	9.00	1.00	26.45	1.88	0	0	35.40	2.88
Hydrogen Sulfide H_2S	1.17	11.1	0.694	90.3	804.0	0	0	0	0.529	1.00	4.67	5.64	1.88	1.00	7.08	6.64
Methane CH_4	0.552	23.7	1.48	106.3	942.8	11.7	2.75	1.00	2.25	2.00	13.24	7.52	0	0	18.24	10.5
Naphthalene $C_{10}H_8$	4.41	2.96	0.185	102.5	911.7	18.1	3.44	10.0	0.563	4.00	9.91	45.1	0	0	13.83	59.1
Octane C_8H_{18}	—	—	—	105.0	934.7	14.6	3.08	—	1.42	—	11.81	-	0	0	16.32	—
Propane C_3H_8	1.52	8.41	0.525	106.1	943.5	13.8	3.00	3.00	1.64	4.00	12.06	18.8	0	0	16.7*	25.8
Propylene C_3H_6	1.45	9.05	0.565	108.2	962.0	15.5	3.14	3.00	1.29	3.00	11.35	16.9	0	0	15.78	22.9
Sulfur S	—		—	70.5	628.4	0	0	0	0	0	3.31	—	2.00	—	5.31	—

* Relative to standard air at 60 F
† Dry
‡ Pounds of combustion product per pound of fuel, or kg/kg, or any consistent weight units
△ Cubic feet of combustion product per ft³ of fuel, or m³/m³, or any consistent volume units

Example 3-1. Find the air required to burn a certain coke oven gas having the following volumetric analysis: 32.3% CH_4, 2.5% C_2H_6, 3.2% C_4H_{10}, 51.9% H_2, 5.5% CO, 0% O_2, 1.0% CO_2, and 3.6% N_2. Substituting in formula 3/1, (32.3 × 0.0956) + (2.5 × 0.1673) + (3.2 × 0.311) + (51.9 × 0.0239) + (5.5 × 0.0239) = 5.87 cubic feet of air required per cubic foot of gas.

If the combustion air were supplied at 32 osi pressure (2 psig) and at 300 F, and if the gas were supplied at 60 F and barometric pressure, then by formulas 3/2 and 3/3 or Tables A.2 and A.3, the air/fuel ratio should be $5.87 \times \frac{14.7}{14.7 + 2} \times \frac{300 + 460}{60 + 460} = 7.55$ actual cubic feet of air per cubic foot of fuel.

Liquid and Solid Fuels. The amount of air required for perfect combustion of one pound of any liquid or solid fuel is given by the formula:

$$[3/4] \quad \frac{\text{ft}^3\text{ air}}{\text{lb fuel}} = (\%C \times 1.514) + (\%H \times 4.54) + (\%S \times 0.568) - (\%O \times 0.568)$$

where all percentages are by weight. The cubic feet of air obtained from formula 3/4 must be measured at 60 F (15.6 C) and 14.7 psia (760 mm Hg) pressure. For other temperatures and pressures apply the correction factors as in the second paragraph of Example 3-1. For fuel oils containing negligible amounts of sulfur, oxygen, and inerts, formulas 2/5 and 2/10 may be combined with formula 3/4 to give the approximate expression

$$
\begin{aligned}
[3/5] \quad & \text{ft}^3\text{ air/gal oil} = (1906 \times sg) - [379 \times (sg)^2] \text{ when } sg \text{ is between } 0.825 \text{ and } 0.875\\
& \text{ft}^3\text{ air/gal oil} = (1900 \times sg) - [379 \times (sg)^2] \text{ when } sg \text{ is between } 0.875 \text{ and } 0.934\\
& \text{ft}^3\text{ air/gal oil} = (1896 \times sg) - [379 \times (sg)^2] \text{ when } sg \text{ is between } 0.934 \text{ and } 1.007\\
& \text{ft}^3\text{ air/gal oil} = (1878 \times sg) - [379 \times (sg)^2] \text{ when } sg \text{ is between } 1.007 \text{ and } 1.076
\end{aligned}
$$

where sg is the specific gravity (60/60 F)* of the fuel oil. (The term "inerts" refers to non-combustible substances in the fuel, such as CO_2, N_2, ash, and water.) The cubic feet of air obtained from this formula must be measured at 60 F and 14.7 psia pressure. For other temperatures and pressures, apply correction factors as in the second paragraph of Example 3-1. Results from formula 3/5 may be read on Table 2.3. A *rule of thumb* is: 25 cfm of air are required for each gallon per hour of oil.

Example 3-2. Find the air required to burn a fuel oil that weighs 6.99 lb per gallon (sg = 0.838) and has the following ultimate analysis: 86.14% C, 13.24% H, 0.22% S, 0.02% N, 0.00% ash, and 0.38% O.

Substituting in formula 3/4, $\frac{\text{ft}^3\text{ air}}{\text{lb fuel}} = (86.14 \times 1.514) + (13.24 \times 4.54) + (0.22 \times 0.568) - (0.38 \times 0.568) = 190.4$ ft³/lb or 6.99 × (190.4) = 1331 ft³/gal.

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* See Part 2 for a discussion of specific gravities of oils

Using formula 3/5, we obtain (1906 × 0.838) − [379 × (0.838)²] = 1331 ft³/gal. The rule of thumb is based on 25 cfm/gph × 60 min/hr = 1500 ft³/gal.

All the above data have specified the air requirements for *perfect* combustion. In some instances it is desirable to burn fuels with a deficiency of air in order to obtain a reducing (non-oxidizing) atmosphere. In other instances an excess of air is intentionally supplied. This condition is usually described by specifying the *percent excess air*. Thus, if 1331 ft³ of air are required for perfect combustion of one gallon of a fuel oil, but ten percent excess air is to be supplied, then the air supply should be 1331 + (0.10 × 1331) or simply 1.10 × 1331 = 1464 ft³/gal.

PRODUCTS OF COMBUSTION (poc)

It is often desirable to predict the quantity and analysis of the products of combustion of a fuel in order to determine proper flue sizes and furnace pressure, and to predict the magnitude of stack or flue gas losses. Table 3.1 lists the products resulting from perfect combustion of several chemical compounds. Formulas 3/6 through 3/17 permit calculation of the quantities of gases in the combustion products of *gaseous fuels* either by volume or by weight. The percentages to be substituted in all of these formulas are percentages by volume. Formulas 3/18 through 3/29 permit calculation of the quantities of gases (by weight or by volume) in the combustion products of *liquid and solid fuels*. The percentages to be substituted in these formulas are all percentages by weight.

Care should be exercised in the use of formulas 3/11 through 3/15 and 3/23 through 3/29 because they give the volume of the various flue gases at 60 F and 14.7 psia pressure (15.6 C and 760 mm Hg). These volumes must be corrected to the actual temperature and pressure conditions by use of formulas 3/2 and 3/3 or Tables A.2 and A.3 in the same manner as previously illustrated for correcting air volumes. At temperatures below 250 F the water vapor in the flue gases no longer behaves as a gas and may even condense. Therefore volumes calculated from formulas 3/11, 3/15, 3/23, and 3/27 are hypothetical at 60 F and are meaningless unless corrected to some temperature above 250 F.

For approximate calculations, a *rule of thumb* would say that the volume of combustion products equals the sum of air and gas (fuel) volumes. A quick scan of Table 2.12c shows this to be close for natural gases and some manufactured gases. For LP gases, ft³ cp/ft³ fuel = ft³ air/ft³ fuel + 2. For oils, the ft³ cp/gal = ft³ air/gal + 85.

For cases in which an excess of air is supplied, it is merely necessary to add the weight or volume of the excess nitrogen and excess oxygen to the other combustion products. This procedure is illustrated in Example 3-4.

Table 3.2. Formulas for determining products of complete combustion of gaseous fuels. (All percentages are percents by volume, all volumes at stp—60 F and 29.92 in. Hg.)

(3/6) $\frac{\text{lb comb prod}}{\text{ft}^3\text{ fuel}} = (\%CO \times 0.002\,555) + (\%H_2 \times 0.001\,872) + (\%CH_4 \times 0.007\,70) + (\%C_2H_6 \times 0.013\,53) + (\%C_3H_8 \times 0.019\,30) + (\%C_4H_{10} \times 0.025\,16) + (\%CO_2 \times 0.001\,161) + (\%N_2 \times 0.000\,739) + (\%SO_2 \times 0.001\,686) + (\%H_2O \times 0.000\,475) - (\%O_2 \times 0.002\,794) + (\%XSA/100) \times 0.001\,816 \times \oplus$

(3/7) $\frac{\text{lb }CO_2}{\text{ft}^3\text{ fuel}} = (\%CO \times 0.001\,161) + (\%CH_4 \times 0.001\,161) + (\%C_2H_6 \times 0.002\,322) + (\%C_3H_8 \times 0.003\,483) + (\%C_4H_{10} \times 0.004\,644) + (\%CO_2 \times 0.001\,161)$

(3/8) $\frac{\text{lb }H_2O}{\text{ft}^3\text{ fuel}} = (\%H_2 \times 0.000\,475) + (\%CH_4 \times 0.000\,950) + (\%C_2H_6 \times 0.001\,425) + (\%C_3H_8 \times 0.001\,900) + (\%C_4H_{10} \times 0.002\,375) + (\%H_2O \times 0.000\,475)$

(3/9a) $\frac{\text{lb }N_2}{\text{ft}^3\text{ fuel}} = (\%N_2 \times 0.000\,739) + [(1 + \%XSA/100) \times 0.001\,397 \times \oplus]$

(3/9b) $\frac{\text{lb }O_2}{\text{ft}^3\text{ fuel}} = (\%XSA/100) \times (0.000\,422) \times \oplus$

(3/10) $\frac{\mu g\ SO_2}{\text{m}^3\text{ fuel}} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 45\,760$

(3/11) $\frac{\text{volume cp}^\dagger}{\text{volume fuel}} = (\%CO \times 0.028\,8) + (\%H_2 \times 0.028\,8) + (\%CH_4 \times 0.105\,6) + (\%C_2H_6 \times 0.182\,3) + (\%C_3H_8 \times 0.259\,0) + (\%C_4H_{10} \times 0.335\,7) + (\%\text{inerts}^* \times 0.01) - (\%O_2 \times 0.037\,8) + (\%XSA/100) \times 0.023\,9 \times \oplus$

(3/12) $\frac{\text{volume dcp}^\dagger}{\text{volume fuel}} = (\%CO \times 0.028\,8) + (\%H_2 \times 0.018\,8) + (\%CH_4 \times 0.085\,5) + (\%C_2H_6 \times 0.152\,3) + (\%C_3H_8 \times 0.219\,0) + (\%C_4H_{10} \times 0.285\,7) + (\%\text{inerts}^* \times 0.01) - (\%O_2 \times 0.037\,8) + (\%XSA/100) \times 0.023\,9 \times \oplus$

(3/13) $\frac{\text{volume }CO_2}{\text{volume fuel}} = (\%CO \times 0.01) + (\%CH_4 \times 0.01) + (\%C_2H_6 \times 0.02) + (\%C_3H_8 \times 0.03) + (\%C_4H_{10} \times 0.04) + (\%CO_2 \times 0.01)$

(3/14) $\frac{\%CO_2\text{ in dcp}^\dagger}{(\text{ultimate }\%CO_2)} = 100 \times \frac{\text{volume of }CO_2}{\text{volume of fuel}} \div \left(\frac{\text{volume of dcp}}{\text{volume of fuel}}\text{ from formula 3/12}\right)$

(3/15) $\frac{\text{volume }H_2O}{\text{volume fuel}} = (\%H_2 \times 0.01) + (\%CH_4 \times 0.02) + (\%C_2H_6 \times 0.03) + (\%C_3H_8 \times 0.04) + (\%C_4H_{10} \times 0.05) + (\%H_2O \times 0.01)$

(3/16a) $\frac{\text{volume }N_2}{\text{volume fuel}} = (\%N_2 \times 0.01) + [(1 + \%XSA/100) \times 0.018\,9 \times \oplus]$

(3/16b) $\frac{\text{volume }O_2}{\text{volume fuel}} = (\%XSA/100) \times 0.005 \times \oplus$

(3/17a) $\frac{\mu g\ SO_2}{\text{m}^3\text{ cp}\ddagger} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 45\,760 \div \left(\frac{\text{vol cp}\ddagger}{\text{vol fuel}}\text{ from formula 3/11}\right)$

(3/17b) $\frac{\text{ppm }SO_2}{(\text{by volume})} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 16.92 \div \left(\frac{\text{vol cp}\ddagger}{\text{vol fuel}}\text{ from formula 3/11}\right)$

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* "inerts" include CO_2, N_2, SO_2, SO_3, argon, helium, and other non-combustibles.

† cp = combustion products (flue gases). dcp = dry combustion products.

‡ To get an answer per volume of dry combustion products, use vol dcp/vol fuel from formula 3/12.

$\oplus = \%CO + \%H_2 + (4 \times \%CH_4) + (7 \times \%C_2H_6) + (10 \times \%C_3H_8) + (13 \times \%C_4H_{10}) - (2 \times \%O_2)$

When there is a deficiency of air it is difficult to predict the volume or the analysis of the combustion products, but the total weight of the products will be equal to the weight of the fuel plus the weight of the air supplied.

Example 3-3. A furnace is fired with 1000 ft³/hr of a natural gas having 0.2 grains of sulfur per 100 ft³, and the following volumetric analysis: 80% CH_4, 16% C_2H_6, 2% O_2, 1% N_2, 1% CO_2.

Determine the volume of CO_2, water vapor, and nitrogen in the flue gases when the correct amount of air is supplied. Calculate the SO_2 concentration in the flue products. Also find the volume flow rate of the combustion products at the point where their temperature is 800 F and the pressure is 3.45 inches of water column (abbreviated "wc) positive (above atmospheric pressure).

From formula 3/13, the amount of CO_2 in the flue gases will be $(80 \times 0.01) + (16 \times 0.02) + (1 \times 0.01) = 1.13$ volume CO_2/volume fuel. Similarly, formulas 3/15 and 3/16 yield 2.08 vol H_2O/vol fuel and 8.10 vol N_2/vol of fuel respectively.

Formula 3/11 gives the volume of the combustion products as $(80 \times 0.1056) + (16 \times 0.1823) + (1 + 1) \times 0.01 - (2 \times 0.0378) = 11.31$ volumes of combustion products per volume of fuel. By formula 3/17a, the SO_2 concentration in the combustion products is $0.2 \times 45\,760 \div 11.31 = 809\ \mu g/m^3$; or by formula 3/17b, $0.2 \times 16.92 \div 11.31 = 0.299$ ppm.

The above 11.31 vol cp/vol fuel is for combustion products at the same temperature and pressure as the fuel. If the fuel is presumed to be measured at stp (60 F and 14.7 psia), the volume of combustion products must be corrected to the specified 3.45"wc and 800 F as follows. From Table C.6 in the Appendix, 1 osi = 1.732"wc; therefore 3.45"wc/1.732 = 1.99 osi. From Table A.3, one cubic foot of gas at that pressure becomes 1.0085 ft³ at standard atmospheric pressure. From Table A.2a the volume of a cubic foot of standard air or gas is increased 2.421 times when it is heated to 800 F. Applying these correction factors,

$$\frac{11.31\text{ ft}^3\text{ cp at stp}}{\text{ft}^3\text{ of fuel}} \times \frac{1.0\text{ ft}^3\text{ at 3.45"wc}}{1.0085\text{ ft}^3\text{ at stp}} \times \frac{2.421\text{ ft}^3\text{ at 800 F}}{1.0\text{ ft}^3\text{ at stp}} = 27.15\text{ ft}^3$$

of combustion products per cubic foot of fuel. At a firing rate of 1000 cfh, the volume flow rate of the flue gases will be 1000 × 27.15 = 27 150 cfh.

Example 3-4. Predict the analysis by volume of products of combustion of the fuel described in Example 3-3 when 15% excess air is supplied.

It is first necessary to use formula 3/1 to determine the volume of air required for perfect combustion. Thus $(80 \times 0.0956) + (16 \times 0.1673) - (2 \times 0.0478) = 10.23$

Therefore 15% excess (XS) air will amount to $10.23 \times \frac{15}{100} = 1.534\ \frac{\text{ft}^3\text{ XSair}}{\text{ft}^3\text{ fuel}}$

Air is 20.99% oxygen and 78.03% nitrogen by volume. Therefore the excess air will be made up of 1.534×0.322 vol O_2/vol fuel and $1.534 \times 0.7803 = 1.197$ vol N_2/vol fuel. Adding these quantities to the flue gas analysis found in Example 3-3 above, combustion of one volume of fuel with 15% excess air will produce 1.13 vol CO_2, 2.08 vol H_2O, 0.322 vol O_2, and $8.10 + 1.197 = 9.30$ volumes of N_2.

Table 3.3. Formulas for determining products of complete combustion of liquid and solid fuels. (All percentages are percents by weight.)$^{\square}$

(3/18) $$\frac{\text{wt cp}^{\dagger}}{\text{wt fuel}} = (\%C \times 0.124\,8) + (\%H \times 0.352\,0) + (\%S \times 0.053\,1) + (\%\text{inerts}^{*} \times 0.01) - [\%O^{\square} \times 0.033\,1] + [\%XSA/100] \times [(\%H \times 0.342\,0) + (\%C \times 0.114\,8) + (\%S \times 0.043\,0) - (\%O \times 0.043\,1)]$$

(3/19) $$\text{wt } CO_2/\text{wt fuel} = (\%C \times 0.036\,6) + (\%CO_2^{\circledast} \times 0.01)$$

(3/20) $$\text{wt } H_2O/\text{wt fuel} = (\%H \times 0.089\,4) + (\%H_2O^{\circ} \times 0.01)$$

(3/21) $$\frac{\text{wt } SO_2}{\text{wt fuel}} = (\%S \times 0.020\,0) + (\%SO_2^{\wedge} \times 0.01)$$

(3/22a) $$\frac{\text{wt } N_2}{\text{wt fuel}} = [(\%C \times 0.088\,2) + (\%H \times 0.262\,6) + (\%S \times 0.033\,0) - (\%O^{\square} \times 0.033\,1)] \times [1 + \%XSA/100] + (\%N \times 0.01)$$

(3/22b) $$\frac{\text{wt } O_2}{\text{wt fuel}} = [(\%C \times 0.026\,6) + (\%H \times 0.079\,4) + (\%S \times 0.009\,98) - (\%O^{\square} \times 0.01)] \times [\%XSA/100]$$

(3/23) $$\frac{\text{ft}^3\text{ cp}^{\dagger}}{\text{lb fuel}} = (\%C \times 1.508) + (\%H \times 5.433) + (\%S \times 0.565\,0) + (\%CO_2^{\circledast} \times 0.086\,1) + (\%H_2O^{\circ} \times 0.210\,4) + (\%N \times 0.135\,3) - (\%O^{\square} \times 0.447\,7) + [\%XSA/100] \times [(\%C \times 1.508) + (\%H \times 4.483) + (\%S \times 0.565\,0) - (\%O^{\square} \times 0.565\,2)]$$

(3/24) $$\frac{\text{ft}^3\text{ dcp}^{\dagger}}{\text{lb fuel}} = (\%C \times 1.508) + (\%H \times 3.553) + (\%S \times 0.565\,0) + (\%CO_2^{\circledast} \times 0.086\,1) + (\%N \times 0.135\,3) - (\%O^{\square} \times 0.447\,7) + [\%XSA/100] \times [(\%C \times 1.508) + (\%H \times 4.483) + \%S \times 0.565\,0) - (\%O^{\square} \times 0.565\,2)]$$

(3/25) $$\text{ft}^3\ CO_2/\text{lb fuel} = (\%C \times 0.316\,5) + (\%CO_2^{\circledast} \times 0.086\,1)$$

(3/26) $$\%CO_2 \text{ in dcp}^{\dagger} = 100 \times \frac{\text{ft}^3\ CO_2}{\text{lb fuel}} \div \frac{\text{ft}^3\text{ dcp}}{\text{lb fuel}}$$

(3/27) $$\text{ft}^3\ H_2O/\text{lb fuel} = (\%H \times 1.880) + (\%H_2O^{\circ} \times 0.210\,4)$$

(3/28a) $$\text{ft}^3\ SO_2/\text{lb fuel} = (\%S \times 0.118\,2) + (\%SO_2^{\wedge} \times 0.059\,2)$$

(3/28b) $$\frac{\mu g\ SO_2}{m^3\text{ cp}^{\ddagger}} = \left(\frac{\text{wt } SO_2}{\text{wt fuel}} \text{ from formula 3/21}\right) \times 1.602 \times 10^{10} \div \left(\frac{\text{ft}^3\text{ cp}^{\ddagger}}{\text{lb fuel}} \text{ from formula 3/23}\right)$$

(3/28c) $$\frac{\text{ppm } SO_2}{\text{(by volume)}} = \left(\frac{\text{ft}^3\ SO_2}{\text{lb fuel}} \text{ from formula 3/28a}\right) \times 1 \times 10^{6} \div \left(\frac{\text{ft}^3\text{ cp}^{\ddagger}}{\text{lb fuel}} \text{ from formula 3/23}\right)$$

(3/29a) $$\frac{\text{ft}^3\ N_2}{\text{lb fuel}} = [(\%C \times 1.193) + (\%H \times 3.553) + (\%S \times 0.446\,8) - (\%O^{\square} \times 0.447\,7)] \times [1 + \%XSA/100] + [\%N \times 0.135\,3]$$

(3/29b) $$\frac{\text{ft}^3\ O_2}{\text{lb fuel}} = [(\%C \times 0.316\,5) + (\%H \times 0.940\,0) + (\%S \times 0.118\,2) - (\%O^{\square} \times 0.118\,4)] \times [\%XSA/100]$$

---

* "Inerts" include CO$_2$, N$_2$, SO$_2$, SO$_3$, argon, helium, and other non-combustibles.

† cp = combustion products (flue gases); dcp = dry combustion products.

‡ To get an answer per ft³ of dry combustion products, use ft³ dcp/lb fuel from formula 3/24.

□ These equations may be used for gaseous fuels containing no CO. If the values substituted in the above equations for %C, %H, and %S are the percentages of total carbon, hydrogen, and sulfur, (available plus unavailable), then the %O should be the total (free and combined) oxygen. If the values substituted in the above equations for %C, %H, and %S are the percentages of available carbon, hydrogen, and sulfur respectively, then the %O should be the free oxygen only.

⊛ If %C includes the unavailable carbon already in the form of CO$_2$, this CO$_2$ term should be omitted and note □ observed. ○ If %H includes the unavailable hydrogen already in the form of H$_2$O, this H$_2$O term should be omitted and note □ observed. ^ If %S includes the unavailable sulfur already in the form of SO$_2$, this SO$_2$ term should be omitted and note □ observed.

Example 3-6. Predict the gravimetric (weight) analysis of the flue gases resulting from the perfect combustion of a 15°API oil having the following gravimetric analysis: 88.50% C, 10.50% H, 0.10% N, 0.80% S, 0.06% O. Find %CO$_2$ in the dry flue gas.

When the correct amount of air is supplied, the quantity of CO$_2$ in the flue gas (by formula 3/19) will be (88.5 × 0.0366) = 3.24 wt CO$_2$/wt fuel. Similarly, formulas 3/20, 3/21, and 3/22 give 0.94 wt H$_2$O/wt fuel, 0.016 wt SO$_2$/wt fuel, and 10.59 wt N$_2$/wt fuel. These total 3.24 + 0.94 + 0.016 + 10.59 = 14.79 wt cp/wt fuel. The %CO$_2$ by weight is therefore (3.24/14.79) × 100 = 21.9. Similarly for the other combustion products, the gravimetric flue gas analysis is 21.9% CO$_2$, 6.4% H$_2$O, 0.1% SO$_2$, 71.6% N$_2$.

To predict the volumetric %CO$_2$ in the dry flue gases, formulas 3/24, 3/25, and 3/26 may be used as follows: (88.50 × 1.508) + (10.50 × 3.553) + (0.80 × 0.5650) + (0.10 × 0.1353) − (0.06 × 0.4477) = 171.2 ft³ dry flue gases/lb fuel; (88.50 × 0.3155) = 27.92 ft³ CO$_2$/lb fuel; so 100 × (27.92/171.2) = 16.3% CO$_2$ in dry flue gases. This is the so-called "ultimate %CO$_2$," which is discussed in the following section.

FLUE GAS ANALYSES

Flue gas analyses are used to indicate the air/fuel ratio and to indicate the degree of completeness of combustion. If the mixing is poor, an excess of air must be supplied so that every particle of fuel will contact some air and burn. Figure 3.4 shows the effects of poor mixing or quenching. If the flame or hot intermediate combustion gases contact a cold surface or meet a blast of cold air, gas, or water, they may be suddenly chilled to a temperature level at which the combustion reaction cannot promptly go to completion. This quenching action may result in incomplete combustion with gases such as O$_2$, CO, H$_2$, and aldehydes in the flue products, as with cases of poor mixing.

Significance of %CO$_2$, O$_2$, and combustibles. With good mixing, perfect combustion is obtained when the flue gas analysis shows no CO, H$_2$, or O$_2$ and when the %CO$_2$ is at a maximum. The theoretical maximum %CO$_2$ in the dry flue gases is termed the *ultimate* %CO$_2$. By adjusting the air/fuel ratio until the maximum %CO$_2$ is obtained, and until the minimum %O$_2$ and combustibles are indicated, an operator can set a burner close to the point of best fuel efficiency. This permits approximate setting of the air/fuel ratio on single-burner furnaces without metering the fuel and the air flow. For applications requiring either reducing or oxidizing combustion, the flue gas analysis may be used as a means of duplicating certain desired conditions if all other conditions are exactly the same.

With poor mixing such as results when coal is burned on grates or when gas or oil is burned in a delayed mixing type of burner, the manner in which the flue gas analysis varies with changes in the air/fuel ratio is a function of the physical arrangement of the burner and combustion chamber. The poor-mixing curves of Figure 3.4 represent only one of many possibilities for this case. These curves demonstrate, however, that the flue gas analysis may be used as an indication of the air/fuel ratio or of the relative completeness of combustion. Table 3.5 shows the %CO₂ readings that should be obtained with perfect mixing of various amounts of air with some of the specific fuels described in Tables 2.1 and 2.12 of Part 2

Figure 3.4. Effect of air/fuel ratio on flue gas analysis for 1100 Btu/ft³ natural gas (0.63 gas gravity) containing 83% CH₄ and 16% C₂H₆. Values for rich mixtures depend somewhat on combustion chamber design. The average values shown are within ½% of correct for H₂, CO, and CO₂ but may be as much as 2% low for other constituents. Some external heat is usually required for mixtures with less than 70% aeration (dotted lines). Dashed lines show the trends with poor mixing or quenching. Gas constituent percentages are on a dry basis to allow comparison with gas analyzer readings, that measure the gas volumes after water vapor has condensed out of the sample. With the correct amount of air (10.58 ft³), each cubic foot of the fuel gas produces 2.14 ft³ H₂O, 1.15 ft³ CO₂, 8.38 ft³ N₂ so %CO₂ = 100 × 1.15 ft³ CO₂ ÷ (1.15 + 8.38) ft³ dry flue gas = 12.1%. See also Figure 3.1.

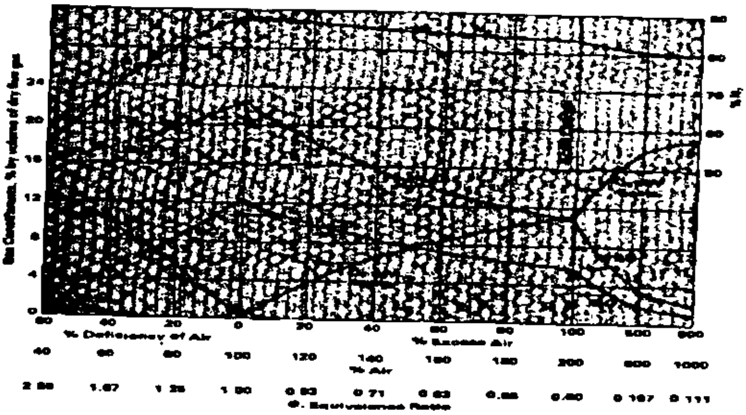

Table 3.5a. Effect of excess air on %O₂ and %CO₂ in combustion products of fuels from Tables 2.1a and b

%O₂ wet %O₂ dry %CO₂ dry a/f ratio*	%Excess air 0	10	20	40	60	80	100	200	400	1000
φ, Equivalence ratio	1.00	0.91	0.83	0.71	0.62	0.56	0.50	0.33	0.20	0.09
Natural gas (Birmingham)	0	1.73	3.20	5.55	7.35	8.77	9.92	13.5	16.4	18.8
	0	2.00	3.80	6.43	8.36	9.83	11.0	14.4	17.1	19.2
	11.7‡	10.6	9.81	8.14	7.05	6.22	5.57	3.65	2.16	0.97
	9.44	10.4	11.3	13.2	15.1	17.0	18.9	28.3	47.2	104
Blast furnace gas	0	0.89	1.70	3.15	4.30	5.47	6.42	9.82	13.4	17.1
	0	0.89	1.71	3.17	4.41	5.50	6.45	9.86	13.4	17.1
	25.5‡	24.4	23.4	21.7	20.1	18.8	17.6	13.5	9.17	4.88
	0.68	0.75	0.82	0.95	1.09	1.23	1.36	2.04	3.41	7.49
Producer gas (W-G, bituminous)	0	1.23	2.37	4.18	5.70	6.97	8.04	11.6	14.9	18.0
	0	1.35	2.54	4.54	6.14	7.46	8.56	12.1	15.4	18.3
	18.5‡	17.3	16.2	14.5	13.1	11.9	10.9	7.75	4.90	2.33
	1.30	1.43	1.56	1.82	2.08	2.34	2.60	3.90	6.50	14.3
Coke oven gas (by-product)	0	1.69	3.12	5.43	7.21	8.63	9.78	13.3	16.3	18.8
	0	2.10	3.82	6.46	8.39	9.87	11.0	14.4	17.1	19.2
	10.8‡	9.71	8.82	7.46	6.46	5.70	5.10	3.34	1.98	0.89
	5.44	5.98	6.53	7.62	8.70	9.79	10.9	16.3	27.2	59.8
Propane (natural)	0	1.77	3.26	5.64	7.46	8.89	10.0	13.6	16.5	18.9
	0	2.06	3.75	6.36	8.28	9.73	10.9	14.3	17.0	19.2
	13.7‡	12.3	11.2	9.53	8.27	7.31	6.55	4.30	2.55	1.15
	23.8	26.2	28.5	33.3	38.0	42.8	47.6	71.3	119	262
Butane (natural)	0	1.77	3.27	5.65	7.47	8.90	10.1	13.6	16.5	18.9
	0	2.05	3.74	6.34	8.26	9.73	10.9	14.3	17.0	19.2
	14.0‡	12.6	11.5	9.75	8.46	7.48	6.70	4.41	2.61	1.18
	30.9	33.7	36.8	42.9	49.0	55.2	61.3	91.9	153	337

* ft³ air/ft³ fuel, m³ air/m³ fuel, or any ratio of volumes in consistent units.

‡ Ultimate %CO₂

Table 3.5b. Effect of excess air on %O₂ and %CO₂ in combustion products of fuels from Tables 2.1a and b

Fuels		%Excess air 0	10	20	40	60	80	100	200	400	1000
	φ, Equivalence ratio	1.00	0.91	0.83	0.71	0.62	0.56	0.50	0.33	0.20	0.09
#1 Distillate oil	%O₂ wet	0	1.79	3.31	5.71	7.64	8.97	10.1	13.8	16.5	18.9
	%O₂ dry	0	2.02	3.69	6.27	8.18	9.65	10.8	14.3	17.0	19.1
	%CO₂ dry	15.4‡	13.9	12.6	10.8	9.35	8.27	7.42	4.89	2.91	1.31
	a/f ratio†	190	209	228	267	305	343	381	571	952	2090
#2 Distillate oil	%O₂ wet	0	1.80	3.31	5.72	7.55	8.99	10.1	13.7	16.5	18.9
	%O₂ dry	0	2.02	3.68	6.26	8.16	9.83	10.8	14.2	16.9	19.1
	%CO₂ dry	15.6‡	14.1	12.9	11.0	9.53	8.44	7.57	4.99	2.97	1.34
	a/f ratio†	188	207	225	263	301	338	376	564	939	2070
#5 Residual oil	%O₂ wet	0	1.81	3.33	5.75	7.58	9.02	10.2	13.7	16.6	18.9
	%O₂ dry	0	2.00	3.65	6.22	8.13	9.59	10.8	14.2	16.9	19.1
	%CO₂ dry	16.3‡	14.7	13.4	11.4	9.05	8.81	7.90	5.22	3.11	1.40
	a/f ratio†	182	200	219	255	291	328	364	546	911	2000
#6 Residual oil	%O₂ wet	0	1.82	3.35	5.77	7.61	9.04	10.2	13.7	16.6	18.9
	%O₂ dry	0	1.99	3.64	6.20	8.10	9.56	10.7	14.2	16.9	19.1
	%CO₂ dry	16.7‡	15.1	13.8	11.8	10.2	9.07	8.14	5.38	3.21	1.45
	a/f ratio†	175	193	210	246	281	316	351	526	877	1930
Bituminous coal	%O₂ wet	0	1.83	3.37	5.80	7.64	9.08	10.2	13.8	16.6	18.9
	%O₂ dry	0	1.95	3.57	6.10	7.99	9.45	10.6	14.1	16.8	19.1
	%CO₂ dry	18.5‡	16.8	15.3	13.1	11.4	10.1	9.10	6.04	3.61	1.64
	a/f ratio†	141	155	169	197	225	254	282	423	704	1550
Coke	%O₂ wet	0	1.89	3.46	5.94	7.80	9.25	10.4	13.9	16.7	19.0
	%O₂ dry	0	1.91	3.50	5.99	7.86	9.32	10.5	14.0	16.7	19.0
	%CO₂ dry	20.4‡	18.6	17.0	14.6	12.6	11.3	10.2	6.80	4.08	1.85
	a/f ratio†	132	145	158	184	211	237	263	395	658	1450

† ft³ air/lb fuel.
‡ Ultimate %CO₂.

Instruments. Many types of instruments are available for analyzing flue gases. Most indicate the percent by volume of the various compounds in the dry flue gas. One of the most common instruments is the Orsat apparatus, which works on the principle of selective *absorption* of the gases by chemical solutions. The Orsat apparatus indicates percentages of CO₂, O₂, and CO. The percent CO₂ is often the only analysis made. *Conductivity type analyzers*, which sense the difference in the cooling effect of different gases, can be very accurate if calibrated properly and frequently. Analysis of *combustibles* in the flue gases (CO, H₂, and hydrocarbons) may be accomplished by burning the combustibles with a measured volume of air or oxygen, usually in the presence of a catalyst. The percentage of combustibles in the flue gas is then proportional to the measured heat released.

Oxygen analysis can be determined continuously and without time delay by use of a solid electrolyte, zirconium oxide. The galvanic action yields an output signal in the form of a variable electromotive force that can be used for automatic air/fuel ratio control. Note in Table 3.5 that %O₂ changes very little with changes in fuel analysis.

COMBUSTION EFFICIENCY

For any furnace, oven, kiln, or boiler, the overall combustion efficiency, or fuel *efficiency, is 100% minus the summation of all losses*. As illustrated by the Sankey diagram of Figure 3.6.

$$\text{[3/30]} \quad \text{efficiency, \%} = \left(\frac{\text{useful output}}{\text{gross input}}\right) \times 100, \text{ or } \left(\frac{\text{gross input} - \text{total losses}}{\text{gross input}}\right) \times 100$$

where the input, the output, and the losses are all measured in consistent units such as Btu/hr, kcal/s, joules/kg of fuel, or gallons of fuel per ton of product.

The losses to conveyors, fixtures, walls, and openings can be calculated using specific heat data from the Appendix and heat transfer data from Part 4. The *flue gas losses (stack loss)* are described and evaluated in this section. They include the heat carried away by the dry flue gases (such as CO₂, N₂, O₂, and CO) and the heat carried away by the moisture (H_2O) in the flue gases. This moisture loss is the latent and sensible heat in water formed by combustion of hydrogen in the fuel.

Dry flue gas loss (dfg loss) is equal to the amount of heat given up by the dry combustion products as they cool from the final exit temperature (after all heat recovery devices) to the base temperature used in evaluating the gross calorific value of the fuel (usually 60 F or 15.6 C). This loss can be calculated by the following formulas.

[3/31] dfg loss = dfg flow rate × (dfg heat content at flue temperature − dfg heat content at base temperature)

or, in American weight units,	Btu/hr = lb dfg/hr × (Btu/lb from Table 3.7a − 0)
or, in American volume units,	Btu/hr = cfh dfg × (Btu/scf from Table 3.7b − 0)
or, in Metric weight units,	kcal/hr = kg dfg/hr × (kcal/kg from Table 3.7c − 0)
or, in Metric volume units,	kcal/hr = m^3 dfg/hr × (kcal/m^3 from Table 3.7d − 0)

For flue gases consisting of mixtures of gases, the losses due to each of the flue gas constituents should be added:

[3/32] dfg loss = CO_2 flow rate × CO_2 heat content + N_2 flow rate × N_2 heat content + O_2 flow rate × O_2 heat content + etc.

Tables 3.7a, b, c, d list heat contents (enthalpies) measured above a base of 60 F or 15.6 C.

Figure 3.6. Sankey diagram for a furnace heat balance. Gross input − moist flue gas loss = net input; net input − dry flue gas loss = available heat input. These terms can be evaluated in any consistent heat or energy units per unit of time per unit of fuel, or per unit of production output. A diagram such as this makes it easier to visualize areas of possible improvement in furnace efficiency.

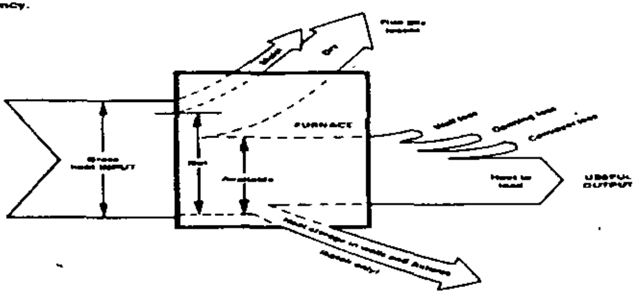

Table 3.7a. Heat contents of combustion gases,* in Btu/lb

Gas temperature, F	Air †	CO	CO_2	H_2	H_2O ‡	N_2	O_2	SO_2
60	0	0	0	0	0	0	0	0
100	9.7	9.9	8.1	139.1	17.7	9.9	8.7	6.0
200	34.0	34.7	29.6	486.9	62.4	34.8	30.6	21.8
300	58.4	59.9	52.0	834.9	108.0	59.7	53.5	37.7
400	75.7	86.3	76.2	1 183.0	184.4	85.0	76.5	54.4
500	108	111.1	99.4	1 533.0	201.7	110.6	99.8	71.7
600	136	137.1	124.3	1 883.2	248.7	136.4	123.8	89.6
800	170	190.2	176.5	2 586.9	346.4	188.6	174.1	120.5
1000	233	244.3	231.4	3 298.9	450.4	242.3	231.0	165.2
1200	288	299.6	288.7	4 011.3	555.8	296.8	272.0	208.3
1400	343	356.0	347.6	4 734.1	664.5	352.3	324.9	246.2
1600	397	413.3	408.6	5 465.8	775.6	408.8	376.6	288.0
1800	451	471.6	470.5	6 207.5	892.3	466.3	428.6	330.3
2000	510	530.6	533.2	6 960.3	1011.1	524.7	481.4	373.7
2200	566	590.6	596.1	7 725.3	1133.4	584.1	537.2	416.0
2400	626	651.7	659.6	8 503.9	1258.5	644.4	591.7	458.6
2600	685	713.3	722.5	9 287.1	1,385.5	705.7	645.1	498.1
2800	742	770.6	784.3	10 106.1	1521.2	767.9	699.8	538.7
3000	801	838.0	848.2	10 942.2	1657.4	831.0	753.3	577.1
3200	860	903.3	904.6	11 776.4	1797.0	895.0	805.2	614.4
3400	918	966.5	962.1	12 640.0	1940.2	956.6	857.5	649.6
3600	975	1031.3	1017.4	13 524.2	2085.9	1025.6	909.1	683.0
3800	1046	1098.4	1059.8	14 430.0	2237.0	1092.2	960.6	711.6

Table 3.7b. Heat contents of combustion gases,* in Btu/scf ^

Gas temperature, F	Air †	CO	CO_2	H_2	H_2O ‡	N_2	O_2	SO_2
60	0	0	0	0	0	0	0	0
100	0.74	0.73	0.88	0.73	0.84	0.73	0.74	1.02
200	2.60	2.59	3.44	2.57	3.00	2.58	2.61	3.61
300	4.47	4.43	6.04	4.41	5.13	4.41	4.52	6.26
400	6.1	6.30	8.74	6.25	7.27	6.28	6.46	9.15
500	8.1	8.20	11.54	8.09	9.88	8.17	8.43	12.10
600	9.6	10.13	14.44	9.94	11.88	10.08	10.44	15.11
800	13.7	14.06	20.49	13.65	16.56	13.96	14.52	21.36
1000	17.6	18.06	26.87	17.39	21.30	17.90	18.73	27.86
1200	22.0	22.14	33.51	21.17	26.40	21.92	23.01	34.64
1400	26.3	26.30	40.38	24.98	31.60	26.03	27.30	41.58
1600	30.4	30.63	47.44	28.84	36.90	30.20	31.62	48.63
1800	34.6	34.84	54.63	32.76	42.37	34.46	36.30	55.77
2000	39.0	39.21	61.91	36.73	48.02	38.77	40.82	62.94
2200	43.2	43.65	68.71	40.77	53.63	43.10	45.36	70.06
2400	47.6	48.14	75.60	44.86	59.31	47.61	49.91	77.18
2600	52.4	52.70	82.61	49.00	65.64	52.14	54.47	84.11
2800	56.6	57.30	91.06	53.33	72.26	56.73	59.01	90.86
3000	61.3	61.96	98.11	57.60	78.71	61.76	63.52	97.46
3200	65.7	66.66	105.02	62.14	85.46	66.12	67.99	103.75
3400	70.2	71.40	111.70	66.70	92.73	70.91	72.40	109.77
3600	74.6	76.15	118.11	71.37	99.11	75.77	76.76	115.34
3800	80.2	81.00	124.21	76.15	106.84	80.66	81.02	120.63

* Computer-calculated data based on formulas from Reference 3 a listed at end of Part 3, except †. None of the values in Table 3.7 are corrected for dissociation.

† From Reference 3 b

Table 3.7c. Heat contents of combustion gases,* in kcal/kg

Gas temperature, C (kcal/kg)	Air†	CO	CO_2	H_2	H_2O‡	N_2	O_2	SO_2
15.6	0	0	0	0	0	0	0	0
100	20.5	20.9	17.9	292.8	37.8	20.9	18.6	13.0
200	42.1	46.1	40.8	640.3	83.5	46.0	41.4	29.4
300	66.1	71.9	65.0	988.1	130.8	71.8	64.8	46.8
400	92.6	[illegible]	90.7	1336.8	179.8	97.6	88.8	65.1
500	119	125.1	117.7	1692.3	230.1	124.1	113.5	84.1
600	146	152.5	145.6	2047.7	282.0	151.1	138.0	103.8
700	174	180.7	174.8	2406.3	335.4	178.8	164.2	124.1
800	201	208.6	204.5	2766.8	380.3	206.4	190.1	144.7
900	228	237.3	235.3	3134.8	446.8	234.7	216.4	166.7
1000	256	266.5	266.2	3508.6	504.7	263.5	242.9	186.8
1100	285	296.1	297.5	3881.6	564.2	292.7	269.6	207.9
1200	314	326.0	329.0	4262.4	625.3	322.3	296.5	229.0
1300	343	356.8	360.8	4651.0	687.8	352.4	323.4	249.9
1400	373	387.0	391.8	5045.3	752.0	382.6	350.3	270.6
1500	401	418.0	422.9	5446.3	817.8	413.7	377.1	290.7
1600	431	448.3	453.6	5854.8	884.9	446.0	403.8	310.4
1700	460	480.6	483.6	6271.3	953.7	476.7	430.4	328.4
1800	489	511.7	512.6	6698.2	1024.0	508.6	456.6	347.6
1900	518	544.8	541.2	7130.0	1098.9	541.3	482.6	365.0
2000	548	577.3	568.5	7573.1	1168.5	574.1	508.2	381.3
2100	565	608.7	594.5	8028.0	1344.5	607.4	533.4	396.5

Table 3.7d. Heat contents of combustion gases,* in kcal/m³**

Gas temperature, C (kcal/m³)	Air†	CO	CO_2	H_2	H_2O‡	N_2	O_2	SO_2
15.6	0	0	0	0	0	0	0	0
100	25.0	24.7	33.2	24.7	28.6	24.6	25.2	35.1
200	53.9	54.6	75.6	54.1	63.5	54.3	55.9	78.4
300	83.2	85.0	120.7	81.5	98.6	84.6	87.6	124.6
400	113	116.2	166.6	113.1	136.6	115.4	120.1	175.9
500	145	147.8	215.8	142.8	174.8	146.8	153.3	227.4
600	178	180.3	271.0	172.9	214.4	178.7	187.3	280.6
700	212	213.5	326.0	203.2	255.0	211.1	221.9	335.3
800	246	246.7	380.5	233.6	296.7	244.1	256.9	391.1
900	280	280.6	437.1	264.8	339.6	277.6	292.4	447.7
1000	313	316.3	494.7	296.1	383.7	311.6	328.3	504.7
1100	348	350.1	552.9	327.8	428.9	346.1	364.4	561.9
1200	383	386.5	611.4	360.1	475.5	381.1	400.6	619.0
1300	419	421.3	669.9	392.8	523.6	416.6	437.0	676.5
1400	456	457.8	728.2	426.1	571.6	452.7	473.3	731.2
1500	490	494.2	786.3	460.0	621.5	488.2	509.6	785.8
1600	526	531.2	842.8	494.5	672.8	526.2	546.7	836.5
1700	562	568.6	898.5	530.7	724.9	563.6	581.6	886.3
1800	597	606.3	953.6	566.5	778.4	601.6	617.1	936.5
1900	633	644.2	1008.6	603.2	833.1	640.0	652.2	986.4
2000	668	682.4	1058.3	639.8	886.9	678.9	686.8	1030.5
2100	714	720.9	1104.7	677.9	946.0	718.2	720.8	1071.8

‡ Water vapor. Does not include latent heat of vaporization. See Tables A.5a and A.5b.

** The standard cubic foot (scf) and the cubic metre (m³) are measured at a temperature of 60 F (15.6 C) and at an atmospheric pressure of 29.92"Hg (760 mm Hg).

Moisture loss is equal to the amount of heat that is given up by the water vapor in the flue gases as it cools from the furnace exit temperature to the base temperature used in evaluating the calorific value of the fuel. Most of the moisture loss is the latent heat of condensation of the water vapor formed by combustion of hydrogen in the fuel. As illustrated in Figure 3.6, the *gross heating value minus the moisture loss per unit of fuel is equal to the net heating value per unit of fuel.*

[3/33] moisture loss = lb H_2O/hr* × (vapor enthalpy at flue temperature − liquid enthalpy at base temperature)

where the liquid enthalpy is (base temperature (F) − 32), and the vapor enthalpy can be obtained from Table A.5 in the Appendix. As an alternate, the following approximate formula may be used:

[3/34] moisture loss, in Btu/hr = lb H_2O/hr* × [1066 + 0.46 × (t_e − 60)]

where t_e is the furnace exit temperature (F) and 60 is the base temperature (F) used to evaluate the gross heating value of the fuel.

Available heat is the gross quantity of heat released within a combustion chamber, minus both the dry flue gas loss and the moisture loss. It represents the amount of heat remaining for useful heating, plus wall, conveyor, (storage) and opening losses. Figure 3.8 shows how the concept of available heat is used to simplify analyses of furnace losses. Figure 3.9 shows the variation in available heat with exit gas temperature for several typical fuels under conditions of perfect combustion. Figure 3.10 is a generalization for all fuels giving percent available heat with various flue temperatures and various amounts of excess air.† The percent additional loss due to a *deficiency of air* (excess fuel) will be approximately equal to the percent deficiency of air or $\frac{\%\text{ excess fuel}}{100 + \%\text{ excess fuel}}$.

Either excess air or excess fuel reduces the % available heat. The *perfect* combustion or 0% excess air line on Figure 3.10 represents the best possible efficiency, as for a perfect furnace with no losses through walls, openings, fixtures, conveyors, or storage.

Example 3-6. *Determine the efficiency of a boiler using 70 gal/hr of #2 fuel oil (137 080 Btu/gal, 7.22 lb/gal) if the temperature of the flue gases after the last pass is 500 F. The radiation and convection losses from the walls have been estimated as 3% of the gross input. (Calculation of wall losses is explained in Part 4, page 100.)*

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* If moisture in the flue gas has been expressed in scf H_2O, as from formula 3/18, such figures can be converted to lb H_2O by multiplying by 0.0475

† See footnote (†) on page 71

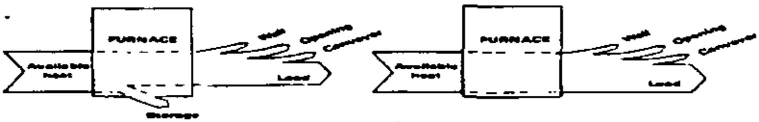
Simplified solution. From Figure 3.9, curve B, at 600 F, the available heat is 114 000 Btu/gal or (70 × 114 000) = 7 980 000 Btu/hr. The % available heat = 114 000/137 080 = 83%. The sum of the dry gas loss and the moisture loss is then 100 − 83 = 17%. There should be no loss due to incomplete combustion or due to radiation through furnace openings in this case. The total loss is therefore the sum of the dry flue gas loss, the moisture loss, and the wall loss or 17 + 3 = 20%. The percent of the gross input which goes into evaporating water in the boiler is then 100 − 20 = 80%, and this is the efficiency of the unit. If excess air is used, Figure 3.10 can be used to estimate the additional loss. From Figure 3.13 a 20% deficiency of air will result in about 60% available heat. This minus 3% wall loss will result in 57% efficiency.

Detailed solution. A more accurate calculation of the efficiency may be had by use of formula 3/32 to calculate the dry flue gas loss and formula 3/33 to calculate the moisture loss. To use these formulas, it is first necessary to determine the fuel analysis (from the supplier, Table 2.1, or Table 2.12) and then calculate constituents of the flue gas by formulas 3/25, 3/27, 3/28a, and 3/29a of Table 3.3 (or formulas 3/13, 3/15, and 3/16 of Table 3.2 for gaseous fuels)..using data from Table 2.1 in this case..

ft^3 CO_2/lb fuel = 87.3 × 0.3155 = 27.54
ft^3 H_2O/lb fuel = 12.5 × 1.880 = 23.50
ft^3 SO_2/lb fuel = 0.21 × 0.1182 = 0.02
ft^3 N_2/lb fuel = 87.3 × 1.193 + 12.5 × 3.553 + 0.21 × 0.4466 = 148.7

Substituting in formula 3/32 and taking heat content values from Table 3.7b at 600 F, dfg loss = 27.54 × 11.54 + 148.7 × 8.17 + 0.02 × 12.10 = 1533 Btu/lb of fuel or 1533 × 7.22 lb/gal × 70 gal/hr = 774 700 Btu/hr, which is equivalent to 1533 × 7.22/137 080 = 8.07%. From formula 3/33*, the moisture loss = 23.50 × 0.0476 × [1287.3 − (60 − 32)] = 1408 Btu/lb of fuel or 711 600 Btu/hr, which is equivalent to 1408 × 7.22/137 080 = 7.42%. Therefore the percent available is 100 − 8.07 − 7.42 = 84.5%. (This compares with 83% by Figure 3.9.) The efficiency of the boiler is then 84.5 − 3 = 81.5%.

Figure 3.8. By starting with available heat instead of gross heat, furnace heat balances are greatly simplified. The Sankey diagram at left is for a batch-type furnace; the one at right, for a continuous furnace.



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* Moisture loss must include latent heat, so Table 3.7 cannot be used.

Figure 3.9. Available heats for some typical fuels. The fuels listed below are identified by their gross heating values. Further information concerning these fuels may be found in Tables 2.1 and 2.12. (See Example 3-6.) All available heat figures are based upon perfect combustion and a fuel input temperature of 60 F.

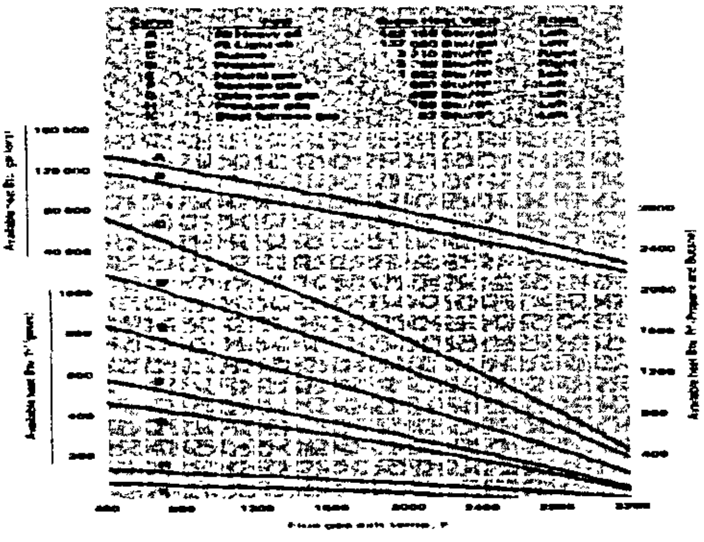
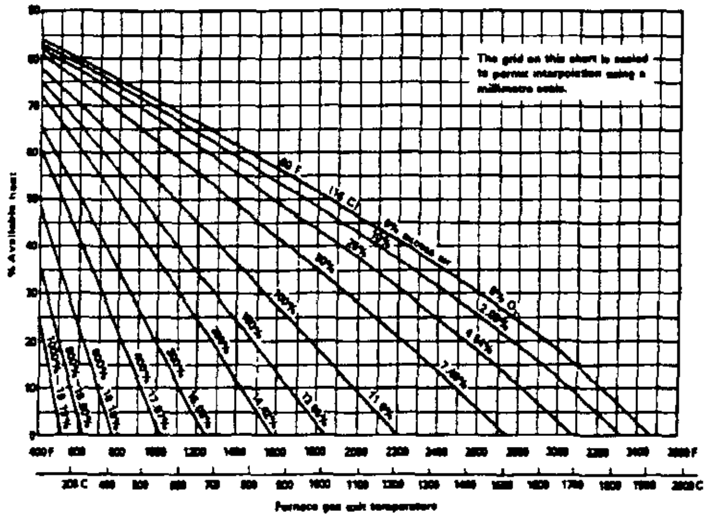


Figure 3.10. Available heat chart for 1000 Btu/ft³ natural gas*, showing the effect of excess air upon available heat. Based on 60 F (16 C) air. Applicable only if there is no unburned fuel in the products of combustion. Corrected for dissociation of CO_2 and H_2O. See also Figures 3.11, 12, 15, 17. See Examples 3-6, 7, 8. See footnote (1) on page 71. The x-intercept is the adiabatic flame temperature (hot max temperature) for that particular curve. Example: With 25% excess air with natural gas (4.54% O_2 in the furnace exit gas), the adiabatic flame temperature is 3070 F or 1688 C.



The grid on this chart is scaled to permit interpolation using a millimetre scale.

*For other fuels, see Figure 3.8.

Example 3-7. *Find the air required to maintain 25% excess air through 16 burners on a hardening furnace with 1000 C (1800 F) exit gas temperature if the available heat required is 0.81 million kcal/hr (3.2 million Btu/hr). The fuel is Algeria LNG (Table 2.12b) having 10 132 gross kcal/m³ (1139 gross Btu/ft³) and requiring 10.76 volumes of air per volume of fuel.*

From Figure 3.10, at 1000 C and 25% excess air, read 43% available. Therefore the gross input required is 810 000/0.43 = 1 880 000 kcal/hr. Select 16 burners each with at least 1 880 000/16 = 117 700 kcal/hr capacity each.

The fuel gas input required will be 1 880 000/10 132 = 185.6 m³/hr. The air required for stoichiometric combustion would be 185.6 × 10.76 = 1997 m³/hr; but for the requested 25% excess air, the required burner air capacity will be 1.25 × 1997 = 2496 m³/hr.

Operating experience with high velocity recirculating burners will probably show that the 25% excess air is not required, so fuel can be conserved by adjusting the fuel/air ratio closer to the stoichiometric ratio.

Example 3-8. *Select burners and a blower for a dual-purpose furnace with the following specifications:*

	Hardening	Drawing
Available Btu/hr required	4 200 000	92 000
Flue gas exit temp., F	1 800	1 000

Solution: For the hardening operation, Figure 3.10 gives 48% available heat with perfect combustion.

$$\text{Therefore } \frac{4\,200\,000}{0.48} = 8\,750\,000 \text{ gross Btu/hr}$$

Burners selected: fourteen 6422-4 Burners, each rated 6300 cfh air (or 630 000 Btu/hr) with 16 osi air pressure at the burners for a total gross input of 8 820 000 Btu/hr.

$$\text{Blower capacity required} = \frac{8\,820\,000 \text{ gross Btu/hr}}{100 \text{ gross Btu/ft}^3 \text{ air}} = 88\,200 \text{ cfh}$$

Blower selected: 2324-35/2-15 Turbo Blower (rated 96 000 cfh at 24 osi).

Example 3-9: *How much excess air for low fire?* For holding during the low temperature operation on the above furnace, the fuel flow will be reduced and the air left on at high fire rate, thus providing excess air. How much excess air should be used at low fire?

$$\text{Solution: First find the ratio, } \frac{\text{available Btu required at low fire}}{\text{cfh air supplied with air on full}} = \frac{92\,000}{88\,200} = 1.04.$$

Then, from Figure 3.11 (follow the dotted arrow) read 380% excess air and 4.8 to 1 required valve turndown. If no excess air were used, the required valve turndown would have been the same as the gross Btu turndown, or 8 240 000 ÷ (92 000/0.71) = 63.6 to 1. (0.71 is from 71% available at 1000 F, read from Figure 3.10.)

The 6422-4 Burner selected above is stable with more than the required 380% excess air, so it will still operate satisfactorily. However, a look at Figure 3.10 shows that the % available heat at 1000 F and 380% excess air is only about 6%; so the drawing operation will have a poor fuel efficiency.

Example 3-10. *How much uniformity can be expected from the combination selected in Example 3-9?*

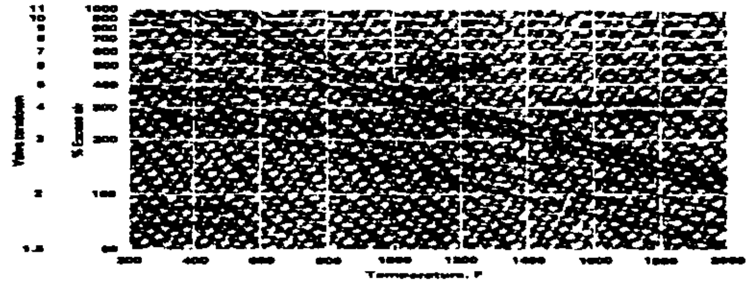
Solution. By interpolation from Figure 3.11, it is found that for 1.04 Btu available/ft³ of air supplied, the hot mixture issuing from the flame tip is only about 50° above the flue gas exit temperature. This can also be surmised from Figure 3.12 or from the x-intercept of Figure 3.10.

This is the maximum temperature differential within the furnace gases. The maximum temperature differential within the work would be a fraction of this. Just how small a fraction depends on placement of the work and is not a function of burner operation.

Example 3-11. A forge furnace is fired with heavy oil (13° API, 152 000 Btu/gallon) and operates at 2200 F. The flue gas exit temperature is approximately 2400 F. The radiation loss through openings has been estimated at 1 152 000 Btu/hr and the wall loss at 162 000 Btu/hr. The firing rate is 50 gallons per hour. What efficiency can be expected from this furnace, and how much steel can it heat per hour?

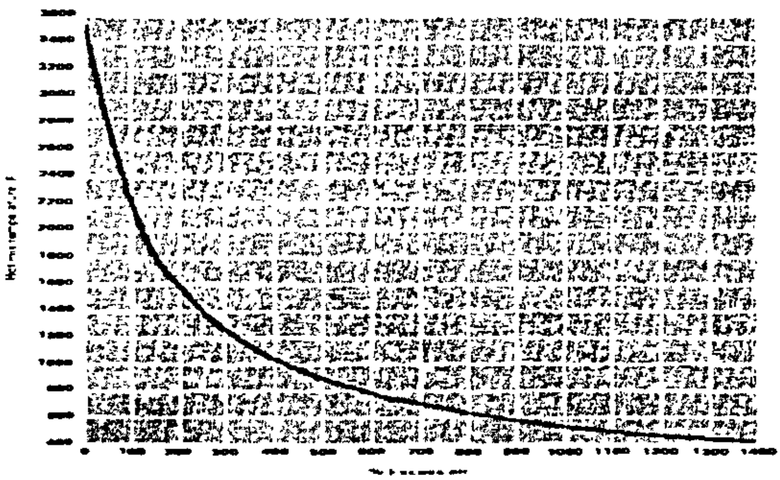
Simplified solution. The gross input rate is (50 gal/hr) × (152 000 Btu/gal) = 7 600 000 Btu/hr. From Figure 3.9 the available heat of a 152 000 Btu/gal oil is 65 000 Btu/gal. Subtracting the losses through openings and walls from the available heat, the heat left for heating the steel is (65 000 Btu/gal) × (50 gal/hr) − 1 152 000 Btu/hr − 162 000 Btu/hr = 1 936 000 Btu/hr. The efficiency is therefore $\frac{1\,936\,000}{7\,600\,000}$ = 25.5%.

Figure 3.11. Excess air required for various temperature differentials.



From Figure A.7 in the Appendix, the heat content of steel at 2200 F is 440 Btu/lb. Therefore the furnace can heat 1 936 000 ÷ 440 = 4400 pounds of steel per hour.

Figure 3.12. Effect of excess air on hot mix temperature. [illegible]



Detailed solution. The gross input rate is (50 gal/hr) × (152 000 Btu/gal) = 7 600 000 Btu/hr. From formulas 2/5 and 2/6, 13°API is found to be equivalent to a specific gravity of 0.98 and a specific weight of 8.17 lb/gal. By formula 2/10, the %hydrogen is found to be $25 - \frac{2122.5}{13 + 131.5} = 10.3$. Assuming that about 98% of the fuel is combustible material (the remainder being water, sediment, oxygen, and nitrogen), the hydrogen will constitute 10.3 × 0.98 = 10.1% of the fuel. This leaves 98 − 10.1 = 87.9% carbon.

Determining the flue gas constituents from formulas 3/19, 3/20, and 3/22a,

lb CO_2/lb fuel = 87.9 × 0.0366 = 3.22; so lb CO_2/hr = 3.22 lb CO_2/lb fuel × 8.17 lb fuel/gal × 50 gal/hr = 1315.

lb H_2O/lb fuel = 10.1 × 0.0894 = 0.903; so lb H_2O/hr = 0.903 × 8.17 × 50 = 369

lb N_2/lb fuel = 87.9 × 0.0882 + 10.1 × 0.2626 = 10.41; so lb N_2/hr = 10.41 × 8.17 × 50 = 4252.

Using formula 3/32 and Table 3.7a, dfg loss = 1315 × 659.5 + 4252 × 644.4 = 3 607 000 Btu/hr. From formula 3/34, moisture loss = 369 × [1066 + 0.46 × (2400 − 60)] = 799 000 Btu/hr. The total loss is the sum of the dry flue gas loss, the moisture loss, the opening loss, and the wall loss, or 3 607 000 + 799 000 + 1 152 000 + 162 000 = 5 720 000 Btu/hr, which is 5 720 000/7 600 000 = 75% of the gross input. The efficiency is therefore 100 − 75 = 25%. The heat left for heating the steel is 7 600 000 − 5 720 000 = 1 880 000 Btu/hr. From Figure A.7 in the Appendix, the heat content of steel at 2200 F is 340 Btu/lb. Therefore the furnace can heat 1 880 000/340 = 5529 pounds of steel per hour

Losses due to *incomplete* combustion include the loss due to incomplete burning of carbon monoxide, hydrogen, and hydrocarbons (including aldehydes from poor mixing or quenching, as described in Figure 3.4), and the loss due to unburned solid fuel which becomes trapped in the refuse.

Incomplete combustion may be intentional, as in instances where the process requires a reducing atmosphere. The percent loss due to a deficiency of air is roughly equal to the percent deficiency. Figure 3.13 shows the loss due to incomplete combustion of natural gas, more precisely.

Example 3-12. If perfect combustion of a fuel requires 10 ft³ of air *per ft³ of fuel, but* only 9 ft³ of air is supplied per ft³ of fuel, then the percent deficiency of air is [(10 − 9)/10] × 100 = 10%. This 10% deficiency of air results in a loss due to incomplete combustion of about 10%.

Optimum Air Supply. The optimum air supply for best thermal efficiency in a furnace is that at which the sum of the loss due to incomplete combustion and the loss due to heat in the flue gases is a minimum. In cases where thorough high speed mixing is possible, the optimum air/fuel ratio is the chemically correct air/fuel ratio. This is usually the case when the fuel is gas or oil. When the mixing is poor, it is often necessary to add excess air to increase the completeness of combustion. This excess air then adds to the quantity of the flue gases. Accurate determination of the optimum point

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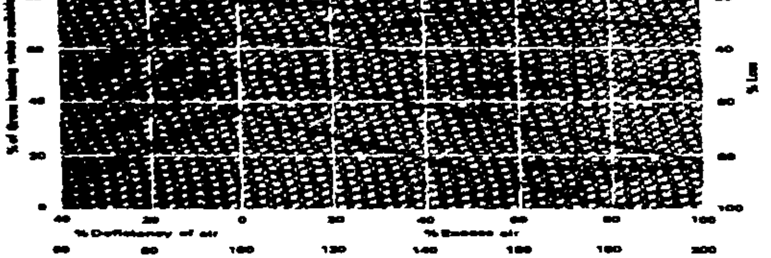
requires a series of furnace tests at a variety of air/fuel ratios, but the point may be approximated by finding the air/fuel ratio that produces the maximum $\%CO_2$.

Figure 3.13 illustrates the manner in which the various losses change with the air/fuel ratio. If the mixing were thorough, the incomplete combustion loss would be zero at the chemically correct air/fuel ratio, and the minimum total loss (maximum % available) would also occur at the chemically correct air/fuel ratio.

Figure 3.13. Variation of furnace losses and available heat with air/fuel ratio. This graph is based on 1100 Btu/ft³ natural gas (0.63 gas gravity, 83% CH_4, 16% C_2H_6). As an example, with 80% aeration (20% deficiency of air) reading down on the right-hand scale, the loss to vaporization of water formed by combustion of hydrogen in the fuel is 7%, leaving 93% net. The incomplete combustion loss is (33 − 7) = 26%. If the flue gas leaves the furnace at 1600 F, the dry flue gas loss is (65 − 33) = 32%, leaving (100 − 65) = 35% available for useful heating and to balance losses through wall, openings, and conveyors.



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ANEXOS

DEL 19 AL 30 DE ABRIL

ING. ALFREDO SÁNCHEZ FLORES
PALACIO DE MINERÍA
ABRIL DE 2004

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2.6 ▪ ECUACIÓN DE ESTADO DE GAS IDEAL

Las tablas de propiedades proporcionan información muy exacta, pero son voluminosas y vulnerables a los errores tipográficos. Un enfoque más práctico y deseable es tener algunas relaciones simples entre las propiedades, que sean suficientemente generales y precisas.

Cualquier ecuación que relacione la presión, la temperatura y el volumen específicos de una sustancia se denomina ecuación de estado. Las relaciones de propiedades que comprenden otras propiedades de una sustancia en estados de equilibrio, también se conocen como **ecuaciones de estado**. Hay varias ecuaciones de estado, algunas sencillas y otras muy complejas. La ecuación de estado más sencilla y conocida para sustancias en la fase gaseosa es la ecuación de estado de gas ideal. Esta ecuación predice el comportamiento P-v-T de un gas con bastante exactitud, dentro de cierta región elegida adecuadamente.

Las palabras *gas* y *vapor* a menudo se utilizan como sinónimos. La fase de vapor de una sustancia suele considerarse como un *gas* cuando su temperatura es más alta que la temperatura crítica. El *vapor* implica un gas que no se encuentra muy alejado del estado de condensación.

En 1662 el inglés Robert Boyle observó durante sus experimentos con una cámara de vacío que la presión de los gases es inversamente proporcional a su volumen. En 1802, J. Charles y J. Gay-Lussac, determinaron de modo experimental que a bajas presiones el volumen de un gas es proporcional a su temperatura. Esto es,

$$P = R\left(\frac{T}{v}\right)$$

o

$$Pv = RT \qquad \textbf{(2.9)}$$

donde la constante de proporcionalidad, R, se denomina la **constante de gas**. La ecuación 2.9 es la **ecuación de estado de gas ideal**, o sencillamente la **relación de**

gas ideal; un gas que obedece esta relación recibe el nombre de **gas ideal**. En esta ecuación, P es la presión absoluta, T es la temperatura absoluta y v es el volumen específico.

La constante de gas R es diferente para cada gas (figura 2.45) y se determina de

$$R = \frac{R_u}{M} \qquad (\text{kJ/kg} \cdot \text{K o kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}) \tag{2.10}$$

donde R_u es la **constante universal de gas** y M es la masa molar (llamada también *peso molecular*) del gas. La constante R_u es la misma para todas las sustancias y su valor es

$$R_u = \begin{cases} 8.314 \text{ kJ/kmol} \cdot \text{K} \\ 8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 0.08314 \text{ bar} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 1.986 \text{ Btu/lbmol} \cdot \text{R} \\ 10.73 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R} \\ 1\,545 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R} \end{cases} \tag{2.11}$$

La **masa molar** M se define como *la masa de un mol* (llamada también un *gramo-mol*, abreviado gmol) *de una sustancia en gramos*, o, *la masa de un kmol* (llamada también un *kilogramo-mol*, abreviado kgmol) *en kilogramos*. En unidades inglesas es la masa de 1 lbmol en lbm. Advierta que la masa molar de una sustancia tiene el mismo valor numérico en ambos sistemas de unidades, por la forma en que se define. Cuando se dice que la masa molar del nitrógeno es 28, ello significa que la masa de un kmol de nitrógeno es 28 kg, o que la masa de 1 lbmol de nitrógeno es 28 lbm. Esto es, M = 28 kg/kgmol = 28 lbm/lbmol. La masa de un sistema es igual al producto de su masa molar M y el número de moles N:

$$m = MN \qquad (\text{kg}) \tag{2.12}$$

Los valores de R y de M para varias sustancias se presentan en la tabla A.1.

La ecuación de estado de gas ideal se escribe de varias maneras diferentes:

$$V = mv \longrightarrow PV = mRT \tag{2.13}$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_uT \tag{2.14}$$

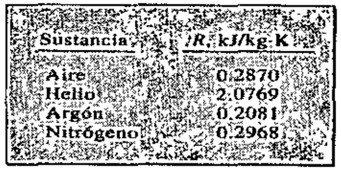
$$V = N\bar{v} \longrightarrow Pv = R_uT \tag{2.15}$$

donde $\bar{v}$ es el volumen específico molar, esto es, el volumen por unidad de mol (en m³/kmol o ft³/lbmol). En este texto un *guión* arriba de una propiedad denotará valores *basados en unidad de mol* (figura 2.46).

Escribiendo la ecuación 2.13 dos veces para una masa fija y simplificando, las propiedades de un gas ideal en dos estados diferentes se relacionan entre sí por medio de

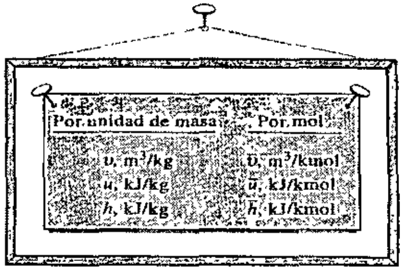
$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \tag{2.16}$$

Un gas ideal es una sustancia *imaginaria* que obedece a la relación $Pv = RT$ (figura 2.47). Se ha observado experimentalmente que la relación de gas ideal se aproxima mucho al comportamiento P-v-T de los gases reales a bajas densidades. A bajas presiones y altas temperaturas la densidad de un gas disminuye y éste se comporta como gas ideal en estas condiciones. Lo que constituye baja presión y alta temperatura se explica en la siguiente sección.



Sustancia	R, kJ/kg·K
Aire	0.2870
Helio	2.0769
Argón	0.2081
Nitrógeno	0.2968

FIGURA 2.45
Diferentes sustancias tienen diferentes constantes de gas.



Por unidad de masa	Por mol
v, m³/kg	$\bar{v}$, m³/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

FIGURA 2.46
Las propiedades por mol se denotan con un guión en la parte superior

FIGURA 2.47
La relación de gas ideal a menudo no es aplicable a los gases reales; por ello, debe tenerse cuidado cuando se use.

En el rango de interés práctico, muchos gases familiares como el aire, nitrógeno, oxígeno, hidrógeno, helio, argón, neón, kriptón e incluso gases más pesados como el dióxido de carbono, pueden tratarse como gases ideales con un error despreciable (con frecuencia menor de 1%). Sin embargo, los gases densos, como el vapor de agua en las centrales eléctricas y el vapor de refrigerante en los refrigeradores, no deben considerarse como gases ideales. Deben utilizarse las tablas de propiedades para estas sustancias.

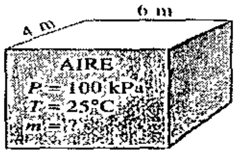


FIGURA 2.48
Dibujo para el ejemplo 2.10.

EJEMPLO 2.10 **Masa del aire contenido en un espacio cerrado**

Determine la masa del aire en una habitación cuyas dimensiones son 4 m × 5 m × 6 m a 100 kPa y 25°C.

SOLUCIÓN Determine la masa de aire contenida en un espacio cerrado.

Análisis En la figura 2.48 se presenta un dibujo del cuarto. El aire en las condiciones especificadas puede tratarse como un gas ideal. En la tabla A-1 la constante de gas del aire es $R = 0.287$ kPa · m³/kg · K, y la temperatura absoluta es $T = 25°C + 273 = 298$ K. El volumen del cuarto es

$$V = (4\text{ m})(5\text{ m})(6\text{ m}) = 120\text{ m}^3$$

La masa del aire en un espacio cerrado se determina a partir de la relación de gas ideal siguiente

$$m = \frac{PV}{RT} = \frac{(100\text{ kPa})(120\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})} = \mathbf{140.3\text{ kg}}$$

¿Es el vapor de agua un gas ideal?

Esta pregunta no se contesta con un simple sí o no. El error involucrado al considerar al vapor de agua como un gas ideal se calcula y grafica en la figura 2.49. Es claro, a partir de esta figura, que a presiones menores de 10 kPa, el vapor de agua se puede considerar un gas ideal, independientemente de su temperatura, con un error despreciable (menor que 0.1%). A presiones superiores, la suposición de gas ideal produce errores inaceptables, en particular en la vecindad del punto crítico y de la línea de vapor saturado (arriba del 100%). Por tanto, en aplicaciones para acondicionamiento de aire, el vapor de agua en el aire puede tratarse como un gas en esencia ideal casi sin error, puesto que la presión del vapor de agua es muy baja. En contraste, en las aplicaciones del vapor en centrales eléctricas, las presiones implicadas son muy altas; de modo que no deben usarse las relaciones de gas ideal.

2.7 • FACTOR DE COMPRESIBILIDAD, UNA MEDIDA DE LA DESVIACIÓN DEL COMPORTAMIENTO DE GAS IDEAL

La ecuación de gas ideal es muy sencilla y por ello su uso es conveniente. Pero, como ilustra la figura 2.49, los gases se desvían del comportamiento de gas ideal, de manera significativa, en estados cercanos a la región de saturación y al punto crítico. Es posible explicar con exactitud esta desviación del comportamiento de gas ideal a una temperatura y presión determinadas mediante la introducción de un factor de corrección llamado **factor de compresibilidad** Z, definido como

$$Z = \frac{Pv}{RT} \tag{2.17}$$

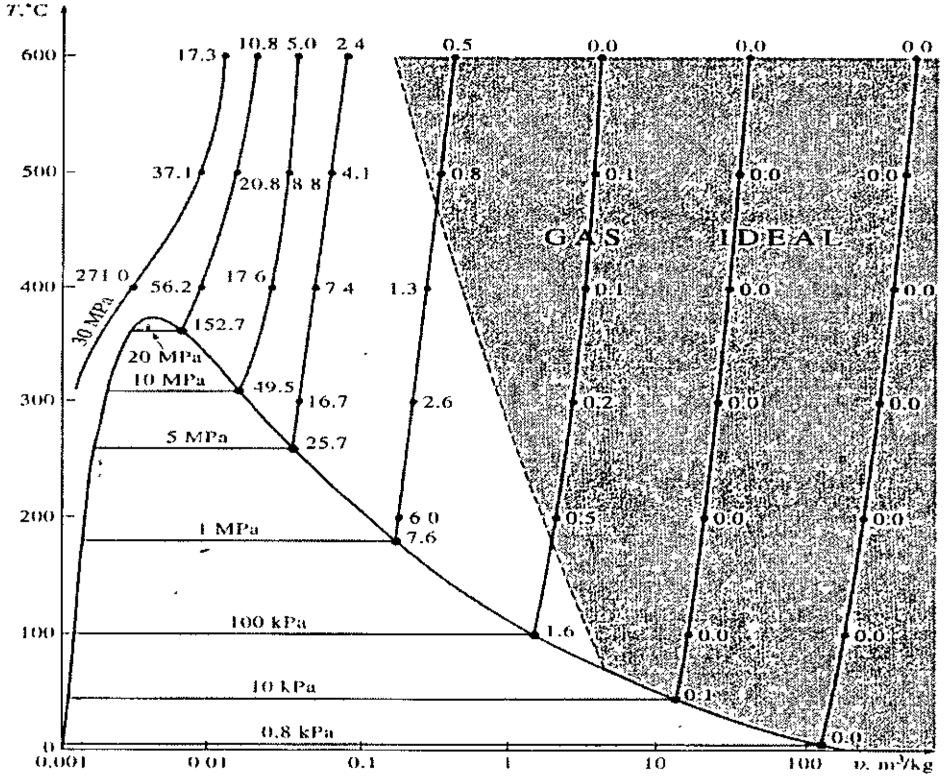


FIGURA 2.49
Porcentaje de error ($[|v_{\text{tabla}} - v_{\text{ideal}}|/v_{\text{tabla}}] \times 100$) implicado al suponer que el vapor es un gas ideal; y región donde el vapor puede tratarse como un gas ideal con un error menor de 1%.

o

$$Pv = ZRT \tag{2.18}$$

También se expresa como

$$Z = \frac{v_{\text{actual}}}{v_{\text{ideal}}} \tag{2.19}$$

donde $v_{\text{ideal}} = RT/P$. Es evidente que $Z = 1$ para gases ideales. Para gases reales Z puede ser mayor o menor que la unidad (figura 2.50). Cuanto más lejos se encuentra Z de la unidad, mayor es la desviación del gas del comportamiento de gas ideal.

Se ha dicho repetidas veces que los gases siguen la ecuación de gas ideal con gran precisión a bajas presiones y altas temperaturas. ¿Pero qué es exactamente lo que constituye baja presión y alta temperatura? ¿Es −100°C una temperatura baja? Es definitivo que lo es para muchas sustancias, pero no para el aire. El aire (o el nitrógeno) puede tratarse como gas ideal a esta temperatura y a la presión atmosférica con un error menor de 1% debido a que el nitrógeno se encuentra bastante arriba de su temperatura crítica (−147°C) y lejos de la región de saturación. A esta temperatura y presión, sin embargo, la mayor parte de las sustancias existirían en la fase sólida. Por consiguiente, la presión o temperatura de una sustancia es alta o baja en relación con su temperatura o presión crítica.

FIGURA 2.50
El factor de compresibilidad es la unidad para los gases ideales.

Los gases se comportan de manera diferente a una temperatura y presión determinadas, pero se comportan de manera muy parecida a temperaturas y presiones normalizadas respecto de sus temperaturas y presiones críticas. La normalización se efectúa como

$$P_R = \frac{P}{P_{cr}} \quad \text{y} \quad T_R = \frac{T}{T_{cr}} \tag{2.20}$$

Aquí P_R recibe el nombre de **presión reducida** y T_R de **temperatura reducida**. El factor Z para todos los gases es aproximadamente el mismo a la misma presión y temperatura reducidas. Lo anterior recibe el nombre de **principio de estados correspondientes**. En la figura 2.51 los valores de Z determinados experimentalmente se grafican para el caso de P_R y T_R para varios gases. Los gases parecen obedecer bastante bien al principio de estados correspondientes. Al ajustar los datos se obtiene la **carta de compresibilidad generalizada**, que puede utilizarse para todos los gases (figura A.30).

A partir de la carta de compresibilidad generalizada son posibles las siguientes observaciones:

1. A presiones muy bajas ($P_R \ll 1$) los gases se comportan como un gas ideal sin considerar la temperatura (figura 2.52),

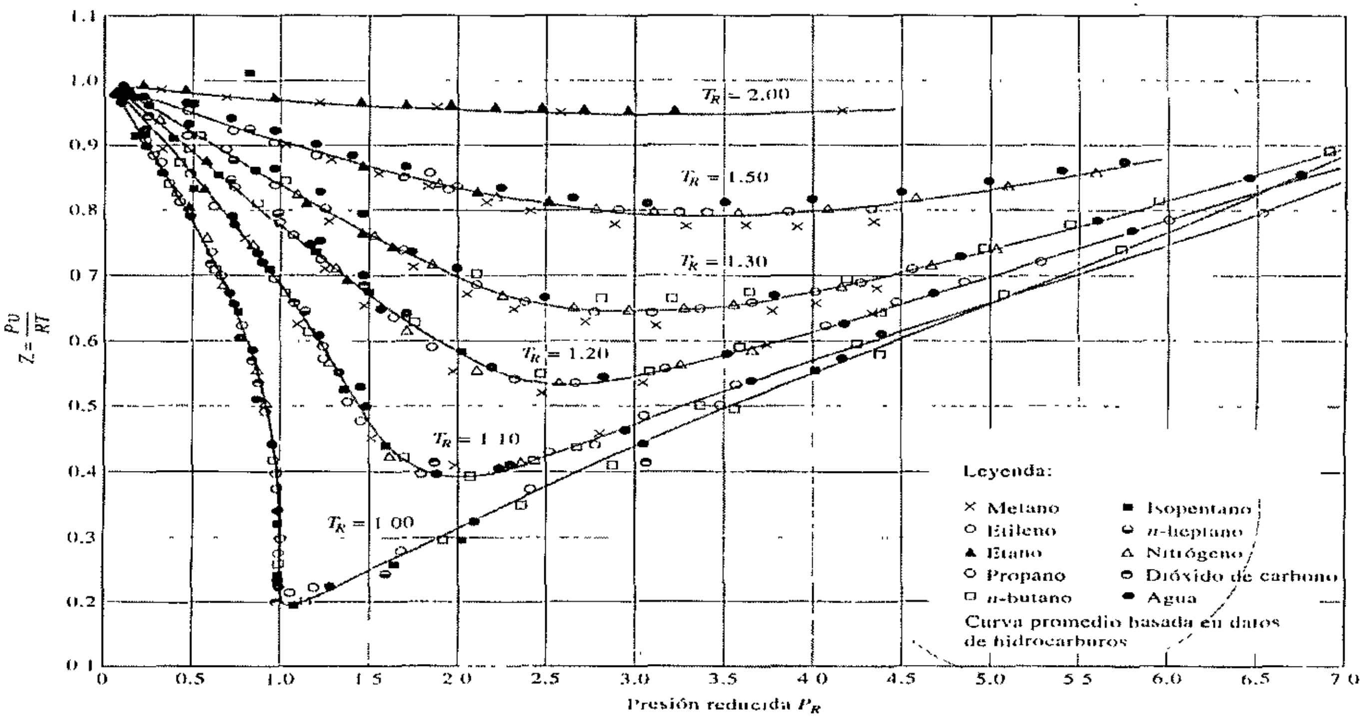


FIGURA 2.51

Comparación de los factores Z para diferentes gases.

(Fuente: Gour-Jen Su, "Modified Law of Corresponding States" en Ind. Eng. Chem. (ed. intern.), 38 (1946), p. 803.)

2. A elevadas temperaturas ($T_R > 2$), el comportamiento de gas ideal puede suponerse con buena precisión sin importar la presión (excepto cuando $P_R \gg 1$).
3. La desviación de un gas del comportamiento de gas ideal es mayor cerca del punto crítico (figura 2.53).

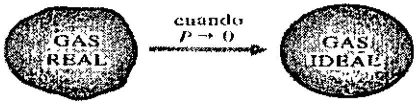


FIGURA 2.52
A presiones muy bajas todos los gases se acercan al comportamiento de gas ideal (sin importar su temperatura).

EJEMPLO 2.11 El uso de cartas generalizadas

Determine el volumen específico del refrigerante 134a a 1 MPa y 50°C, utilizando: *a*) la ecuación de estado de gas ideal y *b*) la carta de compresibilidad generalizada. Comparar los valores obtenidos con el valor real de 0.02171 m³/kg y determinar el error implicado en cada caso.

SOLUCIÓN Se debe determinar el volumen específico del refrigerante 134a suponiendo un comportamiento tanto de gas ideal como de gas no ideal.

Análisis La constante de gas, la presión crítica y la temperatura crítica del refrigerante 134a se determinan a partir de la tabla A.1:

$$R = 0.0815 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$$
$$P_{cr} = 4.067 \text{ MPa}$$
$$T_{cr} = 374.3 \text{ K}$$

a) El volumen específico del refrigerante 134a bajo la suposición de gas ideal es

$$v = \frac{RT}{P} = \frac{(0.0815 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(323 \text{ K})}{1\,000 \text{ kPa}} = \mathbf{0.02632\ m^3/kg}$$

Por lo tanto, considerando el vapor del refrigerante 134a como un gas ideal se obtendría un error de (0.02632 − 0.02171)/0.02171 = **0.212** o 21.2% para este caso.

b) Para determinar el factor de corrección Z a partir de la carta de compresibilidad es necesario calcular la presión y temperatura reducidas:

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} = \frac{1 \text{ MPa}}{4.067 \text{ MPa}} = 0.246 \\ T_R &= \frac{T}{T_{cr}} = \frac{323 \text{ K}}{374.3 \text{ K}} = 0.863 \end{aligned}\right\} \quad Z = 0.84$$

Entonces

$$v = Zv_{\text{ideal}} = (0.84)(0.02632 \text{ m}^3/\text{kg}) = \mathbf{0.02211\ m^3/kg}$$

Discusión El error en este resultado es menor de 2%. Por tanto, ante la ausencia de datos tabulados, la carta de compresibilidad generalizada puede emplearse con confianza.

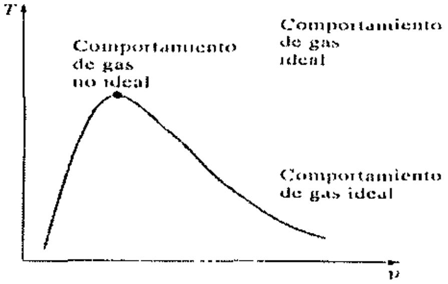


FIGURA 2.53
Los gases se desvían del comportamiento de gas ideal en la cercanía del punto crítico.

Incluso cuando P y v, o T y v, se dan en lugar de P y T, la carta de compresibilidad generalizada puede utilizarse para determinar la tercera propiedad, pero implicaría el tedioso método de ensayo y error. En consecuencia, resulta conveniente definir una propiedad reducida más, llamada el **volumen específico pseudorreducido** v_R como

$$v_R = \frac{v_{\text{actual}}}{\text{[illegible]}} \qquad \textbf{(2.21)}$$

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned}\right\} \begin{aligned} &Z = \ldots \\ &\text{(Fig. A-30)} \end{aligned}$$

FIGURA 2.54
El factor de compresibilidad también puede determinarse a partir del conocimiento de P_R y V_R.

Observe que v_R se define de manera diferente que P_R y T_R. Se relaciona con T_{cr} y P_{cr} en vez de v_{cr}. También se añaden líneas de v_R constante a las cartas de compresibilidad, y esto permite determinar T o P sin tener que recurrir a las tediosas iteraciones (figura 2.54).

EJEMPLO 2.12 Uso de las cartas generalizadas para determinar la presión

Determine la presión de vapor de agua a 600°F y 0.514 ft³/lbm, empleando: *a)* las tablas de vapor, *b)* la ecuación de gas ideal y *c)* la carta de compresibilidad generalizada.

SOLUCIÓN Se determinará la presión del vapor de agua por tres maneras diferentes.

Análisis En la figura 2.55 se presenta un dibujo del sistema. La constante de gas, la presión crítica y la temperatura crítica del vapor se obtienen de la tabla A-1E:

$$\begin{aligned} R &= 0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R} \\ P_{cr} &= 3\,204 \text{ psia} \\ T_{cr} &= 1\,165.3 \text{ R} \end{aligned}$$

H_2O
$T = 600°F$
$v = 0.514$ ft³/lbm
$P = ?$

FIGURA 2.55
Dibujo para el ejemplo 2.12.

a) De la tabla A-6E se obtiene que la presión del vapor en el estado especificado es igual a

$$\left.\begin{aligned} v &= 0.514 \text{ ft}^3/\text{lbm} \\ T &= 600°\text{F} \end{aligned}\right\} \quad P = \mathbf{1\,000 \text{ psia}}$$

Éste es el valor determinado experimentalmente y, por ello, el más preciso.

b) A partir de la relación de gas ideal se determina que la presión del vapor bajo la suposición de gas ideal es

$$P = \frac{RT}{v} = \frac{(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1\,060 \text{ R})}{0.514 \text{ ft}^3/\text{lbm}} = \mathbf{1\,228 \text{ psia}}$$

Por tanto, tratar al vapor como un gas ideal resultaría en un error de (1 228 − 1 000)/1 000 = 0.228, o 22.8% en este caso.

c) Para determinar el factor de corrección Z a partir de la carta de compresibilidad (figura A-30), primero se debe calcular el volumen específico pseudorreducido y la temperatura reducida:

$$\left.\begin{aligned} v_R &= \frac{v_{\text{actual}}}{RT_{cr}/P_{cr}} = \frac{(0.514 \text{ ft}^3/\text{lbm})(3\,204 \text{ psia})}{(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1\,165.3 \text{ R})} = 2.373 \\ T_R &= \frac{T}{T_{cr}} = \frac{1\,060 \text{ R}}{1\,165.3 \text{ R}} = 0.91 \end{aligned}\right\} \quad P_R = 0.33$$

Por tanto,

$$P = P_R P_{cr} = (0.33)(3\,204 \text{ psia}) = \mathbf{1\,057 \text{ psia}}$$

Discusión El empleo de la carta de compresibilidad reduce el error de 22.8 a 5.7%, que es aceptable para la mayor parte de los propósitos de la ingeniería (figura 2.56). Un diagrama más grande, desde luego, brindaría mejor resolución y reduciría los errores de lectura. Advierta que no fue necesario determinar Z en este problema puesto que P_R se lee directamente del diagrama.

	P, psia
Exacto	1 000
Carta Z	1 057
Gas ideal	1 228

(del ejemplo 2.11)

FIGURA 2.56
Los resultados obtenidos al utilizar la carta de compresibilidad suelen estar dentro de un pequeño porcentaje de los valores determinados experimentalmente.

TABLA A.1

Masa molar, constante de gas y propiedades del punto-crítico

Sustancia	Fórmula	Masa molar, M kg/kmol	Constante de gas, R kJ/kg · K*	*Propiedades del punto crítico* Tempera-tura, K	Presión, MPa	Volumen, m^3/kmol
Agua	H_2O	18.015	0.4615	647.3	22.09	0.0568
Aire	—	28.97	0.2870	132.5	3.77	0.0883
Alcohol etílico	C_2H_5OH	46.07	0.1805	516	6.38	0.1673
Alcohol metílico	CH_3OH	32.042	0.2595	513.2	7.95	0.1180
Amoniaco	NH_3	17.03	0.4882	405.5	11.28	0.0724
Argón	Ar	39.948	0.2081	151	4.86	0.0749
Benceno	C_6H_6	78.115	0.1064	562	4.92	0.2603
Bromo	Br_2	159.808	0.0520	584	10.34	0.1355
Cloro	Cl_2	70.906	0.1173	417	7.71	0.1242
Cloroformo	$CHCl_3$	119.38	0.06964	536.6	5.47	0.2403
Cloruro metílico	CH_3Cl	50.488	0.1647	416.3	6.68	0.1430
Diclorodifluorometano (R-12)	CCl_2F_2	120.91	0.06876	384.7	4.01	0.2179
Diclorofluorometano (R-21)	$CHCl_2F$	102.92	0.08078	451.7	5.17	0.1973
Dióxido de carbono	CO_2	44.01	0.1889	304.2	7.39	0.0943
Dióxido de sulfuro	SO_2	64.063	0.1298	430.7	7.88	0.1217
Etano	C_2H_6	30.070	0.2765	305.5	4.48	0.1480
Etileno	C_2H_4	28.054	0.2964	282.4	5.12	0.1242
Helio	He	4.003	2.0769	5.3	0.23	0.0578
Hidrógeno (normal)	H_2	2.016	4.1240	33.3	1.30	0.0649
Kriptón	Kr	83.80	0.09921	209.4	5.50	0.0924
Metano	CH_4	16.043	0.5182	191.1	4.64	0.0993
Monóxido de carbono	CO	28.011	0.2968	133	3.50	0.0930
n-Butano	C_4H_{10}	58.124	0.1430	425.2	3.80	0.2547
Neón	Ne	20.183	0.4119	44.5	2.73	0.0417
n-Hexano	C_6H_{14}	86.179	0.09647	507.9	3.03	0.3677
Nitrógeno	N_2	28.013	0.2968	126.2	3.39	0.0899
Óxido nitroso	N_2O	44.013	0.1889	309.7	7.27	0.0961
Oxígeno	O_2	31.999	0.2598	154.8	5.08	0.0780
Propano	C_3H_8	44.097	0.1885	370	4.26	0.1998
Propileno	C_3H_6	42.081	0.1976	365	4.62	0.1810
Tetracloruro de carbono	CCl_4	153.82	0.05405	556.4	4.56	0.2759
Tetrafluoroetano (R-134a)	CF_3CH_2F	102.03	0.08149	374.3	4.067	0.1847
Triclorofluorometano (R-11)	CCl_3F	137.37	0.06052	471.2	4.38	0.2478
Xenón	Xe	131.30	0.06332	289.8	5.88	0.1186

*La unidad en kJ/(kg · K) es equivalente a kPa · m^3/(kg · K). La constante de gas se calcula de $R = R_u/M$, donde R_u = 8.314 kJ/(kmol · K) y M es la masa molar

Fuente K. A. Kobe y R. E. Lynn, *Chemical Review* 52 (1953), pp. 117-236; y ASHRAE [Sociedad Americana de Ingenieros de Calefacción, Refrigeración y Acondicionamiento de Aire], *Handbook of Fundamentals* (Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc , 1993), pp

TABLA A.2

Calores específicos de gas ideal de varios gases comunes

a) A 300 K

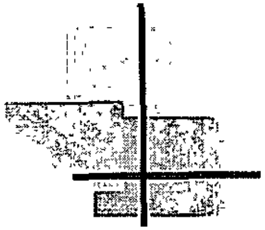
Gas	Fórmula	Constante de gas, R kJ/kg · K	C_p kJ/kg · K	C_v kJ/kg · K	k
Aire	—	0.2870	1.005	0.718	1.400
Argón	Ar	0.2081	0.5203	0.3122	1.667
Butano	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Dióxido de carbono	CO_2	0.1889	0.846	0.657	1.289
Etano	C_2H_6	0.2765	1.7662	1.4897	1.186
Etileno	C_2H_4	0.2964	1.5482	1.2518	1.237
Helio	He	2.0769	5.1926	3.1156	1.667
Hidrógeno	H_2	4.1240	14.307	10.183	1.405
Metano	CH_4	0.5182	2.2537	1.7354	1.299
Monóxido de carbono	CO	0.2968	1.040	0.744	1.400
Neón	Ne	0.4119	1.0299	0.6179	1.667
Nitrógeno	N_2	0.2968	1.039	0.743	1.400
Octano	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxígeno	O_2	0.2598	0.918	0.658	1.395
Propano	C_3H_8	0.1885	1.6794	1.4909	1.126
Vapor	H_2O	0.4615	1.8723	1.4108	1.327

Nota: La unidad kJ/(kg · K) es equivalente a kJ/kg · °C

Fuente: Gordon J. Van Wylen y Richard E. Sonntag, *Fundamentals of Classical Thermodinamics*, versión inglés/SI, 3a. ed. (Nueva York: John Wiley & Sons, 1986), p. 687, tabla A-8SI.

Part 1. BASIC PRINCIPLES OF COMBUSTION SCIENCE

WHAT IS COMBUSTION?



Combustion, or burning, is a rapid combination of oxygen with a fuel, resulting in release of heat.

The oxygen comes from the air, which is about 21% oxygen and 78% nitrogen by volume. (See Table 1.1.)

Most fuels contain carbon, hydrogen, and sometimes sulfur. (See Table 1.4.) As a simplification, we might say that combustion consists of the following three processes:

$$\text{carbon} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{heat}$$
$$\text{hydrogen} + \text{oxygen} \longrightarrow \text{water vapor} + \text{heat}$$
$$\text{sulfur} + \text{oxygen} \longrightarrow \text{sulfur dioxide} + \text{heat}$$

The three products of combustion listed above are called **chemical compounds**, and they are made up of molecules in which elements are combined in

Table 1.1. Composition of air[1]

% by Volume (mols) % by Weight	Dry Bulb Temperature (db) and Relative Humidity (rh) 60 F db 0% rh[2]	60 F db 80% rh	60 F db 100% rh	90 F db 20% rh	90 F db 80% rh	90 F db 100% rh
Oxygen, O_2	20.99 **23.20**	20.70 **23.00**	20.62 **22.94**	20.79 **23.06**	20.19 **22.63**	19.99 **22.50**
Nitrogen, N_2	78.03 **75.46**	76.94 **74.86**	76.67 **74.63**	77.29 **75.01**	75.06 **73.61**	74.32 **73.18**
Argon, Ar	0.94 **1.30**	0.93 **1.29**	0.92 **1.29**	0.93 **1.29**	0.90 **1.27**	0.90 **1.26**
Other[3]	0.04 **0.04**	0.04 **0.04**	0.04 **0.04**	0.04 **0.04**	0.04 **0.04**	0.04 **0.04**
Water, H_2O	0.00 **0.00**	1.40 **0.87**	1.75 **1.10**	0.95 **0.59**	3.81 **2.45**	4.76 **3.02**
Equiv. molecular weight	28.96	28.81	28.77	28.86	28.55	28.45
Density, lb/ft³	0.07632	0.07592	0.07581	0.07189	0.07111	0.07086
Density, kg/m³	1.222	1.216	1.214	1.152	1.139	1.135

[1] For easy computation, it is convenient to remember these ratios:
$Air/O_2 = 100/20.99 = 4.76$ by volume (mols); $Air/O_2 = 100/23.20 = 4.31$ by weight
$N_2/O_2 = 3.76$ by volume (mols); $N_2/O_2 = 3.31$ by weight

[2] From International Critical Tables; all other columns calculated from I.C.T. data and from Reference 1.i at the end of Part 1.

[3] CO_2 (about 0.03%), H_2 (about 0.01%), Neon, Helium, Krypton, Xenon.

certain fixed proportions. For example, a molecule of carbon dioxide contains one atom of carbon plus two atoms of oxygen; a molecule of water vapor contains two atoms of hydrogen plus one atom of oxygen. (See Table 1.4.)

It is an established law of science that matter* is neither created nor destroyed in the process of combustion, and that the heat given off in any combustion process is merely excess energy which the new molecules are forced to liberate because of their internal make-up.

Let us now use equations to show how one carbon atom plus two oxygen atoms (one molecule) burn to form one carbon dioxide molecule and heat:

Fig. 1.2. $C + O_2 \longrightarrow CO_2$ + heat.

Likewise, when two hydrogen atoms burn, one molecule of water is formed.

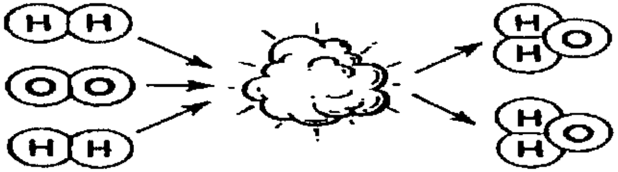


Fig. 1.3. $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ + heat, or $2H_2 + O_2 \longrightarrow 2H_2O$ + heat.

The second of the above two forms is the more common way of writing this process, because oxygen usually comes in *package units*, or di-atomic molecules, containing two oxygen atoms. The amount of heat released in this case is twice as great as when only one oxygen atom and two hydrogen atoms are used.

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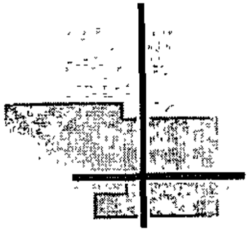
*Matter is anything which has weight and occupies space. Energy does not have weight and does not occupy space.

PERFECT COMBUSTION



Perfect combustion is obtained by mixing and burning just exactly the right proportions of fuel and oxygen so that nothing is left over, as in Figures 1.2 and 1.3. This is like a situation which exists at the assembly line in an automobile factory. Each chassis needs four wheels, and this is the only proportion (4 to 1) that will go together properly. If the conveyor supplying the wheels moves too slowly, some chassis will go by incomplete. But if the wheel conveyor goes too fast, there will be some wheels left over.

Table 1.4. Elements and compounds commonly encountered in combustion*

Element (E) or Compound	Symbol	Relative (mol) Weight†	Normal State	Found In	lb/ft³ at stp	*kg/m³ at stp*	Gas Gravity
Air□	—	28.95	gas	—	0.0763	1.225	1.000
Butane, n-	n-C_4H_{10}	58.12	vapor or liquid	fuels	0.1582	2.533	2.067
Carbon (E)	C	12.01	solid	fuels†, flue gas‡	138	2209	—
Carbon dioxide	CO_2	44.01	gas	flue gas	0.1170	1.873	1.528
Carbon monoxide	CO	28.01	gas	fuels, flue gas‡	0.0740	1.185	0.967
Ethane	C_2H_6	30.07	gas	fuels	0.0803	1.286	1.049
Hydrogen (E)	H	1.01	—	—	—	—	—
Hydrogen	H_2	2.02	gas	fuels	0.00532	0.085	0.0696
Hydrogen sulfide	H_2S	34.08	gas	fuels	0.0898	1.438	1.177
Methane	CH_4	16.04	gas	fuels	0.0424	0.679	0.554
Nitrogen (E)	N	14.01	—	—	—	—	—
Nitrogen	N_2	28.01	gas	air, fuels△, flue gas	0.0744	1.191	0.972
Octane, n-	n-C_8H_{18}	114.23	liquid	fuels	—	—	—
Oxygen (E)	O	16.00	—	—	—	—	—
Oxygen	O_2	32.00	gas	air, fuels△, flue gas	0.0846	1.354	1.105
Propane	C_3H_8	44.10	vapor or liquid	fuels	0.1196	1.915	1.562
Sulfur (E)	S	32.06	solid	fuels△	119-130	1905-2081	—
Sulfur dioxide	SO_2	64.06	gas	fuels△, flue gas	0.1733	2.775	2.264
Sulfur trioxide	SO_3	80.06	gas	flue gas	0.2109	3.378	2.765
Water	H_2O	18.02	liquid	fuels△,	62.4	1000	—
Water	H_2O	18.02	vapor	flue gas	0.0475	0.761	0.622

* Parts of this table are derived from data from Reference 1.1--see list of references at the end of Part 1.

△ Usually in minor amounts in fuels, a trace constituent.

□ Air is neither an element nor a compound, but a mixture of both. See Table 1.1. Air is listed here only for comparison.

† If the element or compound is in the gaseous state, the density of the gas in lb/ft³ will be the relative (mol) weight divided by 379, the ft³/lb mol at 60 F and 14.696 psia, or 359 at 0 F. The density in kg/m³ will be the relative (mol) weight divided by 22.4 m³/kg mol at 0 Celsius and 760 mm Hg. Example: for N_2 or CO, $28 \div 379 = 0.0739$ lb/ft³ at 60 F; $28 \div 359 = 0.0780$ at 0 F; $28 \div 22.4 = 1.250$ kg/m³ at 0 C.

‡ Not found in combustion products if a good burner is properly adjusted at stoichiometric or slightly lean air/fuel ratio.

If too much oxygen (excess air) is supplied, we say that the mixture is **lean** and that the fire is **oxidizing**. This results in a flame that tends to be shorter and clearer. The excess oxygen plays no part in the process. For example, if four atoms of oxygen (instead of two) were mixed with an atom of carbon, two oxygen atoms would be left over. (This is like having six wheels for every chassis.)

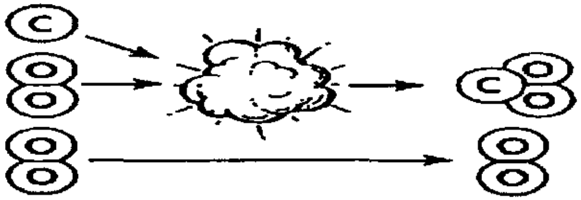


Fig. 1.5. $C + 2O_2 \rightarrow CO_2 + O_2 +$ heat.

If too much fuel (or not enough oxygen) is supplied we say that the mixture is **rich** and that the fire is **reducing**. (This results in a flame that tends to be longer and sometimes smoky.) This is usually called **incomplete combustion**; that is, all of the fuel particles combine with *some* oxygen, but they cannot get enough oxygen to burn completely. (Like chassis with only three wheels.) For example, if we mix two atoms of carbon (instead of one) with two atoms of oxygen, the carbon atoms may share the available oxygen, but neither has enough to become carbon dioxide. Instead they may form carbon monoxide (CO), a compound which will burn to carbon dioxide if given more oxygen later.

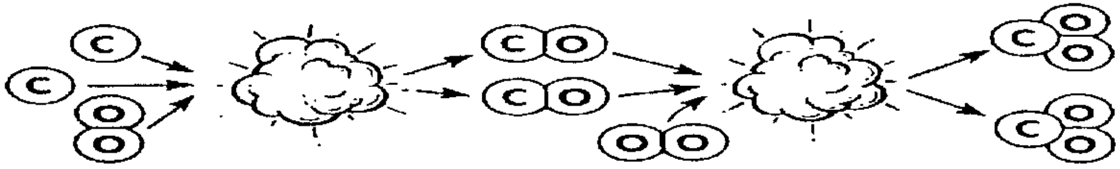


Fig. 1.6. $2C + O_2 \rightarrow 2CO +$ heat, and later, $2CO + O_2 \rightarrow 2CO_2 +$ heat.

Table 1.7 lists the proper proportions for perfect combustion of several typical fuels. The fuel and air must not only be properly proportional but also thoroughly mixed. Otherwise one part of the fire may be rich while the other part remains lean.

The **oxygen supply** for combustion usually comes from the air. Because air contains a large proportion of nitrogen, the required volume of air is much larger than the required volume of pure oxygen. (See Table 1.1.)

The nitrogen in the air does not take part in the combustion reaction—it just goes along for the ride. It does, however, absorb some of the heat with the result that the heat energy is *spread thinly* throughout a large quantity of nitrogen and the combustion products. This means that a much lower flame temperature results from using air instead of pure oxygen. The same phenomenon occurs when excess air is supplied, as in Figure 1.5. The effect of excess air on efficiency and flame temperature is covered in Figures 3.10 and 3.12 of Part 3.

Primary air is that air which is mixed with the fuel at (or in) the burner. **Secondary air** is usually that air brought in around the burner. **Tertiary air** is usually that air brought in downstream of secondary air or through other openings in the furnace.

COMBUSTION OF PRACTICAL FUELS

Carbon, hydrogen, and sulfur are seldom burned in their pure forms. Most fuels are mixtures of chemical compounds called **hydrocarbons** (combinations of hydrogen and carbon some of which are listed in Table 1.4). When these burn, the final products are carbon dioxide and water vapor unless there is a shortage of oxygen, in which case the products may contain carbon monoxide, hydrogen, unburned hydrocarbons, and free carbon.

Up to now, we have spoken only of the *final* products of combustion. Although these final products are usually limited to the same few compounds for all

Table 1.7. Proper combining proportions for perfect combustion
(See also Tables 1.10, 2.1, 2.12, 3.1)

Fuel	$\frac{\text{vol } O_2}{\text{vol fuel}}$	$\frac{\text{vol air}}{\text{vol fuel}}$	$\frac{\text{wt } O_2}{\text{wt fuel}}$	$\frac{\text{wt air}}{\text{wt fuel}}$	$\frac{\text{ft}^3\ O_2}{\text{lb fuel}}$	$\frac{\text{ft}^3 \text{ air}}{\text{lb fuel}}$	$\frac{m^3\ O_2}{kg\ fuel}$	$\frac{m^3\ air}{kg\ fuel}$
Acetylene, C_2H_2	2.50	11.9	3.08	13.3	36.5	174	2.28	10.8
Benzene, C_6H_6	7.50	35.7	3.08	13.3	36.5	174	2.28	10.8
Butane, C_4H_{10}	6.50	31.0	3.59	15.5	42.5	203	2.65	12.6
Carbon, C	—	—	2.67	11.5	31.6	150	1.97	9.39
Carbon monoxide, CO	0.50	2.38	0.571	2.46	6.76	32.2	0.422	2.01
Ethane, C_2H_6	3.50	16.7	3.73	16.1	44.2	210	2.76	13.1
Hydrogen, H_2	0.50	2.38	8.00	34.5	94.7	451	5.92	28.2
Hydrogen sulfide, H_2S	1.50	7.15	1.41	6.08	16.7	79.5	1.04	4.97
Methane, CH_4	2.00	9.53	4.00	17.2	47.4	226	2.96	14.1
Naphthalene, $C_{10}H_8$	—	—	3.00	12.9	35.5	169	2.22	10.6
Octane, C_8H_{18}	—	—	3.51	15.1	41.6	198	2.60	12.4
Propane, C_3H_8	5.00	23.8	3.64	15.7	43.1	205	2.69	12.8
Propylene, C_3H_6	4.50	21.4	3.43	14.8	40.6	193	2.54	12.1
Sulfur, S	—	—	1.00	4.31	11.8	56.4	0.74	3.52

hydrocarbon fuels, they are not always produced by the same combustion process. Within different flames, many varied and unknown processes and intermediate products occur, even though the final products are the same.

The carbon and hydrogen form and reform into a succession of unstable aldehydes and other compounds which finally combine to form CO_2 and H_2O. The types of intermediate compounds formed, and their speed of formation, depend upon such factors as the temperature, pressure, amount of oxygen present, and degree of mixing.

Good combustion requires (a) proper proportioning of fuel and air, (b) thorough mixing of the fuel and air, and (c) initial and sustained ignition of the mixture. These, together with flame positioning, are the functions of a combustion system.

Proportioning. Basic proportioning requirements were discussed on previous pages. See also Part 3. Proportioning equipment is discussed in Volume II.

Mixing. Good mixing of the fuel and air is important so that the mixture will be uniform throughout--every particle of fuel must contact a particle of air. Most fuels actually turn into a gas before they burn. A highly turbulent *scrubbing* action aids this conversion to gas and the mixing of the gas with the air.

Liquid fuels are usually evaporated, and the resulting combustible vapors then burn as gases. **Atomization** of the liquid speeds evaporation because it produces millions of tiny liquid particles, thus providing a large amount of surface for evaporation. Heat from the adjacent flame will sometimes cause the fuel to *crack*, or decompose, before it can evaporate. This cracking usually produces a lighter hydrocarbon (which burns like a gas) and a heavier hydrocarbon (which may burn like solid carbon, producing a very luminous yellow flame).

When solid carbon is burned the process is further complicated by the fact that each atom of oxygen must contact the carbon surface, form CO gas, and then move out of the way so that more oxygen may move in. Thus combustion of solid fuels consists of a mass transport phenomenon (of oxygen to the surface and CO away from the surface), plus mixing, plus chemical combination. If solid fuels are to be burned at high rates comparable to those attainable with gaseous and liquid fuels, they must be *pulverized* to increase the surface area for mass transfer. (This may be compared with the situation existing in a bus station with only one loading platform. No matter how many busses are waiting outside or how many people are waiting inside, the maximum rate with which the people can be taken away depends upon how fast one bus can pull up to the platform and how quickly it can pull away to let in the next bus. Pulverizing a solid fuel or atomizing a liquid fuel is like adding more loading platforms.)

Ignition. Chemical combination of fuels and air will occur at room temperature, but only very slowly. If a pile of coal is located in a confined place, the small amount of heat liberated by this slow oxidation will gradually build up, thus raising the temperature of the coal pile. As the temperature gradually rises, the rate of oxidation increases and the temperature rises some more. This goes on until a full-fledged fire is in progress. This is known as **spontaneous ignition.** It can happen only in very confined places where the heat is allowed to collect in the combustible material and in the adjacent stagnant air.

When we wish to ignite a fuel-air mixture, we cannot usually arrange to collect heat in a confined space. (Even if we could, this process would be too slow to be practical.) Instead it is necessary to apply a lot of heat to a very localized area. For example: a match will not light a log, but it will start a twig. This is because the log has so much mass that it conducts heat away from the match flame so fast that no part of the log gets hot enough to burn. The twig, however, has much of its surface exposed to the match flame, but little mass to absorb the heat; so localized hot spots develop and burst into flame.

Ignition is usually accomplished by speeding the oxidation reaction by addition of an external heat source until the reaction itself releases heat faster than heat is lost to the surroundings--until it continuously ignites itself without the external heat source. The lowest temperature at which this is possible is the **minimum ignition temperature** of the fuel-air mixture. It can be lowered by increasing the pressure on a mixture. Table 1.10 lists some approximate ignition temperatures. Ignition devices are discussed in Volume II.

A cold blast of air or contact with a cold wall may quench parts of a flame, cooling it below the ignition temperature; so some of the fuel goes unburned.

Flame Stabilizing, which can make the difference between useful and useless combustion, is usually a function of burner nozzle/tile configuration. A flame holder positions the area of flame initiation by providing (a) ignition temperature, (b) localized fuel-air mixture within the flammability limits, and (c) feed-speed equal to the flame speed. Practical industrial burners must provide flame stability over a wide range of firing rates and fuel/air ratios.

Heat Available from Fuels. Heat quantities are measured in *Btu, kilocalories, watt-seconds,* or *joules.* See Table C.6 and Glossary.

Experimental measurements have been made to determine the heat released by perfect combustion of various fuels. If a certain fuel is mixed with proper amount of air and placed in a closed chamber where the heat given off by combustion can be collected and measured, the total amount of heat collected will depend on the final temperature of the products of combustion. For example, one pound of light oil releases about 18 500 Btu *(4662 kcal, 19.5 MJ)* if the products are cooled to 60 F *(15.6 C)*, but releases only about 16 300 *(4108 kcal, 17.2 MJ)* if cooled to 500 F *(260 C)*. When a perfect mixture of a fuel and air, originally at 60 F *(15.6 C)* is ignited and then cooled to 60 F *(15.6 C)* the total heat released is termed the **higher heating value** or **gross heating value** of the fuel. The term **lower heating value** or **net heating value** is seldom used in this country, but this quantity is equal to the gross heating value minus the heat released by condensation of the water vapor in the combustion products. Values of gross and net heating values for various fuels are listed in Table 1.8. The products are seldom cooled to 60 F (15.6 C) in practical combustion applications, so the gross heating value is seldom attained. The so-called **available heat** is a much more useful figure. Values of available heats are listed in Part 3.

Flame Temperatures. The heat released by the chemical combination of a fuel with air (a) heats up the combustion products and the incoming fuel-air mixture, (b) radiates to the surroundings, or (c) is carried away by direct contact with the surroundings. Naturally, the flame temperature is highest when

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Table 1.8. Gross and net heating (calorific) values of simple fuels*

Fuels (Heat of vaporization at boiling temperature and 14.7 psia, Btu/lb) [ft³ ideal gas per USgallon liquid]‡	Gross heating value *Net heating value*	Heating value per unit volume			Heating value per unit weight	
		Btu/ft³	kcal/m³	MJ/m³	Btu/lb	kcal/kg	MJ/kg
Acetylene, C_2H_2 †		1477 *1426*	13140 *12690*	55.01 53.11	21502 *20769*	11946 11539	50.014 *48.309*
Butane, n-C_4H_{10}† (165.9) [31.80]		3271 *3018*	29110 *26860*	121.8 112.4	21321 *19678*	11846 *10933*	49.593 *49.771*
Carbon, C		— —	— —	— —	14093 *14093*	7830 *7830*	32.780 *32.780*
Carbon monoxide, CO		321 *321*	2856 *2860*	12.0 *12.0*	4347 *4347*	2415 *2415*	10.11 *10.11*
Ethane, C_2H_6 (210.7) [37.48]		1773 *1622*	15780 14430	66.04 *60.41*	22323 *20418*	12402 *11344*	51.923 *47.492*
Hydrogen, H_2		325 *275*	2892 2450	12.11 *10.2*	61095 *51623*	33944 *28681*	142.11 *120.08*
Hydrogen sulfide, H_2S†		646 *595*	5749 5300	24.06 22.2	7097 *6537*	3943 3632	16.51 *15.21*
Methane, CH_4 (219.7) [59.1]		1012 *911*	9005 *8110*	37.69 *33.9*	23875 *21495*	13265 *11942*	55.533 *49.997*
Methanol, CH_3OH		752 *651*	— —	— —	9700 *8400*	5389 *4667*	— —
Octane, C_8H_{18}† (131.9) [19.58]		6260 *5806*	55710 *51670*	233.2 *216.3*	20796 *19291*	11554 *10718*	48.371 *44.871*
Propane, C_3H_8† (183.5) [36.41]		2524 *2322*	22460 *20660*	94.01 *86.49*	21669 *19937*	12039 *11077*	50.402 *46.373*
Sulfur, S		— —	— —	— —	3980 *3980*	2211 2211	9.257 *9.257*

*Derived from Reference 1.i at the end of Part 1.

†Heating values may be somewhat less for commercial forms of these compounds.

‡From Reference 1.k at the end of Part 1.

the losses to the surroundings are smallest. Addition of excess air or excess fuel only provides more material to absorb the heat of combustion so the flame temperature cannot go as high as with a perfect fuel-air mixture, just as a furnace which will heat a small house to 68 F *(20 C)* might heat a large house to only 60 F *(15.6 C)*.

Under certain conditions, particularly high temperatures, a phenomenon known as **dissociation** occurs. Dissociation is simply reverse combustion; that is, it is the breaking down of the combustion products into combustibles and oxygen again. This process *absorbs* the heat which was originally liberated by combustion. For example:

$$\text{Heat} + CO_2 \longrightarrow CO + \tfrac{1}{2}O_2 \qquad \text{and} \qquad \text{Heat} + H_2O \longrightarrow H_2 + \tfrac{1}{2}O_2$$

The higher the temperature, the greater is this tendency to dissociate. So, the hotter the flame, the greater is the amount of heat re-absorbed by this reversing process, and the rising flame temperature comes to a halt at some equilibrium temperature in the range of 3400 F to 3600 F *(1870 C to 2090 C)* for most fuels. This equilibrium temperature has been calculated for many common fuels and is listed as **calculated flame temperature** in Table 1.10. It is *theoretical* because no account has been taken of losses to the surroundings. For this reason, actual flame temperatures are always lower than the listed figures. The data in Table 1.10 are for perfect combustion only.

A simplified formula for **theoretical adiabatic flame temperature** is:

$$\frac{\text{net heating value of the fuel} - \text{effect of dissociation}}{(\text{weight of combustion products}) \times (\text{specific heat of combustion products})}$$

With large amounts of excess air, this is often called **hot mix temperature**.

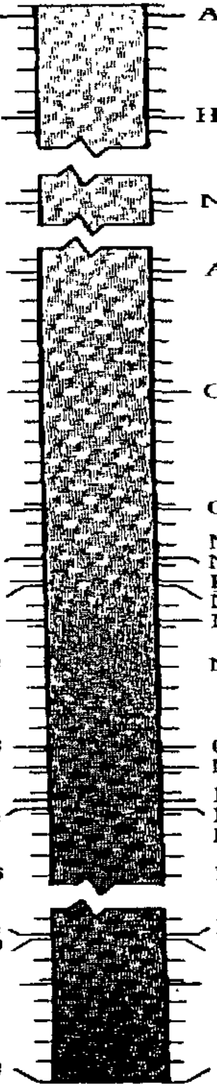
The **actual flame temperature** is the theoretical flame temperature minus the temperature drop caused by heat transferred to the load and surroundings before the heat release process is completed.

The **furnace temperature** can equal the theoretical flame temperature only if the flame transfers no heat to its surrounding, i.e. if the furnace wall is a perfect insulator (not available) and if there is no load in the furnace (furnace is useless).

In most cases, special refractory materials are needed and a special furnace design required (to avoid localized overheating of the load), to take advantage of temperatures such as listed in Table 1.9.

Unless the fuel and air are so poorly mixed that incomplete combustion results, theoretical flame temperature is not a function of burner design. However, the actual flame temperature is intentionally lowered by increasing the heat transferred from the flame in burners designed for excess air, luminous flames, or delayed mixing.

Table 1.9. Comparison of some flame temperatures (See also Table 1.10)



Observed flame temperature F	Observed flame temperature C	Theoretical flame temperature F	Theoretical flame temperature C	Fuel	Air (or O_2) temp., F/C	Equivalence ratio
		5630	3110	Acetylene in O_2	(60/16)	—
		5385	2974	Hydrogen in O_2	(60/16)	—
		5120	2827	Natural gas in O_2	(60/16)	—
4207	2319	4770	2632	Acetylene	60/16	1.00
3812	2100	4475[1]	2468	Carbon monoxide	60/16	1.00
4190	2310			Gasoline		
		4100	2260	Natural gas	1400/760	1.00
		4070	2243	Natural gas	1400/760	1.11 (rich)
3713	2045	4010[1]	2210	Hydrogen	60/16	1.00
		4000	2204	Natural gas	1100/593	1.00
		3920	2160	Natural gas	900/482	1.00
		3800	2093	Natural gas	600/316	1.00
3155[2]	1735[2] }	3610	1988	Coke oven gas	60/16	1.00
3416	1880 }	3562	1961	Natural gas	60/16	1.00
				Methane[3]	60/16	1.00
		3460	1904	Methanol	60/16	1.00
		3400	1871	Natural gas	60/16	1.18 (rich)
		3300	1816	Natural gas	60/16	0.86 (lean)
		3010	1654	Producer gas	60/16	1.00
		3000	1649	Natural gas	60/16	1.49 (rich)
		2895	1591	Natural gas	60/16	0.70 (lean)
		2650	1454	Blast furnace gas	60/16	1.00

[1] Not corrected for dissociation.

[2] In an actual production furnace firing refractories.

[3] Methane, ethane, propane, butane have theoretical flame temperatures in the 3484 F to 3583 F (1918 C to 1973 C) range; observed flame temperatures in 3416 F to 3497 F (1880 C to 1925 C) range.

A small amount of excess air or excess fuel can greatly reduce the flame temperature. In Table 1.9, 16.2% excess air *(0.86 equivalence ratio)* lowers the flame temperature by 262 degrees. If high flame and furnace temperature is desired, accurate fuel/air ratio control is most critical.

Flame Speeds. A flame is merely an envelope or zone within which the combustion reaction is occurring at such a rate as to produce visible radiation. The flame front is the 3-dimensional contour along which combustion starts, the dividing line between the fuel-air mixture and the combustion products.

In stable burner flames, the flame front appears to be stationary. This is because the flame is moving toward the burner with the same speed that the fuel-air mixture is coming out of the burner. (This may be compared with a fish swimming upstream at 5 miles per hour in a 5 mph current.)

If the fuel-air mixture is fed into the burner at too fast a rate, the flame may **blow off** (like a 5 mph fish being washed downstream by a 6 mph current). Most burners, however, allow a considerable range of feed rates by proper design of the burner nozzle.

If the fuel-air mixture is fed into the burner at too slow a rate, the flame may **flashback** into the burner (like a 5 mph fish making headway in a 3 mph stream). The flame may flashback as far as the mixing point, or it may be *quenched* by the cool burner wall.

Flame velocity depends on such factors as pressure, temperature, fuel, primary fuel/air ratio, turbulence (mixing), and cooling effects of surroundings, and it cannot be reliably predicted except in very specific cases. Table 1.10 indicates some typical flame velocities measured on simple Bunsen-type gas burners. Note that these are *maximum* flame velocities for the given fuels, and that they are for the listed fuel-air mixtures only. Preheating of the gas-air mixture results in a considerable increase in flame velocity. For other terms and related properties, see **Flame velocity** in the Glossary.

Flammability Limits. Not all mixtures of a fuel with air or oxygen will burn continuously in self-sustained combustion. Table 1.10 shows limiting lean (lower limit) mixtures and rich (upper limit) mixtures beyond which practical combustion is impossible. A common example of this is the *flooding* of an automobile engine—an excess of fuel produces a mixture too rich to burn (above the upper limit of flammability).

Even within the flammability limits, there are certain practical limitations to the fuel-air mixtures that may be used. One of these is the unsafe combustible gases or poisonous CO produced by a rich fire. Another limit is the temperature or atmosphere required for certain processes.

Table 1.10. Combustion characteristics of fuels* (See also Tables 1.7, 1.9, 2.1, 2.12, 3.1, and Appendix, Vol. II)

	Minimum ignition temp, F/C△		Calculated flame temperature,† F/C		Flammability limits % fuel gas by volume○				Maximum flame velocity, fps and m/s		% Theoretical air for max. flame velocity
					in air		in O_2				
Fuel	in air	in O_2	in air	in O_2	lower	upper	lower	upper	in air	in O_2	
Acetylene, C_2H_2	581[c]/305	—	4770/2632	5630/3110	2.5	81.0	—	—	8.75/2.67	37.0/11.3[l]	83
Blast furnace gas	—	—	2650/1454	—	35.0[h]	73.5	—	—	—	—	—
Butane, commercial	896/480	—	3583/1973	—	1.86	8.41	—	—	2.85/0.87	—	—
Butane, n-C_4H_{10}	761/405	541/283[l]	3583/1973	—	1.86	8.41	1.8[n]	49[n]	1.3/0.40	11.6/3.55[l]	97
Carbon monoxide, CO	1128[c]/609	1090/588[l]	3542[b]/1950	—	12.5[f]	74.2[f]	16[m]	94[m]	1.7/0.52	—	55
Carbureted water gas	—	—	3700/2038	5050/2788	6.4	37.7	—	—	2.15/0.66	—	90
Coke oven gas	—	—	3610/1988	—	4.4[f]	34.0[f]	—	—	2.30/0.70	—	90
Ethane, C_2H_6	882[c]/472	—	3540/1949	—	3.0	12.5	3[n]	66[n]	1.56/0.48	—	98
Gasoline	536[f]/280	—	—	—	1.4	7.6	—	—	—	—	—
Hydrogen, H_2	1062[c]/572	1040/560[l]	4010/2045	5385/2974	4.0	74.2	4[m]	94[m]	9.3/2.83	38.5/11.7[l]	57
Hydrogen sulfide, H_2S	558[f]/292	—	—	—	4.3	45.5	—	—	—	—	—
Mapp gas, C_3H_4‡	850/455	—	—	5301/2927	3.4	10.8	—	—	—	15.4/4.69	—
Methane, CH_4	1170[c]/632	1033/556[l]	3484/1918	—	5.0	15.0	5.1[n]	61[n]	1.48[a]/0.45	14.76/4.50	90
Methanol, CH_3OH‡	725/385	—	3460/1904	—	6.7	36.0	—	—	—	1.6/0.49	—
Natural gas	—	—	3525[g]/1941	4790[g]/2643	4.3	15.0	—	—	1.00/0.30	15.2/4.63	100
Producer gas	—	—	3010/1654	—	17.0[f]	73.7	—	—	0.85/0.26	—	90
Propane, C_3H_8	919/493[l]	874/468[l]	3573/1967	5130/2832	2.1	10.1	2.3[n]	55[n]	1.52/0.46	12.2/3.72	94
Propane, commercial	932/500	—	3573/1967	—	2.37	9.50	—	—	2.78/0.85	—	—
Propylene, C_3H_6	—	—	—	5240/2893	2.4[n]	10.3[n]	2.1[n]	53[n]	—	—	—
Town gas (Br. coal)[d]	700/370	—	3710/2045	—	4.8‡	31.0	—	—	—	—	—

* For combustion with air at standard temperature and pressure. Unless otherwise noted, data is from Reference 1.i.

† Flame temperatures are theoretical--calculated for stoichiometric ratio, dissociation considered.

‡ From private communications.

△ See also "autoignition temperature" in the Glossary and in Reference 1.j at the end of Part 1.

○ In a fuel-air mix. Example, for methane, LEL = 5% or 95 volumes air/5 volumes gas = 19.1 air/gas ratio. From p5, stoichiometric ratio is 9.53:1. Therefore excess air is 19 − 9.53 = 9.47 cf air/cf gas or 9.47/9.53 × 100 = 99.4% excess air.

Small letters refer to references at end of Part 1.

Table 1.11. Combustion reaction times and intensities*

Fuel	Combustion situation	Reaction time at normal pressure, seconds	Combustion Intensity Btu/hr ft³ atm	*kcal/h m³ atm*
All	drying and baking ovens		10^2	10^3
Coal	domestic		10^3-10^4	10^4-10^5
"	industrial stokers and pulverized fuel burners	1	10^4-10^5	10^5-10^6
"	possible limit in explosion flames	0.1		
"	fluid bed, cyclone		10^6	10^7
Solid fuel	rocket		10^6-10^7	10^7-10^8
Heavy oils	(carbon forming)	0.1		
" "	air and steam atomizer		10^4-10^5	10^5-10^6
Medium oils	pressure jet and air atomized		10^5-10^6	10^6-10^7
Light oils	domestic		10^3-10^4	10^4-10^5
" "	large drops	0.01		
" "	small drops	0.001		
" "	industrial furnaces		10^5	10^6
" "	gas turbines with pressure jet burners		10^6-10^7	10^7-10^8
" "	ram jets		10^6-10^7	10^7-10^8
Liquid	rockets		10^8	10^9
Gas	nozzle-mix burners† (turbulent diffusion)		10^4-10^6	10^5-10^7
"	pre-mixed,‡ industrial flames	0.001	10^6-10^7	10^7-10^8
"	Wingaersheek torch, PSU countervortex burner		10^8	10^9
"	detonation or shock combustion	0.00001		

* Derived from pages 389-391 of Prof. Robert H. Essenhigh's paper in Reference 1.b listed at the end of Part 1.

† **Furnace** volume used in intensity evaluation.

‡ **Flame** volume used in intensity evaluation.

Flammability limits, also known as **explosive limits** (LEL and UEL), are expressed as volume percentages of fuel in a fuel-air mixture.

Combustion Intensity. Interrelated with flame temperature and flame velocity are **reaction time** and **combustion intensity**, which are approximately the inverse of one another. Combustion intensity, like flame velocity, increases with the absolute pressure. Table 1.11 makes *generalized* comparisons of reaction times and combustion intensities for several combustion situations with solid, liquid, and gaseous fuels.

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Part 2. INDUSTRIAL PROCESS FUELS

CHEMICAL CONSTITUENTS OF FUELS

The physical properties of gaseous, liquid, and solid natural and man-made fuels are discussed later in Part 2. The chemical analyses of typical fuels from each of these categories are listed in Table 2.1. The chemical elements of most importance to the combustion engineer are carbon, hydrogen, and sulfur. Nitrogen, carbon dioxide, oxygen, water, and ash usually appear in minor amounts and contribute nothing but handling problems, and sometimes pollution problems.

Carbon is a major constituent of most fuels. The term **available carbon** is used to describe carbon which is not chemically combined with oxygen in any way. Unless otherwise specified the term **carbon** as used in this handbook will mean available carbon. Complete combustion of one pound of carbon yields a gross heat of 14 500 Btu.

[2/1]
$$\mathbf{1\ lb\ C + 2\tfrac{2}{3}\ lb\ O_2 \longrightarrow 3\tfrac{2}{3}\ lb\ CO_2 + 14\,500\ Btu}$$
$$\text{or } 1\text{ kg C} + 2\tfrac{2}{3}\text{ kg } O_2 \longrightarrow 3\tfrac{2}{3}\text{ kg } CO_2 + 8\,056\text{ kcal or } 33.73\text{ MJ}$$

Incomplete combustion (producing carbon monoxide instead of carbon dioxide) would yield only 4 350 Btu (per pound of carbon).

[2/2]
$$\mathbf{1\ lb\ C + 1\tfrac{1}{3}\ lb\ O_2 \longrightarrow 2\tfrac{1}{3}\ lb\ CO + 4\,350\ Btu}$$
$$\text{or } 1\text{ kg C} + 1\tfrac{1}{3}\text{ kg } O_2 \longrightarrow 2\tfrac{1}{3}\text{ kg CO} + 2\,417\text{ kcal or } 10.12\text{ MJ}$$

Further addition of oxygen and re-ignition would yield 14 500 minus 4 350 or 10 150 Btu (per pound of the original carbon).

[2/3]
$$\mathbf{2\tfrac{1}{3}\ lb\ CO + 1\tfrac{1}{3}\ lb\ O_2 \longrightarrow 3\tfrac{2}{3}\ lb\ CO_2 + 10\,150\ Btu}$$
$$\text{or } 2\tfrac{1}{3}\text{ kg CO} + 1\tfrac{1}{3}\text{ kg } O_2 \longrightarrow 3\tfrac{2}{3}\text{ kg } CO_2 + 5\,639\text{ kcal or } 23.61\text{ MJ}$$

Carbon in the form of a solid fuel is difficult to ignite and, as explained in Part 1, is slow to burn unless finely pulverized. In liquid or gaseous fuels, carbon appears in hydrocarbon compounds or carbon monoxide. If not burned properly, the hydrocarbon compounds may "crack" producing soot. Despite these disadvantages, carbon is one of man's primary sources of heat; so combustion engineers try to overcome these difficulties. In the case of solid fuels, rapid efficient combustion is often best accomplished by burning in a fluidized bed or in pulverized form in suspension. The soot problem with gaseous and liquid fuels is minimized by design of the burners and combustion chamber to provide adequate air and turbulence, and to avoid excessive heating of the fuel prior to its contact with the air.

Table 2.1a. Comparative data (by weight) for some typical fuels

FUELS — see also Tables 2.1b, 2.11, 2.12	Analysis, in % by weight: C available / H available C total / H available	Gas gravity rel to air[3] Specific gravity relative to water[4]	Constituents: C, available/total	H, available	S	O	N	Ash	Moisture
Blast furnace gas	56	1.02	5.6/15.8	0.1	[5]	27.3	56.8	[5]	[5]
Coke oven gas	1.81	0.40	41.1/48.3	22.7	[5]	16.0	13.0	[5]	[5]
Producer gas[1]	4.94	0.86	8.4/17.1	1.7	[5]	23.3	57.9	[5]	[5]
Natural gas[2]	3.08	0.60	69.4/69.4	22.5	[11]	0	8.1	0	0
Propane, natural[13]	4.43	1.55[8]	81.6/81.6	18.4	0	0	0	0	0
Butane, refinery[13]	5.10	2.00[8]	83.6/83.6	16.4	0	0	0	0	0
Methanol	1.50	0.791	18.8/37.5	12.5	—	50.0	—	—	—
Gasoline, motor[6]	5.94	0.733	85.5/85.5	14.4	0.1	0	0	0	0
#1 Distillate oil, 6.79#/USgal	6.51	0.814	86.6/86.6	13.3	0.14	—	—	—	—
#2 Distillate oil, 7.21#/USgal	6.98	0.865	87.3/87.3	12.5	0.21	—	—	—	—
#4 Fuel oil, 7.59#/USgal	7.45	0.910	86.4/86.4	11.6	1.99	—	—	0.018	0.2[12]
#5 Residual oil, 7.93#/USgal	8.29	0.951	88.7/88.7	10.7	0.57[7]	—	—	0.02	0.4[12]
#6 Residual oil, 8.45#/USgal	9.49	1.013	88.3/88.6	9.3	0.85[7]	0.7	0.3	0.04	0.2[12]
Wood, non-resinous	5.26	.4-.8	/37.9	7.2	0	53.8	0.1	1.0	[9]
Coal, bituminous	16.0	.6-.9	/80.1	5.0	1.0	5.2	0	7.2	3.1
Coal, anthracite	33.6	.7-.9	/80.6	2.4	1.1	5.9	0	9.5	5.2[12]
Coke	106	.4-.5	/85.0	0.8	1.0	1.2	1.3	10.7	0.8

[1] From a Wellman-Galusha producer using bituminous coal.

[2] Birmingham, AL.

[3] Multiply this figure by 0.0765 to obtain lb/ft³, by 1.226 to obtain kg/m³.

[4] Multiply this figure by 62.43 to obtain lb/ft³, by 8.34 to obtain pound/gallon, by 1000 to obtain kg/m³.

[5] Varies with type of coal or coke used, equipment and process.

[6] From page 269 of Reference 2.f. See list of references at end of Part 2.

[7] Sulfur content may vary from 0.4 to 3.5%, depending on source, refining, and blending.

[8] In the liquid state, specific gravity relative to water is 0.509 for propane, 0.582 for butane.

[9] Seasoned.

[10] Multiply gross Btu/scf air by 8.90 to obtain gross kcal/m³ of standard air.

[11] Sulfur content may be 1 to 2 percent at the gas well, but this is usually reduced to less than 8 ppm by weight before distribution.

[12] See bottom sediment and water, Table 2.11.

[13] Typical liquid propane weighs 4.24#/USgal; typical liquid butane, 4.84#/USgal. See Table 2.12a and Reference 2.g at end of Part 2.

Table 2.1b. Comparative data (by weight) for some typical fuels

	Heating value Btu/lb (and Btu/gal)		Heating value kcal/kg (and kcal/L)		Gross Btu per scf air[10]	Wt air req'd per unit wt fuel (and scf/gal)	Weight of combustion products per wt of fuel (and ft³/gal)				Ultimate vol % CO_2 in dry flue gas
	Gross	Net	Gross	Net			CO_2	H_2O	N_2	Total	
Blast furnace gas	1 179	1 079	665	599	135.3	0.57	0.58	0.01	1.08	1.67	25.5
Coke oven gas	18 595	16 634	10 331	9 242	104.4	13.63	1.51	1.81	8.61	11.93	10.8
Producer gas[1]	2 614	2 459	1 452	1 366	129.2	1.55	0.61	0.15	1.72	2.48	18.4
Natural gas[2]	21 830	19 695	12 129	10 943	106.1	15.73	2.55	2.03	12.17	16.75	11.7
Propane, natural	21 573	19 886	11 986	11 049	107.5	15.35	3.01	1.62	12.01	16.64	13.8
	(91 500)	(84 345)	(6094)	(5617)		(850.8)	(108.11)	(144.39)	(682.06)	(934.57)	
Butane, refinery	20 810	19 183	11 562	10 658	106.1	15.00	3.04	1.53	11.82	16.39	14.3
	(102 600)	(94 578)	(6833)	(6299)		(949.0)	(124.27)	(146.92)	(747.18)	(1018.4)	
Methanol	9 797	8 706	5 444	4 838	115.4	6.47	1.38	1.13	4.97	7.48	15.0
	(64 630)	(57 430)	(4304)	(3825)		(559.5)	(78.4)	(156.8)	(445.3)	(681)	
Gasoline, motor	20 190	18 790	11 218	10 440	104.6	14.80	3.14	1.30	11.36	15.80	15.0
	(123 361)	(114 807)	(8216)	(7646)		(1183)	(165.1)	(166.8)	(940.3)	(1272)	
#1 Distillate oil	19 423	18 211	10 791	10 118	102.1	14.55	3.17	1.20	11.10	15.48	15.4
	(131 890)	(123 650)	(8784)	(8235)		(1292)	(185.7)	(171.0)	(1020)	(1377)	
#2 Distillate oil	18 993	17 855	10 553	9 920	101.2	14.35	3.20	1.12	10.95	15.27	15.7
	(137 080)	(128 869)	(9130)	(8583)		(1354)	(199.1)	(170.6)	(1070)	(1440)	
#4 Fuel oil	18 844	17 790	10 470	9 884	103.0	13.99	3.16	1.04	10.68	14.92	15.8
	(143 010)	(135 013)	(9524)	(8992)		(1388)	(206.7)	(166.1)	(1097)	(1472)	
#5 Residual oil	18 909	17 929	10 506	9 961	104.2	13.88	3.24	0.97	10.59	14.81	16.3
	(149 960)	(142 190)	(9987)	(9470)		(1439)	(221.0)	(161.4)	(1137)	(1520)	
#6 Residual oil	18 126	17 277	10 071	9 599	103.2	13.44	3.25	0.84	10.25	14.36	16.7
	(153 120)	(145 947)	(10 198)	(9720)		(1484)	(236.4)	(149.0)	(1172)	(1558)	
Wood, non-resinous	6 300		3 500		98.4	4.90	1.39	0.65	3.47	5.51	20.3
Coal, bituminous	14 030		7 795		99.3	10.81	2.94	0.49	8.26	11.71	18.5
Coal, anthracite	12 680		7 045		97.8	9.92	2.96	0.22	7.58	10.78	19.9
Coke	12 690		7 051		96.2	10.09	3.12	0.07	7.73	10.94	20.4

Footnotes are on Table 2.1a.

Hydrogen has a heating value that is very high when compared with that of carbon (Table 1.8). However, hydrogen is a very light weight gas; so the heating value of one cubic foot of hydrogen is low in comparison with other gaseous fuels. Hydrogen has a higher flame speed than most gaseous fuels, which partially makes up for its low heat content (on a flame volume basis). The term **available hydrogen** refers to hydrogen which is not already combined with oxygen. Unless otherwise specified, the term **hydrogen** as used in this handbook will mean available hydrogen.

Sulfur is of concern because of its corrosive and pollution effects. In metallurgical and ceramic furnaces it may seriously affect the quality of the product. In boilers, the sulfur dioxide and water vapor in the combustion products may unite to form acids that can be highly corrosive to the breeching. The presence of some gaseous sulfur compounds may lower the dew point of water vapor in the flue gases, further aggravating corrosion problems.

Generalized Comparison of Fuels. Most fuels consist of carbon and hydrogen combined in various proportions. Table 2.1 facilitates a generalized comparison of fuels by studying the C/H ratios and the analyses by weight. The C/H ratio is based on available C and available H except for the last four (solid) fuels. The analyses do not always add up to 100% because some fuels contain CO_2.

It is a rule of thumb among combustion engineers that **one cubic foot of air releases 100 Btu of heat**. The 100 Btu here mentioned is gross heat. Thus one cubic foot of gas with a gross heating value of 1000 Btu requires 10 ft³ of air to burn completely, and one gallon of oil with a gross heating value of 140 000 Btu requires 1400 ft³ of air to burn. Table 2.1b indicates that this rule of thumb is *approximately* correct. It is common practice to determine the air requirement for a commercial fuel from this rule of thumb and the measured heating value rather than by calculation from the chemical analysis. In metric units the rule would be 890 kcal/m³ air or 3.725 MJ/m³ air.

For gaseous fuels, the following empirical formulas are somewhat more accurate:

[2/4a] For fuels having more than 400 gross Btu/ft³ (3560 kcal/m³, 14.92 MJ/m³),

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{gross heating value, Btu/ft}^3}{100} - 0.6, \text{ or } \frac{\text{kcal/m}^3}{890} - 0.6, \text{ or } \frac{\text{MJ/m}^3}{37.3} - 0.6$$

[2/4b] for producer gas,[d]

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{net heating value, Btu/ft}^3}{129} \text{ or } \frac{\text{kcal/m}^3}{1150} \text{ or } \frac{\text{MJ/m}^3}{4.81}$$

Small letters refer to references at end of Part 2.

[2/4c] for blast furnace gas,[d]

$$\frac{\text{req'd air volume}}{\text{fuel gas volume}} = \frac{\text{net heating value, Btu/ft}^3}{141} \text{ or } \frac{\text{kcal/m}^3}{1260} \text{ or } \frac{\text{MJ/m}^3}{5.27}.$$

PROPERTIES OF SOLID FUELS

The designer and the user of fuel handling equipment and furnaces for solid fuels must pay careful attention to a great many properties of the fuel. Among these are calorific value, volatile matter content, ash content, moisture content, ash fusion temperature, grindability, and agglomerating characteristics. For further details about these factors, readers should consult references that specialize in solid fuels.

The above warnings are doubly important when dealing with by-product and waste materials as fuels. It is best to construct some sort of pilot plant to test the burning characteristics of an actual sample of the waste. A competent testing organization should be employed to analyze the waste material and evaluate the properties mentioned above. It must be realized that the analysis and properties of wastes will vary from one source to the next and from time to time for the same source. Because information on waste materials is so difficult to find, Table 2.2 is offered as a rough guide—for preliminary evaluations only.

PROPERTIES OF LIQUID FUELS

Chemical Analysis. Most liquid fuels are petroleum derivatives consisting of mixtures of hydrocarbon compounds. Chemical analysis of the compounds which comprise these mixtures is very difficult; so it is common practice to make an *ultimate* chemical analysis or several physical measurements instead. An ultimate chemical analysis lists the percentages (by weight) of the various chemical elements in the fuel. See Table 2.1a. From a theoretical point of view, a knowledge of percent carbon and hydrogen is useful in determining combustion air requirements and flue gas analysis. See Table 2.1b. The type or grade of an oil cannot be determined from the ultimate analysis alone. Most fuel oils contain 83 to 88% carbon and 6 to 12% hydrogen by weight.

Because all fuel oils are so similar in chemical analysis, and because the physical properties have far greater effect on the operation of fuel burning equipment, the physical properties are much more commonly measured and specified by oil producers. The physical measurements of most significance to the combustion engineer are discussed in the following paragraphs.

Small letters refer to references at end of Part 2.

Table 2.2. Approximate properties of some by-product and waste fuels. Different moisture contents may change these values considerably. Data courtesy of Reference 2.b and 2.a$_1$.

By-product or waste	% Ash/ Moisture	Density		Gross Heat Value	
		lb/ft^3	kg/m^3	Btu/lb	kcal/kg
Animal fats		50-60	801-961	17 000	9·445
Benzene, Benzol	0.5/0	55	881	18 210	10 120
Brown paper	1.0/6	7	112	7 250	4 028
Citrus rinds	0.75/7.5	40	641	1 700	945
Coated milk cartons	1.0/3.5	5	80	11 330	6 295
Coffee grounds	2/20	25-30	400-481	10 000	5 556
Corn cobs	3/5	10-15	160-240	8 000	4 445
Corrugated boxes	5/5	7	112	7 040	3 911
Cotton seed hulls	2/10	25-30	400-481	8 600	4 778
Latex	0/0	45	721	10 000	5 556
Leather	2.1/7.5	20	320	7 250	4 028
Linoleum		90	1442	11 000	6 112
Lubricants, spent				12 000	6 667
Magazines	22.5/5	35	561	5 250	2 917
Naphtha	0/0	41	641	15 000	8 335
Newspapers	1.5/6	7	112	7 975	4 431
Paint				8 000	4 445
Paper, sulfite (44% C, 6% H)	1/0			7 590	4 217
Polyethylene	0/0	40-60	641-961	20 000	11 112
Polyurethane (foamed)	0/0	2	32	13 000	7 223
Rags (silk and wool)	2/5	10-15	160-240	8 500	4 723
Rags (cotton and linen)	2/5	10-15	160-240	7 200	4 000
Refinery gas				21 800	12 112
Rice hulls				5 900	3 278
Rubber waste	20-30/	62-125	993-2000	10 000	5 556
Sludge, industrial				3 950	2 195
Solvents, dirty				13 000	7 223
Toluene, Toluol	0.5/0	53.6	859	18 440	10 247
Waste, Type 0, trash (highly combustible paper, carboard, wood boxes, sweepings; up to 10% plastics and rubber)	5/10	8-10	128-160	8 500	4 723
Waste, Type 1, rubbish (combustible paper, carboard, wood, foliage, sweepings; up to 20% food waste; no plastic/rubber)	10/25	8-10	128-160	6 500	3 611
Waste, Type 2, refuse (even mix of rubbish and garbage)	7/50	15-20	240-320	4 300	2 389
Waste, Type 3, garbage (animal and vegetable food wastes)	5/70	30-35	481-561	2 500	1 389
Waste, Type 4, pathological (human and animal remains)	5/85	45-55	721-881	1 000	556
Waste, Type 6, compact (documents, rubber, plastic, wood)		35-50	561-801	7 500	4 167
Wood bark	3/10	12-20	192-320	9 000	5 000
Wood sawdust and shavings	3/10	10-12	160-192	8 500	4 723

Gravity. This property of liquid fuels is similar to density and specific weight. It is specified by a number of different scales of units, the most common of which are degrees API (American Petroleum Institute) and weight relative to water when both the oil and the water are at 60 F (abbreviated "sp gr 60/60 F" or simply "sg"). The API scale replaces the similar Baumé scale (abbreviated °Bé) originally introduced because it gave a linear scale on a hydrometer, an instrument used for measuring specific gravity. At 60 F (15.6 C), the specific weight of water is 62.3 lb/ft³, 8.34 lb/US gallon, or 1000 kg/m³; the specific gravity of water is 1.0, the API gravity of water is 10.0°. The relationships between these various units are given by the following formulas:

$$[2/5] \quad \text{sp gr } 60/60\text{ F} = \frac{141.5}{°\text{API} + 131.5} \text{ where °API is measured at 60 F (15.6 C)}$$

$$[2/6] \quad \text{sp gr } 60/60\text{ F} = \frac{140}{°\text{Bé} + 130} \text{ where °Bé is measured at 60 F (15.6 C)}$$

$$[2/7] \quad \text{sp gr } 60/60\text{ F} = \frac{\text{lb/ft}^3}{62.3} \text{ where lb/ft}^3 \text{ is measured at 60 F (15.6 C)}$$

$$[2/8] \quad \text{sp gr } 60/60\text{ F} = \frac{\text{lb/gal}}{8.34} \text{ where lb/gal is measured at 60 F (15.6 C)}$$

Table 2.3 facilitates conversions between some of these scales, and lists other properties calculated from gravity.

The specific gravities of liquid fuels change with their temperature due to thermal expansion (as temperature increases) and contraction (as temperature decreases). Whenever a specific gravity is specified (in any scale) the temperature at which it was measured should also be specified. If no temperature is given, it is assumed to be 60 F. Table 2.4 lists the coefficients of thermal expansion for petroleum oils, and Table 2.3 lists the change in API gravity per degree Fahrenheit change above or below 60 F. (Note: API gravity rises as temperature rises, and falls as temperature falls.)

Example 2-1. An oil has a gravity of 40°API at 60 F. What is the gravity of this oil when heated to 100 F?

From Table 2.3 or formulas 2/5 and 2/8, 40°API is equivalent to 6.88 lb/gal. The coefficient of expansion can only be applied to volumes; so it is necessary to find the reciprocal of specific gravity which is specific volume, $\frac{1}{6.88 \text{ lb/gal}} = 0.145$ gal/lb.

Now applying the coefficient from Table 2.4, $0.145 \text{ gal/lb} \times 0.00050/°\text{F} \times (100 - 60)°\text{F} = 0.0029$ gallons expansion per lb. The new volume per pound is therefore $0.145 + 0.0029 = 0.148$ gal/lb. Again taking the reciprocal, $\frac{1}{0.148 \text{ gal/lb}} = 6.76$ lb/gal.

From Table 2.3 or formulas 2/8 and 2/5, this is equivalent to 42.9°API.

Table 2.3. Gravities and related properties of liquid petroleum products
(See Examples 2-1, 2-2, 2-3, and formulas 2/5 through 2/15)

typical of	°API	sp gr 60F/60F (15.6C/15.6C)	lb/gal	*kg*/m^3	gross Btu*/gal	gross *kcal**/*L*	% H, wt*	net Btu*/gal	net *kcal**/*L*	sp ht @40F	sp ht @300F	Temp corrn °API/°F*	ft^3 60F air/gal	ult % CO_2
	0	1.076	8.969	*1075*	160 426	*10 681*	8.359	153 664	*10 231*	0.391	0.504	0.045	1581	—
	2	1.060	8.834	*1059*	159 038	*10 589*	8.601	152 183	*10 133*	0.394	0.508	—	—	—
	4	1.044	8.704	*1043*	157 692	*10 499*	8.836	150 752	*10 037*	0.397	0.512	—	—	18.0
	6	1.029	8.577	*1028*	156 384	*10 412*	9.064	149 368	*9 945*	0.400	0.516	0.048	1529	17.6
	8	1.014	8.454	*1013*	155 115	*10 328*	9.285	148 028	*9 856*	0.403	0.519	0.050	1513	17.1
	10†	1.000†	8.335†	*1000*†	153 881	*10 246*	10.00	146 351	*9 744*	0.406	0.523	0.051	1509	16.7
#6 oil	12	0.986	8.219	*985.0*	152 681	*10 166*	10.21	145 100	*9 661*	0.409	0.527	0.052	1494	16.4
	14	0.973	8.106	*971.5*	151 515	*10 088*	10.41	143 888	*9 580*	0.412	0.530	0.054	1478	16.1
	16	0.959	7.996	*958.3*	150 380	*10 013*	10.61	142 712	*9 502*	0.415	0.534	0.056	1463	15.8
#5	18	0.946	7.889	*945.5*	149 275	*9 939*	10.80	141 572	*9 426*	0.417	0.538	0.058	1448	15.5
	20	0.934	7.785	*933.0*	148 200	*9 867*	10.99	140 466	*9 353*	0.420	0.541	0.060	1433	15.2
	22	0.922	7.683	*920.9*	147 153	*9 798*	11.37	139 251	*9 272*	0.423	0.545	0.061	1423	14.9
#4	24	0.910	7.585	*909.0*	146 132	*9 730*	11.55	138 210	*9 202*	0.426	0.548	0.063	1409	14.7
	26	0.898	7.488	*897.5*	145 138	*9 664*	11.72	137 198	*9 135*	0.428	0.552	0.065	1395	14.5
	28	0.887	7.394	*886.2*	144 168	*9 599*	11.89	136 214	*9 069*	0.431	0.555	0.067	1381	14.3
#2	30	0.876	7.303	*875.2*	143 223	*9 536*	12.06	135 258	*9 006*	0.434	0.559	0.069	1368	14.0
	32	0.865	7.213	*864.5*	142 300	*9 475*	12.47	134 163	*8 933*	0.436	0.562	0.072	1360	13.8
	34	0.855	7.126	*854.1*	141 400	*9 415*	12.63	133 259	*8 873*	0.439	0.566	0.074	1347	13.6
#1	36	0.845	7.041	*843.9*	140 521	*9 356*	12.78	132 380	*8 814*	0.442	0.569	0.076	1334	13.4
	38	0.835	6.958	*833.9*	139 664	*9 299*	12.93	131 524	*8 757*	0.444	0.572	0.079	1321	13.3
	40	0.825	6.877	*824.2*	138 826	*9 243*	13.07	130 689	*8 702*	0.447	0.576	0.082	1309	13.1
	42	0.816	6.798	*814.7*	138 007	*9 189*	—	—	—	0.450	0.579	0.085	—	13.0
	44	0.806	6.720	*805.4*	137 207	*9 136*	—	—	—	0.452	0.582	0.088	—	12.8

* For gravity measured at 60 F (15.6 C) only.

† Same as H_2O.

Table 2.4. Coefficients of thermal expansion for petroleum oils
(See Examples 2-1 and 2-2)

°API at 60 F (15.6 C)	Specific gravity (60/60 F) (15.6/15.6 C)	Specific volume, gallons per lb	*Specific volume, litres/kg*	Coefficient (per F)	*Coefficient (per C)*
Below 14.9	Above 0.9665	Below 0.124	*Below 1.036*	0.000 35	*0.000 63*
15.0 - 34.9	0.8504 - 0.9659	0.1411 - 0.1242	*1.178 - 1.036*	0.000 40	*0.000 72*
35.0 - 50.9	0.7758 - 0.8504	0.1547 - 0.1411	*1.291 - 1.178*	0.000 50	*0.000 90*
51.0 - 63.9	0.7242 - 0.7753	0.1657 - 0.1547	*1.383 - 1.291*	0.000 60	*0.001 08*
64.0 - 78.9	0.6725 - 0.7238	0.1784 - 0.1658	*1.489 - 1.384*	0.000 70	*0.001 26*
79.0 - 88.9	0.6420 - 0.6722	0.1869 - 0.1785	*1.560 - 1.490*	0.000 80	*0.001 44*
89.0 - 93.9	0.6278 - 0.6417	0.1911 - 0.1870	*1.595 - 1.561*	0.000 85	*0.001 53*
94.0 - 100.0	0.6112 - 0.6275	0.1963 - 0.1912	*1.638 - 1.596*	0.000 90	*0.001 62*

Example 2-2. An oil with a specific gravity (at 60/60 F) of 0.91, and with a gross heating value of 146 000 Btu/gal at 60 F, is to be heated to 168 F. Find the specific gravity, lb/gal, and Btu/gal at 168 F.

First, find the lb/gal and specific weight (density) at 60 F. From Table 2.3 or formula 2/8, lb/gal = 7.585. The density of water at 60 F is 62.35 lb/ft^3 and specific gravity is 0.91 relative to water; so, by formula 2/7, the density of the oil at 60 F is 0.91 × 62.35 = 56.74 lb/ft^3. Taking the reciprocal of this, the specific volume at 60 F is 0.0176 ft^3/lb. Applying the appropriate coefficient from Table 2.4, the expansion is 0.0176 ft^3/lb × 0.00040/°F × (168 − 60)°F = 0.00076 ft^3/lb, and the specific volume at 168 F will be 0.0176 + 0.00076 = 0.01836 ft^3/lb. The density will be the reciprocal, $\frac{1}{0.01836 \text{ ft}^3/\text{lb}}$ = 54.47 lb/ft^3 at 168 F. The specific gravity at 168 F will be $\frac{54.47 \text{ lb/ft}^3}{62.35 \text{ lb/ft}^3} = 0.8736$.

By Table 2.3 or formula 2/8, this is equivalent to 7.28 lb/gal at 168 F, whereas the oil weighed 7.59 lb/gal at 60 F. The heating value of a gallon of 168 F oil is therefore reduced to $\frac{146\ 000 \text{ Btu}}{60 \text{ F gal}} \times \frac{7.283 \text{ lb/168 F gal}}{7.585 \text{ lb/60 F gal}} = 140\ 187$ Btu/gal.

Fortunately the simple measurement of specific gravity is the key to a number of other important properties of petroleum oils. Relationships between some of these other properties and the specific gravity (abbreviated *sp gr*) are given in formulas 2/9 through 2/15. These relationships are empirical generalizations and should therefore be resorted to only when more specific data are not available. Different crude sources and refining methods may cause deviations from the values obtained by these formulas.

[2/9] gross heating value, GHV[1], in Btu/lb = 17 887 + (57.5 × °API) − (102.2 × %S)

or GHV[1], in kcal/kg = $5\ 738 + \frac{4521}{\text{sp gr}} - 56.8 \times \%\text{S}$

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[1] Constant volume combustion. See also the footnote on p 24.

[2/10] $$\%\text{ hydrogen, by weight} = F - \frac{2122.5}{°\text{API} + 131.5}$$

$$\begin{aligned} \text{where } F &= 24.50 \text{ for } 0 \leqslant °\text{API} \leqslant 9 && (1.076 \geqslant \text{sp gr} \geqslant 1.007) \\ F &= 25.00 \text{ for } 9 < °\text{API} \leqslant 20 && (1.007 > \text{sp gr} \geqslant 0.934) \\ F &= 25.20 \text{ for } 20 < °\text{API} \leqslant 30 && (0.934 > \text{sp gr} \geqslant 0.876) \\ F &= 25.45 \text{ for } 30 < °\text{API} \leqslant 40 && (0.876 > \text{sp gr} \geqslant 0.825) \end{aligned}$$

[2/11] $$\text{net heating value, NHV}^1\text{, in Btu/lb} = \text{GHV in Btu/lb} - 91.23 \times \%\text{H}$$
$$\text{or NHV}^1\text{, in kcal/kg} = \text{GHV in kcal/kg} - 50.70 \times \%\text{H}$$

[2/12] $$\text{specific heat, c (in Btu/lb °F or kcal/kg °C)} = \frac{0.388 + [0.00045 \times (\text{temp, F})]}{\sqrt{\text{sp gr}}}$$

[2/13] $$\text{latent heat of vaporization, in Btu/lb} = \frac{110.9 - [0.09 \times (\text{temp, F})]}{\text{sp gr}}$$
$$\text{or, in kcal/kg} = \frac{60.02 - [0.09 \times (\text{temp, C})]}{\text{sp gr}}$$

[2/14] $$\text{ft}^3 \text{ air reqd/gal} = [25.1 \times (\text{sp gr}) \times \%\text{H}] + [1260 \times (\text{sp gr})]$$
$$\text{or m}^3 \text{ air reqd/kg} = (0.188 \times \%\text{H}) + 9.43$$

[2/15] temp correction, add °API/°F
$$= (°\text{API} + 131) \times (\text{coefficient of thermal expansion/°F, from Table 2.4})$$
$$\text{or sp gr at } T_2 = \frac{\text{sp gr at } T_1}{1 + (T_2 - T_1) \times (\text{coeff. of th. exp. from Table 2.4})}$$

All of the above formulas are for pure hydrocarbon fuels containing no impurities. Most commercial fuels contain such a small percentage of impurities, however, that the above relationships may be safely applied. Table 2.3 lists some values calculated by formulas 2/9 through 2/15.

Formula 2/12 above is a generalization for the specific heat of all oils. A more specific expression could be written for oils from a limited area. Table 2.5 lists the heat contents (in Btu/gallon) for oils at various temperatures and gravities.

Example 2-3. A fuel oil has an API gravity of 24 degrees measured at 60 F. Determine the number of pounds per gallon at 60 F and at 200 F. Also find the net Btu/gallon and the cubic feet of air required per gallon at 60 F and at 200 F.

Using Table 2.3, read the following information: 7.585 lb/gal, 0.063°API per °F, 1409 ft³ air/gal, and 138 210 net Btu/gal. All this information applies at 60 F only.

---

[1] Constant pressure combustion—the type encountered in industrial heating, but since the heating value for constant volume combustion, as in a gasoline engine, is much more easily measured, it is used more widely. The difference between these two values is very small, and is usually neglected. See Part 1 for an explanation of difference between gross and net heating values.

The "temperature correction" means that an oil whose API gravity is 24° at 60 F increases in API gravity by 0.063° for every degree Fahrenheit rise above 60 F. At 200 F, the API gravity will therefore be 24 + [0.063 × (200 − 60)] = 24 + 8.8 = 32.8°API.

Interpolating in Table 2.3 at 32.8°API, this is found to be equivalent to 7.178 lb/gal. To determine the net Btu/gal and the air required per gallon of 200 F oil, it is necessary to make the following corrections:

$$138\ 210 \text{ net Btu/gal} \times \frac{7.178 \text{ lb/gal (at 200 F)}}{7.585 \text{ lb/gal (at 60 F)}} = 130\ 794 \text{ net Btu/gal of 200 F oil;}$$

$$1\ 434 \text{ ft}^3 \text{ air/gal} \times \text{(same factor)} = 1\ 357 \text{ ft}^3 \text{ air/gal of 200 F oil.}$$

Both of the above calculations apply to gallons of oil measured at 200 F. Those corrections are unnecessary if the oil is metered at 60 F. For correction of air volumes for temperature, see column 4 of Table A.2 in the Appendix. The heating value and air requirement at elevated temperature cannot be read directly opposite the gravity at the elevated temperature in Table 2.3 because the 60 F gravity is the key to the oil composition, and composition does not change with temperature as gravity does.

Example 2-4. A #6 fuel oil of 15°API gravity is to be heated (for pumping) from 32 to 138 F in a tank suction heater using 10 psig dry saturated steam, and from 120 to 295 F (for atomization) by electric booster heaters at the furnaces. (Heat loss from the insulated pipes causes the temperature to drop from 138 to 120 F between the tank and furnaces.)

(a) If the flow through the tank heater is 150 gph, how much steam will be condensed?

Interpolating in the second column of Table 2.5, $\frac{138 - 120}{140 - 120} \times (378 - 305) + 305 = 371$ Btu/gal (which checks Table 2.10b).

From Table A.4a, the latent heat of 10 psig steam is 952.7 Btu/lb; so the steam consumption will be 371 Btu/gal × 150 gal/hr ÷ 952.7 Btu/lb = 58.4 lb/hr.

(b) If the maximum flow to a furnace is 12 gph, what kW heater capacity is required, assuming 10% loss (90% efficiency)?

From Table 2.5, the heat content of the liquid oil at 120 F, is 305 Btu/gal; at 295 F, is 996 Btu/gal (which checks Table 2.10b). Applying the conversion factor, 1kW hr = 3413 Btu, from Table C.6 in the Appendix, the kW requirement is then

$$\frac{(996 - 305) \text{ Btu output/gal} \times 12 \text{ gal/hr}}{3413 \text{ Btu/kW hr} \times 0.90 \text{ output/input}} = 2.70 \text{ kW input.}$$

Viscosity. The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity is the opposite of fluidity. A high viscosity oil approaches the solid state and will not flow easily, whereas a low viscosity oil flows readily. The higher the viscosity of an oil, the higher are the costs of pumping it, and the more difficult it is to atomize.

Viscosity is measured by timing the flow by force of gravity of a test sample through a capillary restriction at a controlled temperature. Since the rate of flow depends upon the density of the oil as well as the viscosity, these measurements are termed **kinematic viscosity**. The **absolute viscosity** is obtained by multiplying the kinematic viscosity by the density of the fluid. A great many different sets of viscosity units are in use. Table 2.6 is a list of conversion factors for various viscosity scales used for fuel oils. Figure 2.7 shows a graphical comparison of some of these scales.

As the temperature of an oil is raised, its viscosity is reduced and it flows more readily. Hence heavy oils are often heated before being pumped into

Table 2.5. Heat contents of various oils* (See Example 2-4)

Heat content in Btu/gallon	**Gravity, °API at 60 F (15.6 C)**							
of liquid / **vaporized**	10	15	20	25	30	35	40	45
	Specific gravity, 60 F/60 F							
Temperature, F	1.0000	0.9659	0.9340	0.9042	0.8762	0.8498	0.8251	0.8017
32	0	0	0	0	0	0	0	0
	0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
60	95	93	92	90	89	87	86	85
								965
100	237	233	229	226	222	219	215	
							1065	**1062**
120	310	305	300	295	290	286	281	
							1116	**1112**
140	384	378	371	366	360	355	349	
							1169	**1164**
160	460	453	445	438	431	425	418	
					1236		**1223**	**1217**
180	538	529	520	511	503	496	488	
					1293		**1278**	**1272**
200	617	607	596	587	577	569	560	
			1371		**1352**		**1335**	**1327**
220	697	686	674	663	652	643	633	
			1434		**1412**		**1393**	**1384**
240	779	766	753	741	729	718	707	
			1498		**1474**		**1452**	**1442**
260	862	848	833	820	807	795	783	
			1563		**1537**		**1513**	**1502**
300	1034	1017	999	984	968	954	939	
			1699		**1668**		**1639**	**1626**
400	1489	1463	1439	1416	1393	1372	1352	1333
		2088	**2064**	**2041**	**2018**	**1997**	**1977**	**1958**
500	1981	1947	1914	1884	1854	1826	1799	1774
		2497	**2464**	**2434**	**2404**	**2376**	**2349**	**2324**
600	2511	2467	2426	2387	2350	2314	2281	2248
		2942	**2901**	**2862**	**2825**	**2789**	**2756**	**2723**
700	3078	3025	2974	2927	2881	2837	2796	2756
	3478	**3425**	**3374**	**3327**	**3281**	**3237**	**3196**	**3156**
800	3683	3619	3559	3502	3447	3395	3345	3297
	4008	**3944**	**3884**	**3827**	**3772**	**3720**	**3670**	**3622**

* See Reference 2.c in the list of references at the end of Part 2.

delivery lines. Figure 2.8 shows how temperature affects the viscosity of some typical fuel oils. Figure 2.8 is plotted on special graph paper prepared by the American Society for Testing and Materials. If the viscosity of a particular oil is known at two different temperatures, a straight line may be drawn between these known points on this special graph paper to obtain the viscosity-temperature characteristics of that oil. Table 2.10a gives some useful viscosity and temperature information for typical oils.

Example 2-5. The oil of Example 2-2 is to be heated to 168 F to reduce its viscosity to 100 SSU. Find its absolute viscosity in centipoise and in pounds mass/hr ft at 168 F.

From Figure 2.7 or formula 2/31, 100 SSU is found equivalent to 20.65 centistokes. In Example 2-2, the specific gravity of the oil at 168 F was 0.873. Applying formula 2/16, the absolute viscosity in centipoise is 20.65 × 0.873 = 18.03 cp.

The absolute viscosity in lb/hr ft can be calculated by formula 2/22: 18.03 cp ÷ 0.413 = 43.7 lb/hr ft. Another method is by formula 2/28 and formula 2/17: 20.65 cs ÷ 25.81 = 0.800 ft^2/hr; then 0.800 ft^2/hr × 54.47 lb/ft^3, the specific weight from Example 2-2, = 43.6 lb/hr ft.

Certain ranges of viscosity have been found best for pumping and for atomization of fuel oils. These ranges are shown as shaded areas on Figure 2.8. Table 2.10a provides a convenient way to find the oil temperature required to attain these viscosities. The affect of viscosity on oil atomization is an important consideration for clean, complete combustion. Good combustion depends on properly atomized oil intimately mixed with air. With low pressure air atomizing burners, an oil viscosity higher than the 70 to 100 SSU range tends to produce oil droplets too large for intimate air and oil mixing and that encourages carbon formation in burner blocks and furnaces. Since the heavy oils tend to carbonize more readily than light oils, good atomization is doubly important for these more viscous oils. Another important consideration is the fact that viscosity variations affect fluid flow through orifices or valves in such a way as to upset controlled air/oil ratios. The degree of oil preheating must be determined by the viscosity required for reliable control and clean combustion. See Tables 2.10a and 2.10b.

Example 2-6. The viscosity of an oil has been measured as 75 SSF at 122 F and 1530 SSU at 100 F.

(a) If this oil is to be burned in a burner whose atomizer requires 100 SSU, to what temperature must it be heated?

Following the horizontal arrows on Figure 2.8, locate the two test measurement points. A line drawn between these points (diagonal dashed arrows) represents the loci of viscosity-temperature conditions for this particular oil. Extending the line until it intersects the horizontal 100 SSU line, read 209 F as the oil temperature required for atomizing.

(b) What temperature range is recommended for this oil for easy pumping? The diagonal dashed arrows on Figure 2.8, from Example 2-6a, intersect the upper and lower extremes of the "easy pumping" viscosity band at 72 F and 93 F; so the thermostat for the heater at the tank should be set in this range.

Table 2.6. Formulas for conversion of viscosity units (See Example 2-5)

μ and ν formulas

[2/16] abs visc in cp = kin visc in cs × specific gravity
[2/17] abs visc in #m/sec ft = kin visc in ft^2/sec × mass density in #m/ft^3
[2/18] abs visc in #f sec/ft^2 = kin visc in ft^2/sec × (mass density in #m/ft^3) ÷ 32.17

μ, absolute viscosity units

[2/19] 1 #f sec/ft^2 = 32.17 #m/sec ft
[2/20] 1 poise = 100 cp = 1 dyne · s/cm^2† = 1 g/s · cm
[2/21] 1 #m/sec ft = 1488 cp = 1.488 Pa · s
[2/22] 1 #m/hr ft = 0.413 cp = 1.488 kgm/hr · m
[2/23] 1 #m/sec in. = 17 850 cp = 178.5 poise
[2/24] 1 #f sec/ft^2 = 47 850 cp = 0.4883 kgf · s/m^2
[2/25] 1 #f hr/ft^2 = 172 260 000 cp = 0.4883 kgf · hr/m^2
[2/26] 1 #f sec/in.^{2} = 6 890 000 cp = 1 Reyn

ν, kinematic viscosity units

[2/27] 1 ft^2/sec = 92 900 cs = 0.0929 m^2/s
[2/28] 1 ft^2/hr = 25.81 cs = 0.0929 m^2/hr
[2/29] 1 in.^{2}/sec = 645.2 cs = 0.000 645 m^2/s
[2/30] 1 stoke = 100 cs = 0.000 1 m^2/s
[2/31] kin visc in centistokes = (0.266 × SSU) − (195/SSU), for SSU 32 to 100
[2/32] kin visc in centistokes = (0.220 × SSU) − (135/SSU), for SSU >100
[2/33] kin visc in centistokes = (2.24 × SSF) − (184/SSF), for SSF 25 to 40
[2/34] kin visc in centistokes = (2.16 × SSF) − (60/SSF), for >40
[2/35] kin visc in centistokes = (0.26 × SR1) − (179/SR1), for SR1 34 to 100
[2/36] kin visc in centistokes = (0.247 × SR1) − (50/SR1), for SR1 >100
[2/37] kin visc in centistokes = (8.0 × °E) − (8.64/°E), for °E 1.35 to 3.2
[2/38] kin visc in centistokes = (7.6 × °E) − (4.0/°E), for °E >3.2

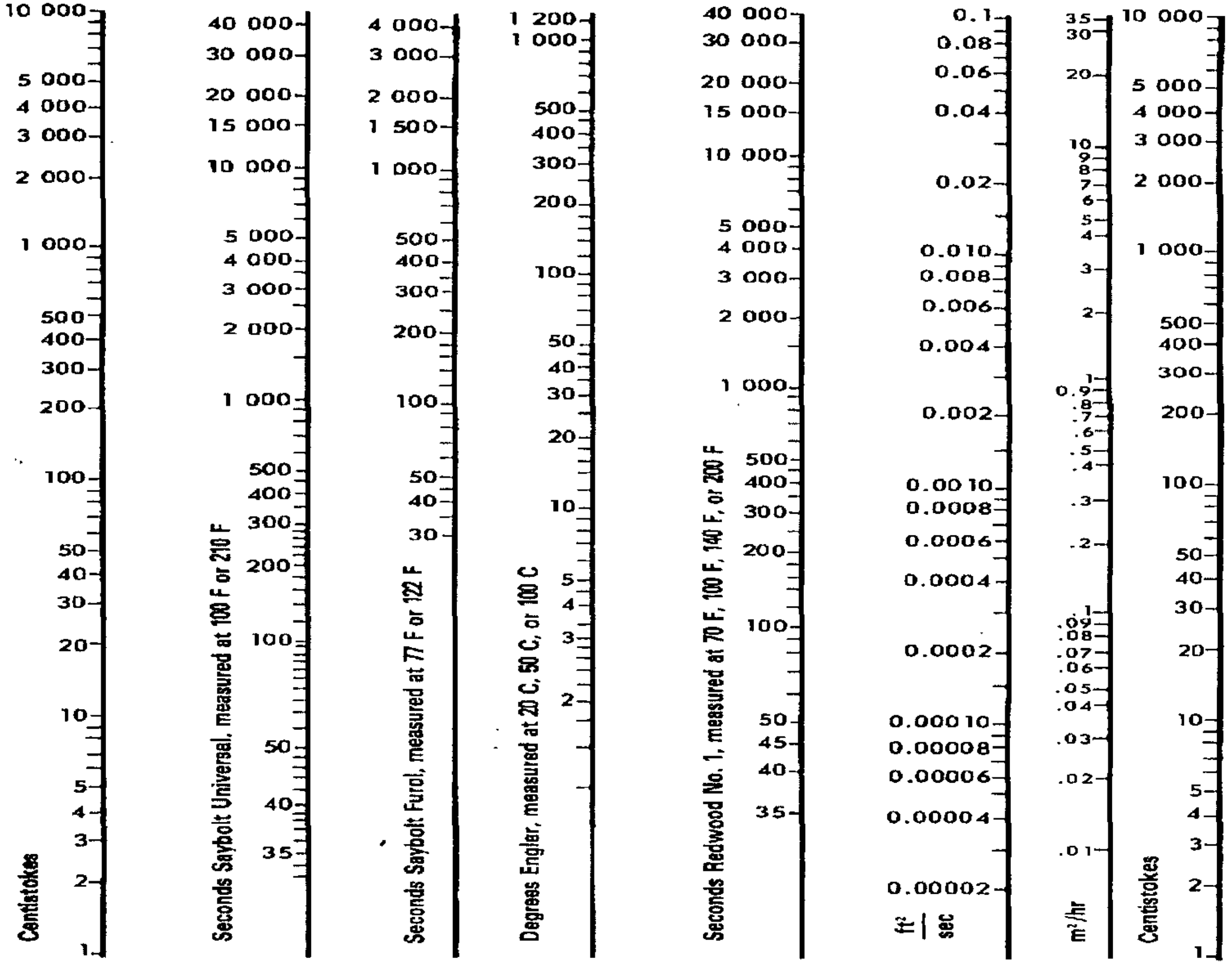
definitions

abs visc is absolute viscosity, μ; kin visc is kinematic viscosity, ν
cp is centipoise (abs visc); cs is centistokes (kin visc)
specific gravity is relative to water, = (mass density in #m/ft^3) ÷ 62.35
#m is pounds mass; #f is pounds force
kgm = kilograms mass; kgf = kilograms force
SSU is kinematic viscosity in seconds, Saybolt Universal
SSF is kinematic viscosity in seconds, Saybolt Furol
SR1 is kinematic viscosity in seconds, Redwood No. 1 (or Redwood Standard)
°E is kinematic viscosity in degrees Engler, 1 °E = 51.28 seconds Engler

	Water*	Air	Nat'l Gas
At 60 F & 14.7 psia, 15.6 C & 760 mm Hg	μ = 1.124 cp	μ = 0.0180 cp	μ = 0.011 cp
	= 2.72 #m/hr · ft	= 0.0436 #m/hr · ft	= 0.0266 #m/hr · ft
	= 2.349 × 10^{-5} #f · s/ft^2	= 3.763 × 10^{-7} #f · s/ft^2	= 2.30 × 10^{-7} #f · s/ft^2
	ν = 1.130 cs	ν = 14.69 cs	ν = 14.92 cs
	= 32 SSU	= 1.469 × 10^{-5} m^2/s	= 1.49 × 10^{-5} m^2/s
	= 0.04378 ft^2/hr	= 0.5691 ft^2/hr	= 0.578 ft^2/hr

* Approximate viscosity of water at 70 F (21 C) is 1 cp and 1 cs.
† A dot between symbols means "times" or "multiply by".

Figure 2.7. Alignment chart for comparing viscosity scales at the same temperature. Use a straightedge to read horizontally across all scales—far left and far right scales are identical. See Example 2-5 and Table 2.6.



Distillation Test. This test evaluates the distillation range of a fuel as to initial boiling point (temperature), end point, and some intermediate points, such as the 10% and 90% points. (The 10% point is the temperature at which 10% of the initial volume has distilled off.) The test is run with specified standard equipment and technique, to obtain comparable and reproducible results. Only light oils are subjected to this test because heavy oils crack before they reach their boiling points. Low initial and 10% points indicate a possibility of vapor lock in heaters. High 90% and end points suggest the possibility of residues and droplet deposits. Table 2.10b lists distillation ranges of some typical fuels.

Figure 2.8. Viscosity-temperature relations for typical fuel oils. The diagonal lines are samples, not standards, for the designated grades of fuel oils. Source of the crude determines the slope of the line. This ASTM chart may be used for plotting properties of other fuel oils. See Example 2-6.

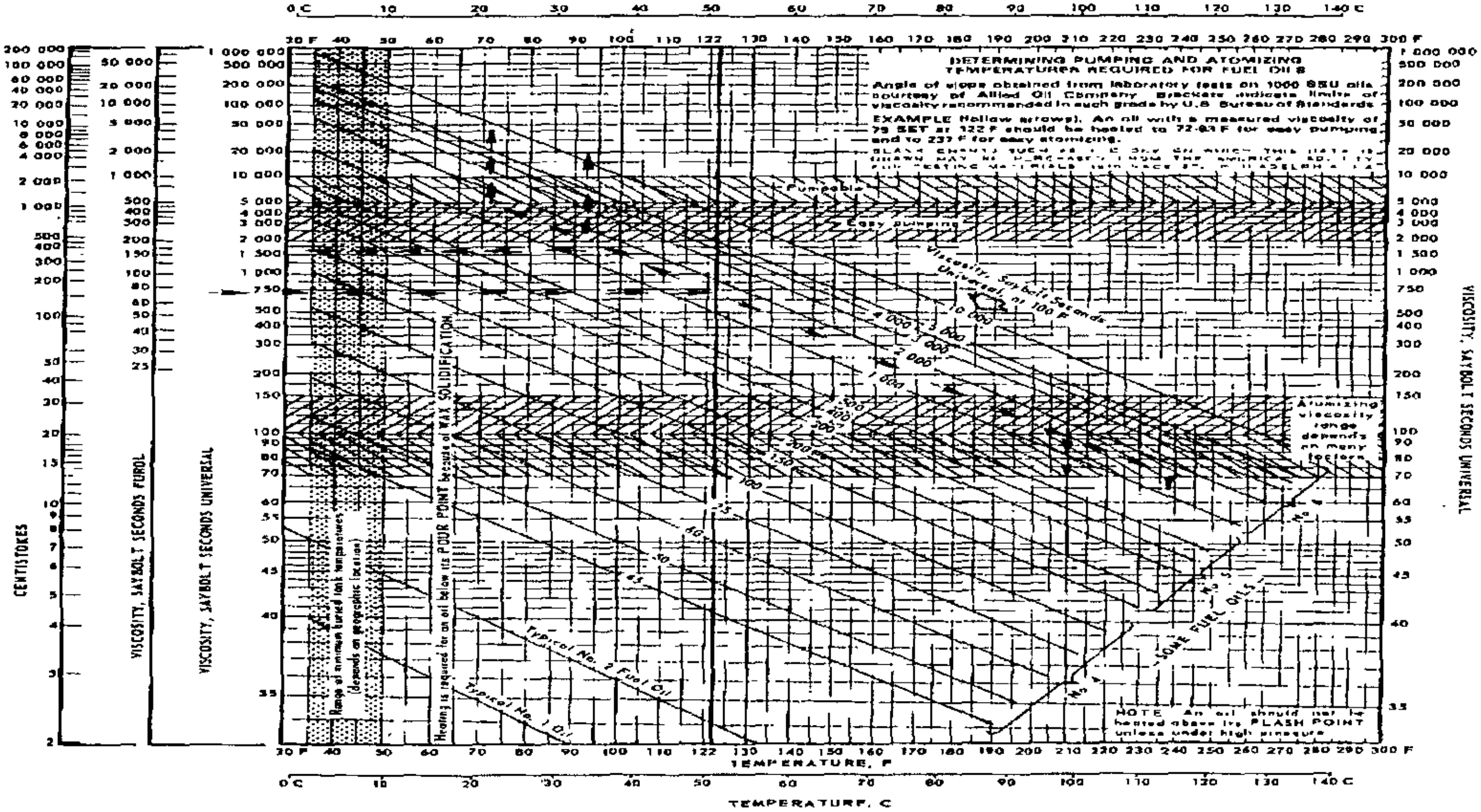


Table 2.9. Analyses and characteristics of selected fuel oils*

		Ultimate analysis (weight)						ppm	% wt	% wt	°API	Flash	HV, Btu/pound		Pour	Viscosity, SSU	
	Source	% C	% H	% N	% S	% ash	% O†	if > 50	Asphaltine	C residue	at 60 F	pt, F	gross	net	pt, F	at 140 F	at 210 F
Distillates	Alaska	86.99	12.07	0.007	0.31	<0.001	0.62	—	—	—	33.1	—	—	—	—	33.0	29.5
	California	86.8	12.52	0.053	0.27	<0.001	0.36	—	—	—	32.8	—	19 330	—	—	30.8	29.5
	West Texas	88.09	9.76	0.026	1.88	<0.001	0.24	—	—	—	18.3	—	—	—	—	32.0	28.8
Residuals	Alaska	86.04	11.18	0.51	1.63	0.034	0.61	50 Ni 67 V	5.6	12.9	15.6	215	18 470	17 580	38	1071	194
	California	86.66	10.44	0.86	0.99	0.20	0.85	‡	8.62	15.2	12.6	180	18 230	17 280	42	720	200
	DFM (shale)	86.18	13.00	0.24	0.51	0.003	1.07	—	0.038	4.1	33.1	182	19 430	18 240	40	36.1	30.7
	Gulf of Mexico	84.62	10.77	0.36	2.44	0.027	1.78	—	7.02	14.8	13.2	155	18 240	17 280	40	835	181
	Indo/Malaysia	86.53	11.93	0.24	0.22	0.036	1.04	101 V	0.74	3.98	21.8	210	19 070	17 980	61	199	65
	Middle East Δ	86.78	11.95	0.18	0.67	0.012	0.41	—	3.24	6.0	19.8	350	19 070	17 980	48	490	131.8
	Pennsylvania □	84.82	11.21	0.34	2.26	0.067	1.3	65 Na 82 V	4.04	12.4	15.4	275	18 520	17 500	66	1049	240
	Venezuela	85.24	10.96	0.40	2.22	0.081	1.10	52 Ni 226 V	8.4	6.8	14.1	210	18 400	17 400	58	742	196.7
	Venezuela desulfurized	85.92	12.05	0.24	0.93	0.033	0.83	101 V	2.59	5.1	23.3	176	18 400	17 300	48	113.2	50.5

* Largely from Reference 2.h at the end of Part 2.

† By difference.

‡ 91 Ca, 77 F_e, 88 Ni, 66 V.

Δ Exxon.

□ Amerada Hess.

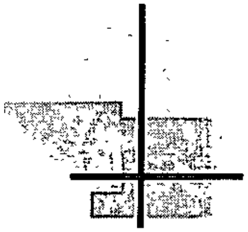


Table 2.10a. Viscosity-temperature information for selected fuel oils. The far right-hand columns list temperatures required to reduce the oil viscosity to levels often required for easy pumping (2000 SSU), and for atomization (100 SSU).

Fuel oil designation	Viscosity at 100 F, 38 C		Required oil temperature, F, C — Kinematic Viscosity 2000 SSU 440 cs		100 SSU 20.7 cs	
6 max	**10 000 SSU**	2200 cs	**138 F**	59 C	**265 F**	129 C
6 min	**1 000**	220	**82**	28	**195**	91
5 max	**750**	165	**72**	22	**182**	83
5 min	**150**	32.1	**20**	- 7	**122**	50
4 max	**100**	20.7	**2**	- 17	**100**	38
4 min	**45**	6.9	**- 75**	- 59	**27**	- 3
2 max	**38**	3.5	—		**2**	- 17

Table 2.10b. Heating requirements for products derived from petroleum (See also Table 2.5 and Example 2-4)

Commercial fuels	Specific gravity at 60/60 F (15.6 C)	Distillation range, F/C[e]	Vapor pressure[1] psia/mm Hg	Latent Btu/gal[2] to vaporize	Btu/gal[2] to heat from 32 F (0 C) to: Pumping temp[3]	Atomizing temp[3]	Vapor
No. 6 oil	0.965	600-1000/300-500	0.054/ 2.8	764	371	996	3619[4]
No. 5 oil	0.945	600-1000/300-500	0.004/ 0.2	749	133	635	3559[4]
No. 4 oil	0.902	325-1000/150-500	0.232/ 12	737	—	313	2725[4]
No. 2 oil	0.849	375- 750/150-400	0.019/ 1	743	—	—	2704[4]
Kerosene[f]	0.780	256- 481/160-285	0.039/ 2	750	—	—	1303[4]
Gasoline[f]	0.733	35- 300/ 37-185	0.135/ 7	772	—	—	1215[4]
Methanol[f]	0.796	148/ 64	4.62 / 239	3140	—	—	3400
Butane[g]	0.582	31/ 0	31/1604	808	—	—	976[5]
Propane[g]	0.509	-44/ -42	124/6415	785	—	—	963[5]

[1] At the atomizing temperature or 60 F, whichever is lower. Based on a sample with the lowest boiling point from column 3.

[2] To convert Btu/US gallon to kcal/litre, multiply by 0.666. To convert Btu/US gallon to Btu/pound, divide by 8.335 × sp gr, from column 2. To convert Btu/US gallon to kcal/kg, divide by 15.00 × sp gr, from column 2.

[3] See Table 2.10a.

[4] Calculated for boiling at mid-point of distallation range, from column 3.

[5] Includes latent heat plus sensible heat of the vapor heated from boiling point to 60 F (15.6 C).

Small letters refer to references at end of Part 2.

Flash and Fire Points. As fuel oil is heated, vapor collects above the liquid surface. If it becomes sufficiently concentrated, exposure to an open flame will result in a flash. The lowest temperature at which this occurs is called the *flash point*, determined by the closed cup (Pensky-Martens) test or the open cup (Cleveland) test. The open cup test readings are 20 to 30 degrees F higher than the closed cup readings for the same oils. The *fire point* determined with the above-mentioned open cup tester, is the temperature at which a flame is sustained for at least five seconds.

The flash and fire points indicate the extent of fractionation. They are of interest from the standpoints of safety and lighting characteristics. Although somewhat arbitrary, they serve to indicate the relative storage hazard of various fuels.

Carbon Residue. When an oil is evaporated, some free carbon may be left, sometimes formed by cracking during the evaporation process. The amount of carbon remaining indicates to some extent the tendency of the oil to carbonize under vaporizing conditions.

Carbon residue is measured by the Conradson test with an open flame or the Ramsbottom test heating through a molten bath. Results are not identical. Formulas are available, however, for converting the results from one test to the equivalent value of the other test. The tests are arbitrary; their value lies in showing the relative soot-forming potentials of oils. The carbon-forming possibilities should not be judged entirely from these tests, because carbonization is also influenced by burner design and operation.

Ash, %, is determined by burning off all the combustible material from a known weight of oil. The mineral matter remaining is the ash and usually consists of a minute quantity of mud or sand. Ash is not usually a problem in burners, but it can foul heat transfer surfaces, or melt and attack refractories.

Water and Sediment (bottom sediment and water, bsw) are determined by centrifuging 50 millilitres of fuel oil mixed with 50 millilitres of 90% benzol at 1400 to 1500 rpm and 120 F. The water and sediment are thrown to the bottom and measured. Any appreciable amount of water will cause discontinuous oil flames. Sediment tends to clog burners and control equipment.

Pour Point. If a sample of oil is gradually cooled, a temperature will ultimately be reached at which the oil will not flow—the **pour point**, mainly dependent on the amount and type of wax contained in the oil.

Standards. Table 2.11 compares some commercial and military standards for fuel oils, specified in terms of the above-mentioned physical properties. Some oil suppliers have established grades other than those listed.

Table 2.11. Comparison of various fuel oil specifications. Local legal limits may supersede these specifications.

		Flash point, F (C),	Pour point, F (C),	Water and sediment, % by volume,	Carbon residue on 10% bottoms, %,	Ash, % by weight,	Distillation temperatures, F (C) 10% point,	Distillation temperatures, F (C) 90% point,		Kinematic viscosity Saybolt seconds Universal at 100 F (38 C),		Kinematic viscosity Saybolt seconds Furol at 122 F (50 C),		Kinematic viscosity Centistokes at 100 F (38 C),		Kinematic viscosity Centistokes at 122 F (50 C),		Gravity, deg API,	Sulfur, %,
		min	max	max	max	max	max	min	max	min	max	min	max	min	max	min	max	min	max
ASTM[1] grades	No. 1	100 (38)	0 (- 18)	trace	0.15	—	420 (216)	—	550 (288)	—	—	—	—	1.4	2.2	—	—	35	0 5
	No. 2	100 (38)	20 (- 7)	0.05	0.35	—	—	540 (282)	640 (338)	32.6	37.91	—	—	2 0	3.6	—	—	30	0 5
	No. 4	130 (55)	20 (- 7)	0 50	—	0.10	—	—	—	45	125	—	—	5.8	26.4	—	—	—	—
	No. 5 (light)	130 (55)	—	1 00	—	0 10	—	—	—	150	300	—	—	32	65	—	—	—	—
	No. 5 (heavy)	130 (55)	—	1.00	—	0.10	—	—	—	350	750	23	40	75	162	42	81	—	—
	No 6	150 (65)	—	2.00	—	—	—	—	—	900	9000	45	300	198	1980	92	638	—	—
Pacific grades (1983)	PS 100	110	—	0 25	—	—	420 (216)	450 (232)	550 (288)	—	—	—	—	—	—	—	—	—	—
	PS 200	150 (65)	—	0.5	—	—	—	600 (316)	—	35	55	—	—	—	—	—	—	—	—
	PS 300	150 (65)	—	1.0	—	—	—	—	—	—	—	25	40	—	—	—	—	—	—
	PS 400	150 (65)	—	2.0	—	—	—	—	—	—	—	60	—	—	—	—	—	—	—
Military grades (1985)[3]	JP-4	—	—	—	—	—	—	470 (243)	—	—	—	—	—	—	—	—	—	45	0 4
	JP-5	140 (60)	—	—	—	—	400 (204)	440[4] (227)[4]	—	—	—	—	—	—	—	—	[2]	36	0.4

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[1] This is not a reproduction of ASTM specifications--merely a comparison of some aspects of the ASTM system with other grading systems. For complete ASTM specifications, purchase a copy of standard D396 form from: American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

[2] 16.5 centistokes at - 30 F (- 34 C).

[3] Includes many additional specifications applicable to use as an aircraft engine fuel.

[4] Typical, per Bowden and Brinkman: "Stability of Alternate Fuels", HYDROCARBON PROCESSING, July, 1980, pp. 77-82.

PROPERTIES OF GASEOUS FUELS

Gaseous fuels may be analyzed volumetrically in terms of the chemical compounds they contain. Other important properties of gaseous fuels are discussed below.

Gas Gravity (specific gravity) is a convenient measure of the density of a gas relative to that of air (0.0763 lb/ft^3 or 1.225 kg/m^3 at stp):

$$\text{[2/39]} \qquad \text{gas gravity} = \frac{\text{gas density}}{\text{air density}} = \frac{\text{gas density, lb/ft}^3}{0.0763} = \frac{\text{gas density, kg/m}^3}{1.222}$$

Heating Value. Although the heating value can be calculated from the gas analysis, it is frequently measured by means of a steady flow constant pressure calorimeter in which the gas is burned in a water-jacketed combustion chamber. The temperature rise of the water is a measure of the calorific value of the fuel. (Part 1 and the Glossary explain gross and net heating values.)

Heating values are expressed in Btu/ft^3 under specified conditions of moisture content, pressure, and temperature. The conditions are not too well standardized. Some gas companies correct all consumption figures to 6 osi gauge pressure, saturated, for billing. Tables A.2a and A.3 in the Appendix contain volume correction factors for temperature and pressure.

Example 2-7. A gas meter in the supply line to a furnace reads 1 219 507 ft^3 at 7 am and 1 224 443 ft^3 at 11 am, same day, at 18 osi and 80 F. If the gas is Pittsburgh natural gas, what was the average hourly Btu input during this period?

1 224 443 − 1 219 507 = 4936 ft^3 in 4 hours, or 4936/4 = 1234 ft^3/hr. From Table A.3 in the Appendix the factor for correcting to standard pressure is 1.0765; from Table A.2a, column 2, the factor for correcting to 60 F is 0.9634. Thus the gas consumption at stp is 1234 × 1.0765 × 0.9634 = 1280 ft^3/hr. From Table 2.12b, the gross heating value of Pittsburgh natural gas is 1129 Btu/ft^3 at stp. The average input rate is 1280 ft^3/hr × 1129 Btu/ft^3 = 1 445 000 Btu/hr.

Condensible Hydrocarbon Content. The terms *wet* and *dry* indicate whether natural gases contain more or less than 0.1 gallon of condensible hydrocarbons (usually natural gasoline) per 1000 ft^3 of gas.

Sulfur Content. The terms *sweet* and *sour* indicate a small or large proportion of hydrogen sulfide or other sulfur compounds.

Gaseous Fuels Data. Tables 2.12a, b, and c list properties of gaseous fuels. Example 2-8 illustrates conversion of combustion product data to another form.

Table 2.12a. Analyses of typical gaseous fuels

Type of Gas	Analysis % by Volume (mol %) CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO	H_2	CO_2	O_2	N_2
Acetylene, commercial			(97.1% C_2H_2, 2.5% C_3H_6O)					0.084	0.28
Blast furnace, B	—	—	—	—	22.7	2.3	19.3	0.7	55.0
Blast furnace, U	—	—	—	—	27.5	1.0	11.5	—	60.0
Butane, commercial, natural gas	—	—	6.0	70.7n- 23.3iso-	—	—	—	—	—
Butane, commercial, refinery gas	—	—	5.0	50.1n- 16.5iso-		(28.3% C_4H_8)			
Coke oven, R	28.3	3.4	0.2	—	4.2	50.6	0.9	1.6	10.8
Coke oven, U	29	3.3	(0.6 H_2S)		5.6	55.4	1.4	0.4	4.3
Digester (Sewage), Bergen, NJ	59.0	0.05	—	—	—	—	39.4	0.16	0.57
Digester (Sewage), Decatur, IL	68.0	—	—	—	—	2.0	22.0	—	6.0
Landfill, Cagistrio, '81	53.4	(other hydrocarbons 0.17)			0.005	0.005	34.3	0.05	6.2
Mapp	—	—	15.0	10.0	(66.0% C_3H_4, 9.0% C_3H_8)				
Natural, Alaska	99.6	—	—	—	—	—	—	—	0.4
Natural, Algeria LNG, Canvey	87.20	8.61	2.74	1.07	—	—	—	—	0.36
Natural, Gaz de Lacq	97.38	2.17	0.10	0.05	—	—	—	—	0.30
Natural, Groningen, Netherlands	81.20	2.90	0.36	0.14	—	—	0.87	—	14.40
Natural, Kuwait, Burgan	86.7	8.5	1.7	0.5n- 0.2iso-	—	—	1.8	—	0.6
Natural, Libya LNG	70.0	15.0	10.0	3.5	—	—	—	—	0.90
Natural, North Sea, Bacton	93.63	3.25	0.69	0.27	—	—	0.13	—	1.78
Natural, Birmingham, AL	90.0	5.0	—	—	—	—	—	—	5.0
Natural, East OH	94.1	3.01	0.42	0.28	—	0.01	0.71	0.01	1.41
Natural, Kansas City, MO	84.1	6.7	—	—	—	—	0.8	—	8.4
Natural, Pittsburgh, PA	83.4	15.8	—	—	—	—	—	—	0.8
Producer, Koppers-Totzek[1,3]		(0.02 cos, 0.28 H_2S)			58.7	32.9	7.0	—	1.1
Producer, Lurgi[2], commercial	5.8	(6.6 H_2O, 0.1 H_2S)			14.1	20.9	12.5	—	40.0
Producer, Lurgi[2], sub-bit.	10.2	(0.4 C_mH_n, 0.3 H_2S)			17.1	40.2	31.4	—	—
Producer, IGT[2], lignite	28.2	(2.1 C_mH_n, 0.4 H_2S)			19.5	24.5	24.6	—	0.6
Producer, BCR[2], West KY	15.6		(1.4 H_2S)		44.0	24.4	14.0	—	0.6
Producer, W-G, bituminous[2]	2.7	—	—	—	28.6	15.0	3.4	0.0	50.3
Producer, Winkler[2]	1	—	—	—	10	12	22	—	55
Propane, commercial, natural gas	—	2.2	97.3	0.5	—	—	—	—	—
Propane, commercial, refinery gas	—	2.0	72.9	0.8		(24.3% C_3H_6)			
Sasol, South Africa	28.0	—	—	—	22.0	48.0	1.0		
SNG, no methanation	79.3	—	—	—	1.2	19.0	0.5	—	—

[1] O_2-blown
[2] air-blown
[3] Illinois coal

Table 2.12b. Properties of gaseous fuels from Table 2.12a (See Example 2-7)

Type of Gas	Gas Gravity	Calorific Value at stp Btu/ft^3 Gross	Calorific Value at stp Btu/ft^3 Net	Calorific Value at stp *kcal/m^3 Gross*	Calorific Value at stp *kcal/m^3 Net*	Gross Btu/ft^3 of Std. Air	*Gross kcal/m^3 of Std. Air*
Acetylene, commercial	0.92	1492	1444	*13 280*	*12 850*	122.9	*1094*
Blast furnace, B	1.06	81	80	*720*	*711*	143.8	*1280*
Blast furnace, U	1.02	92	92	*819*	*815*	135.2	*1203*
Butane, commercial, natural gas	1.98	3219	2991	*28 640*	*26 615*	105.1	*935.1*
Butane, commercial, refinery gas	1.97	3170	2955	*28 200*	*26 289*	105.6	*939.9*
Coke oven, R	0.41	530	475	*4 713*	*4 229*	116.3	*1035*
Coke oven, U	0.36	554	497	*4 929*	*4 421*	115.3	*1026*
Digester (Sewage), Bergen, NJ	0.93	598	544	*5 322*	*4 841*	106.1	*944.2*
Digester (Sewage), Decatur, IL	0.77	695	632	*6 186*	*5 621*	106.2	*944.7*
Landfill, Cagistrio, '81	0.88	540	495	*4 804*	*4 404*	105	*934*
Mapp	1.48	2366	2242	*21 052*	*19 950*	111.4	*990.8*
Natural, Alaska	0.56	1009	917	*8 976*	*8 160*	106.0	*942.7*
Natural, Algeria LNG, Canvey	0.64	1139	1039	*10 132*	*9 245*	105.8	*941.3*
Natural, Gaz de Lacq	0.57	1029	936	*9 154*	*8 326*	105.9	*942.5*
Natural, Groningen, Netherlands	0.64	887	807	*7 894*	*7 184*	105.9	*942.3*
Natural, Kuwait, Burgan	0.64	1094	997	*9 730*	*8 873*	105.8	*941.5*
Natural, Libya LNG	0.78	1339	1227	*11 913*	*10 919*	105.6	*940.0*
Natural, North Sea, Bacton	0.59	1032	939	*9 181*	*8 356*	105.9	*942.2*
Natural, Birmingham, AL	0.60	1000	910	*8 897*	*8 096*	105.9	*942.4*
Natural, East OH	0.59	1027	935	*9 140*	*8 318*	105.8	*942.3*
Natural, Kansas City, MO	0.63	970	883	*8 630*	*7 858*	105.9	*942.1*
Natural, Pittsburgh, PA	0.63	1123	1025	*9 995*	*9 116*	105.8	*941.4*
Producer, Koppers-Totzek[1,3]	0.71	290	275	*2 581*	*2 447*	131.3	*1168*
Producer, Lurgi[2], commercial	0.80	173	158	*1 538*	*1 405*	123.6	*1100*
Producer, Lurgi[2], sub-bit.	0.74	304	275	*2 705*	*2 447*	122	*1087*
Producer, IGT[2], lignite	0.79	499	457	*4 442*	*4 066*	112.8	*1003*
Producer, BCR[2], West KY	0.77	388	362	*3 465*	*3 221*	120.4	*1071*
Producer, W-G, bituminous[2]	0.84	168	159	*1 499*	*1 415*	129.6	*1153*
Producer, Winkler[2]	0.98	117	111	*1 041*	*988*	188.3	*1676*
Propane, commercial, natural gas	1.52	2499	2316	*22 236*	*20 603*	105.1	*935.1*
Propane, commercial, refinery gas	1.50	2462	2289	*21 902*	*20 367*	106.0	*942.7*
Sasol, South Africa	0.41	511	463	*4 544*	*4 117*	118.7	*1056*
SNG, no methanation	0.47	869	787	*7 731*	*7 003*	107.8	*958.7*

See footnotes on page 36.

Table 2.12c. Properties of gaseous fuels from Tables 2.12a, b (See Example 2-8)

Type of Gas	Wobbe Index	vol air / vol fuel	Stoichiometric products of combustion: $\%CO_2$ dry[8]	$\%H_2O$ wet	$\%N_2$ wet	total vol / vol fuel	Flame temperatures[4], F: O_2, See note[5]	Air, See note[6]	Air, See note[7]
Acetylene, commercial	1559	12.14	17.4	8.3	75.8	12.66	5630	4770	3966
Blast furnace, B	78.8	0.56	29.7	1.6	69.2	1.44	—	—	2367
Blast furnace, U	91.0	0.68	25.5	0.7	74.0	1.54	—	2650	2559
Butane, commercial, natural gas	2287	30.6	14.0	14.9	73.2	33.10	—	—	3543
Butane, commercial, refinery gas	2261	30.0	14.3	14.4	73.4	32.34	—	—	3565
Coke oven, R	830	4.56	9.91	22.3	70.0	5.30	—	—	3525
Coke oven, U	920	4.81	9.96	22.5	69.7	5.51	—	—	3532
Digester, (Sewage), Bergen, NJ	619	5.64	18.1	17.8	67.3	6.63	—	—	3285
Digester, (Sewage), Decatur, IL	791.5	6.55	14.7	18.4	69.7	7.52	—	—	3368
Landfill, Cagistrio, '81	581.7	5.16	17.6	17.7	67.9	6.10	—	—	3276
Mapp	1947	21.25	15.6	11.9	74.4	22.59	5301	—	3722
Natural, Alaska	1352	9.52	11.7	18.9	71.6	10.52	—	—	3472
Natural, Algeria, LNG, Canvey	1423	10.76	12.1	18.3	71.9	11.85	—	—	3483
Natural, Gaz de Lacq	1365	9.71	11.7	18.8	71.6	10.72	—	—	3474
Natural, Groningen, Netherlands	1107	8.38	11.7	18.4	72.0	9.40	—	—	3446
Natural, Kuwait, Burgan	1364	10.33	12.2	18.3	71.7	10.40	—	—	3476
Natural, Libya, LNG	1520	12.68	12.5	17.4	72.2	13.90	—	—	3497
Natural, North Sea, Bacton	1345	9.74	11.8	18.7	71.7	10.77	—	—	3473
Natural, Birmingham, AL	1291	9.44	11.7	18.6	71.8	10.47	5120	3565	3468
Natural, East OH	1336	9.70	11.9	18.7	71.7	10 72	—	—	3472
Natural, Kansas City, MO	1222	9.16	11.8	18.5	71.9	10.19	—	3535	3461
Natural, Pittsburgh, PA	1446	10.62	12.0	18.3	71.9	11.70	5150	3562	3474
Producer, Koppers-Totzek	343	2.21	27.2	12.1	63.9	2.75	—	3723	3605
Producer, Lurgi[1], commercial	192.8	1.40	17.7	17.6	67.7	2.22	—	2997	2977
Producer, Lurgi[2], sub-bit	354	2.49	23.4	19.8	61.5	3.20	—	3349	3317
Producer, IGT[3], lignite	562	4.43	18.7	17.5	67.0	5.24	—	3435	3406
Producer, BCR[3], West KY	444	3.23	22.3	14.7	66.0	3.88	—	3578	3514
Producer, W-G, bituminous	183.6	1.30	18.5	9.8	73.5	2.08	—	3214	3167
Producer, Winkler[4]	118.2	0.82	24.1	9.3	68.9	1.31	—	2815	3016
Propane, commercial, natural gas	2029	23.8	13.7	15.5	73.0	25.77	—	—	3532
Propane, commercial, refinery gas	2008	23.2	14.0	14.9	73.2	25.10	—	—	3560
Sasol, South Africa	794.4	4.30	12.8	21.0	68.8	4 94	—	3452	3584
SNG, no methanation	1264	8.06	11.3	19.8	71.1	8.96	—	—	3485

[4] Theoretical (calculated) flame temperatures, dissociation considered. See Figure 1.9 for some measured flame temperatures.

[5] With 100% Oxygen, from data in technical literature, mostly Reference 2.g listed at the end of Part 2.

[6] With air, from data in technical literature, mostly Reference 2.g listed at the end of Part 2.

[7] With air. Although these temperatures are lower than those reported in the literature, they are all computed on the same basis; so they offer a comparison of the relative flame temperatures of various fuels.

[8] ultimate.

Example 2-8. Find the actual analysis of flue products for Birmingham natural gas from data in Table 2.12c.

$$\text{Volume of nitrogen} = \frac{71.8\%}{100} \times 10.47 = 7.52 \text{ ft}^3\ N_2/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of water vapor} = \frac{18.6\%}{100} \times 10.47 = 1.95 \text{ ft}^3\ H_2O/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of dry flue gases} = 10.47 - 1.95 = 8.52 \text{ ft}^3/\text{ft}^3 \text{ fuel}$$

$$\text{Volume of carbon dioxide} = \frac{11.7\%}{100} \times 8.52 = 1.00 \text{ ft}^3\ CO_2/\text{ft}^3 \text{ fuel}$$

Check: Total volume = $7.52 \text{ ft}^3\ N_2 + 1.95 \text{ ft}^3\ H_2O + 1.00 \text{ ft}^3\ CO_2 = 10.47$

INTERCHANGEABILITY OF FUELS

Fuel supply shortages and price fluctuations may make it necessary to substitute one fuel for another, preferably without major changes in combustion chambers, burners, piping, or controls. **Five aspects** that must be considered are: 1) equal heat input rate, 2) fluid handling capability of flues, burners, piping, valves, controls, 3) burner stability, 4) heat release pattern, 5) furnace atmosphere.

Gas to Gas. The **Wobbe index**, formula 2/40b, is used to evaluate interchangeability with respect to items 1) and 2). If the substitute gas has the same Wobbe index as the gas being replaced, no change of valve settings should be necessary when changing fuels.

If the substitute fuel, which may be a fuel-air mixture, has higher gravity than the gas it replaces, fewer cubic feet will flow through the piping, valves, or orifices with the same pressure drop. See formula 5/1a. To compensate for this, the replacement mixture must have enough higher heating value to carry the same original amount of heat to the burner. Conversely, if the substitute has a lower gravity, it must also have lower heating value if the valve settings are to remain unchanged. This means that:

$$[2/40a] \quad \sqrt{\frac{G_o}{G_m}} \text{ must } = \frac{cfh_m}{cfh_o} \quad \text{or} \quad \sqrt{\frac{G_o}{G_m}} = \frac{H_o}{H_m}$$

where G = gravity relative to air as 1.0, H = calorific value, o = original gas, p = pure substitute, a = air, m = substitute mix consisting of p and a. Rearranging 2/40a gives the definition of Wobbe index:

$$[2/40b] \quad \text{Wobbe index} = \frac{H_o}{\sqrt{G_o}} = \frac{H_m}{\sqrt{G_m}}$$

For mixtures, when one ingredient is air,

$$[2/40c]\quad G_m = \left(\frac{\%p}{100} \times G_p\right) + \left(\frac{\%a}{100} \times G_a\right),$$

$$\text{but } G_a = 1.0 \text{ and } \%a = 100 - \%p;\ \text{so}\quad G_m = 1 + \frac{\%p}{100}(G_p - 1)$$

$$[2/40d]\quad H_m = \left(\frac{\%p}{100} \times H_p\right) + \left(\frac{\%a}{100} \times H_a\right),\ \text{but}\ H_a = 0;\ \text{so}\ H_m = \frac{\%p}{100}(H_p)$$

Combining the above formulas, the % of pure substitute in a mixture with air that will be interchangeable with the original gas both heat-release-wise and flow-wise is:

$$[2/41]\quad \%p = \frac{200}{1 - G_p + \sqrt{(G_p - 1)^2 + 4\,G_o\left(\frac{H_p}{H_o}\right)^2}}$$

Example 2-9. If propane is to be substituted for natural gas during curtailments, the different calorific value and gas gravity (density) would necessitate readjustment of the gas limiting orifice valve (see Volume II) when the propane is turned on, and again when resuming with natural gas. For one or a few burners, it may be practical to install duplicate gas trains in parallel. The limiting orifice valve in one gas train would be adjusted for correct air/natural gas ratio; the other for correct air/propane ratio. If fuel changes are frequent or if many burners are involved, a propane-air mix, having the same Wobbe index as the natural gas, can be substituted at the same pressure without readjusting valves.

A 1025 Btu/ft³ natural gas (gas gravity = 0.592) is to be replaced with a propane-air mix using 2615 Btu/ft³ propane (gas gravity = 1.552). Use formula 2/41 to find the % propane to be used in the propane-air mix:

$$\%p = \frac{200}{1 - 1.552 + \sqrt{0.3047 + 4\,(0.592)\left(\frac{2615}{1025}\right)^2}} = 58.6.$$

In the table below, the bold figures are given data. The other figures are derived by substituting given data in the formulas indicated in brackets:

	original	pure substitute	air	mix substitute, [2/41] 58.6% propane
H	**1025 Btu/ft³**	**2615 Btu/ft³**	0	[2/40d] 1532 Btu/ft³
G	**0.592**	**1.552**	1.0	[2/40c] 1.324
Wobbe	[2/40b] 1332	[2/40b] 2099	0	[2/40b] 1332

Liquefied petroleum gases (propane, butane, and mixes of propane and butane) are delivered and stored as liquids in pressurized vessels. For most industrial rates of consumption, a vaporizer is necessary. **The volume of gas available from a gallon of liquid is 36.82 ft³/gal for commercial propane.**

and 31.46 ft^3/gal for commercial butane, when both liquid and gas are measured at 60 F (15.6 C) and the gas is also at 30″Hg. A gas-air mixing station is necessary to automatically maintain the proper ratio of gas to air at all demand rates. See Volume II. For safety in handling, the gas-air mixture should be above the upper limit of flammability, i.e. too rich to burn, until it is further diluted with the normal amount of combustion air at the burners.

Table 2.13. Typical propane-air mixtures usable as substitutes for fuels from Table 2.12, based on refinery propane (H_p = 2504 Btu/ft^3, G_p = 1.77)

Original Fuel				**Mix Substitute**			
Description	H_o	G_o	$Wobbe_o$	%p	H_m	G_m	$Wobbe_m$
Producer, Lurgi	173	0.80	193.4	7.96	199.3	1.061	193.4
Producer, K-T	290	0.71	344.0	14.49	362.9	1.112	344.0
Coke Oven, U	554	0.36	923.3	42.48	1063.7	1.327	923.3
Natl, Kans. C. MO	970	0.63	1222.1	58.83	1473.1	1.453	1222.1
Natl, Birm. AL	1000	0.60	1291.0	62.80	1572.4	1.484	1291.0
LNG, Algeria	1139	0.64	1423.8	70.65	1769.1	1.544	1423.8

Warning: Fuel specs change with locale and time; so these figures should be used only as a guide. Use formulas 2/40 and 2/41 for specific cases.

Burner stability is a function of flame velocity and flammability limits. Although some theoretical methods have been proposed for evaluating flame stability when interchanging fuels, it is advisable to actually try the substitute gas in the burner types to be used at all expected firing rates and gas/air ratios. Premix burners are generally more sensitive, stability-wise, than are most modern nozzle-mix burners. There is usually no stability problem with gaseous fossil fuels (methane, ethane, propane, butane and mixtures thereof) but these fuels sometimes contain soot-forming unsaturates such as propylene and butylene.

Heat release pattern depends on the flame's shape, intensity and luminosity. Natural gas is relatively slow burning; so most substitute fuels will tend to burn with shorter, more intense flames. The effect of such a change can only be evaluated by trial for each process for which a substitute fuel is proposed.

Furnace atmosphere may be seriously affected if the substitute fuel contains a higher concentration of an impurity such as sulfur. Some processes, particularly heat treat atmosphere generators, are sensitive to the changing carbon/hydrogen ratio, which may involve dew point control.

Gas to Oil. The only way to substitute oil burning through existing gas burners is with an external vaporizing system added to **premix** gas burners. If the input per burner can be at least 250 000 Btu/hr (17.5 kcal/s), it is usually less expensive to replace each gas burner with a dual-fuel burner (a combination gas burner and oil burner built into a common housing). Either of these conversion systems (vaporizer or dual-fuel burners) require more first cost than gas-to-gas substitution, but may save on operating (fuel) cost. Selection of the conversion equipment takes care of the first three of the five aspects listed in the introduction to this section on interchangeability.

The fourth aspect, **heat release pattern**, is different for oils because their flames are more luminous. (However, there are a few burners designed to produce blue oil flames, and long luminous flame burners make yellow gas flames.) Because atomization and vaporization time is usually required after the oil leaves the burner nozzle, oil flames often require somewhat more combustion space. If combustion space is very confined or if a lot of flame radiation may be detrimental to the process, conversion to oil might require a combustion chamber revision; but this is not a problem in most conventional general-purpose furnaces because they are designed conservatively.

The fifth aspect, **furnace atmosphere**, was of great concern to the forging industry when converting to cheap natural gas in the 1950's, but serious effects upon scale formation could not be proved except in a handful of very critical cases. As with gas-for-gas substitutions, the effects of changes in sulfur or C/H ratio must be evaluated for each specific fuel and process.

COMPARATIVE COSTS OF FUELS

The most common way to compare fuels is by their heating values, and since gross heating values are more readily available, there figures are usually used. However, this comparison may be misleading for a number of reasons which are discussed in the following paragraphs.

The full gross heating value of a fuel is not available in practical combustion equipment because the exit gas temperature is not low enough to permit condensation of the moisture in the products of combustion. For this reason, a comparison of **net** heating values is much more desirable, if it is possible to do so. Gross and net heating values are not proportional throughout the range of commercially available fuels. Net heating values are readily calculated from the analysis of a gaseous or solid fuel, but the values obtained from formula 2/11 for liquid fuels may be subject to question because of the variation in refining methods.

Combustion efficiencies are not the same with all fuels. For example, fuels of higher hydrogen content produce combustion gases that have high specific heats*; thus the flue gas loss (stack loss) tends to be greater. Generally, gaseous or liquid fuels can be burned more efficiently than solid fuels, because less heat consuming excess air is needed to assure complete combustion. The ash in solid fuels is also cause for loss because it carries heat away from the furnace when it is removed and because some unburned fuel may be removed with the ash.

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* That is, for the same temperature rise, these gases absorb more Btu of heat than do other gases.

Operating costs usually vary widely with different fuels. The costs of handling solid fuels and the resulting ash may be considerable. Liquid fuels must be stored, pumped, and sometimes heated.

Equipment costs, for control, safety, handling, storage, combustion, and pollution abatement are generally less with lighter and cleaner fuels. Combustion chamber linings and breechings may have to be replaced more frequently with some fuels. Determination of the relative operating and equipment costs is a special problem in each individual case.

The figures in Example 2-10 should not be interpreted as typical. They are simply "made up" to illustrate the *method* for cost evaluation. Differing local costs and application requirements could result in entirely different conclusions on other jobs.

Example 2-10. For an existing system using natural gas only, compare the total annual costs of three possible standby systems—propane-air at $3.50 per million Btu, #2 oil at $2.50 per million Btu, and #6 oil at $2.00 per million Btu. Average consumption rate is 14 000 000 Btu/hr. Assume that the system will be on standby fuel about 3000 hours per year.

14 million Btu/hr × 3000 hr/yr = 42 000 million Btu/yr. Annual fuel cost with propane = 42 000 million Btu/yr × $3.50/million Btu = $147,000/yr; with #2 oil, 42 000 × $2.50 = $105,000/yr; with #6 oil, 42 000 × $2.00 = $84,000/yr.

By obtaining equipment and installation cost estimates, the following type of cost comparison table might be developed:

		Standby fuel		
	Estimated costs	**Propane-air**	**#2 Fuel oil**	**#6 Fuel oil**
Equipment & installation	Tanks, grading, insulation	$ 35,000[1]	$ 14,000[2]	$ 21,500[3]
	Piping	4,000	1,500	4,500
	Vaporizer and mixing station	15,000	0	0
	Pumps and heating system	0	2,000	6,500
	Burners and controls	0	3,000	4,000
	Subtotal, first cost	$ 54,000	$ 20,500	$ 36,500
Operating, annual	Annual, 3-yr payout	18,000	6,833	12,167
	Elec. power, supervision, maintenance	3,000	4,000	6,500
	Fuel	147,000	105,000	84,000
	TOTAL ANNUAL COST	$168,000	$115,833	$102,667

WARNING: These figures should not be interpreted as typical. They are simply "made up" to illustrate the **method** for cost evaluation. Differing local costs and application requirements could result in entirely different conclusions on other jobs.

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[1] 30 000 gallon tank, 65′ × 9′ diameter, 10 to 14 days storage capacity.

[2] 20 000 gallon vertical or horizontal above-ground steel tank. If below ground, cost would be about $10,600—no dike or unloading pump required.

[3] 20 000 gallon horizontal heated and insulated steel tank.

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Part 3. COMBUSTION ANALYSIS

It is frequently necessary to predict: the air requirement for burning a fuel, the products of combustion of that fuel, and the losses accompanying its combustion. The tabulated data on typical fuels in Part 2 supplies information of this sort for specific fuels. If none of the fuels listed in Part 2 approximates the particular fuel under consideration, the methods outlined in this Part 3 should be used.

This chapter also discusses the significance of experimental flue gas analyses and means of minimizing the various combustion losses to improve efficiency.

Throughout this handbook, volumes of air and gases are assumed measured at "stp", standard temperature (60 F, 15.6 C) and standard pressure (14.696 psia, 760 mm Hg), unless otherwise specified. It is common practice to refer to air at stp as "standard air."

COMBUSTION AIR REQUIREMENTS

Gaseous Fuels. The amount of air required for perfect combustion of one cubic foot of any gaseous fuel is given by the formula:

$$[3/1] \quad \frac{\text{volume of air}}{\text{volume of fuel}} = [(\%CH_4 \times 0.0956) + (\%C_2H_6 \times 0.1673) + (\%C_3H_8 \times 0.239) + (\%C_4H_{10} \times 0.311) + (\%H_2 \times 0.0239) + (\%CO \times 0.0239) - (\%O_2 \times 0.0478)] \times [1 + \%XSA/100]$$

where all percentages are by volume. Non-combustibles have no effect on the amount of air required for combustion. In formula 3/1, the air and gas volumes must be measured at the same temperature and pressure. If there is some difference between the air and gas temperature or pressure, correction can be made by use of the following formulas:

$$[3/2] \quad \text{volume at } t_2 = \text{volume at } t_1 \times \left(\frac{t_2\,F + 460}{t_1\,F + 460}\right), \text{ or } = \text{volume at } t_1 \times \left(\frac{t_2\,C + 273}{t_1\,C + 273}\right)$$

$$[3/3] \quad \text{vol at } p_2 = \text{vol at } p_1 \times \left(\frac{p_1 \text{ in psi} + 14.7}{p_2 \text{ in psi} + 14.7}\right), \text{ or } = \text{vol at } p_1 \times \left(\frac{p_1 \text{ in mm Hg} + 760}{p_2 \text{ in mm Hg} + 760}\right)$$

Tables A.2 and A.3 in the Appendix list volume correction factors calculated from the above formulas. Tables 1.7, 2.1, 2.3, 2.12 and 3.1 list the combustion air requirements of several chemical compounds and fuels.

Table 3.1. Combustion characteristics of chemical compounds

							Products of perfect combustion per unit of fuel									
							CO_2		H_2O		N_2		SO_2		Total	
Fuel	Gas gravity*	Specific Volume ft³/lb	Specific Volume m³/kg	Gross Btu/ft³ of stand. air	Gross kcal/m³ of stand. air	Ult. % CO_2†	wt‡	vol∆	wt‡	vol∆	wt‡	vol∆	wt‡	vol∆	wt‡	vol∆
Acetylene, C_2H_2	0.897	14.6	0.910	124.1	1105	17.5	3.38	2.00	0.692	1.00	10.18	9.40	0	0	14.28	12.4
Benzene, C_6H_6	2.69	4.86	0.303	105.1	935.0	17.5	3.38	6.00	0.692	3.00	10.18	28.2	0	0	14.26	37.2
Butane, C_4H_{10}	2.00	6.54	0.408	105.5	939.0	14.1	3.03	4.00	1.55	5.00	11.87	24.4	0	0	16.45	33.4
Carbon, C	—	—	—	93.7	834.3	20.9	3.67	—	0	0	8.81	—	0	—	12.5	—
Carbon Monoxide, CO	0.966	13.5	0.845	134.9	1200	34.7	1.57	1.00	0	0	1.89	1.88	0	0	3.46	2.88
Ethane, C_2H_6	1.03	12.6	0.788	106.2	944.8	13.2	2.93	2.00	1.80	3.00	12.36	13.2	0	0	17.09	18.2
Hydrogen, H_2	0.0690	189	11.83	136.5	1215	0	0	0	9.00	1.00	26.48	1.88	0	0	35.48	2.88
Hydrogen Sulfide, H_2S	1.17	11.1	0.696	90.3	804.0	0	0	0	0.529	1.00	4.67	5.64	1.88	1.00	7.08	6.64
Methane, CH_4	0.552	23.7	1.48	106.2	945.0	11.7	2.75	1.00	2.25	2.00	13.24	7.52	0	0	18.24	10.5
Naphthalene, $C_{10}H_8$	4.41	2.96	0.185	102.5	911.8	18.1	3.44	10.0	0.563	4.00	9.93	45.1	0	0	13.93	59.1
Octane, C_8H_{18}	—	—	—	105.0	934.7	14.6	3.09	—	1.42	—	11.61	—	0	0	16.12	—
Propane, C_3H_8	1.52	8.61	0.538	106.1	943.7	13.8	3.00	3.00	1.64	4.00	12.04	18.8	0	0	16.67	25.8
Propylene, C_3H_6	1.45	9.03	0.563	109.2	972.0	15.1	3.14	3.00	1.29	3.00	11.35	16.9	0	0	15.78	22.9
Sulfur, S	—	—	—	70.6	628.0	0	0	0	0	0	3.31	—	2.00	—	5.31	—

* Relative to standard air as 1.0.

† Dry.

‡ Pounds of combustion product per pound of fuel, or kg/kg, or any consistent weight units.

∆ Cubic feet of combustion product per ft³ of fuel, or m³/m³, or any consistent volume units.

Example 3-1. Find the air required to burn a certain coke oven gas having the following volumetric analysis: 32.3% CH_4, 2.5% C_2H_4, 3.2% C_4H_{10}, 51.9% H_2, 5.5% CO, 0% O_2, 1.0% CO_2, and 3.5% N_2. Substituting in formula 3/1, $(32.3 \times 0.0956) + (2.5 \times 0.1673) + (3.2 \times 0.311) + (51.9 \times 0.0239) + (5.5 \times 0.0239) = 5.87$ cubic feet of air required per cubic foot of gas.

If the combustion air were supplied at 32 osi pressure (2 psig) and at 300 F, and if the gas were supplied at 60 F and barometric pressure, then by formulas 3/2 and 3/3 or Tables A.2 and A.3, the air/fuel ratio should be $5.87 \times \dfrac{14.7}{14.7 + 2} \times \dfrac{300 + 460}{60 + 460} = 7.55$ actual cubic feet of air per cubic foot of fuel.

Liquid and Solid Fuels. The amount of air required for perfect combustion of one pound of any liquid or solid fuel is given by the formula:

[3/4] $$\frac{\text{ft}^3\text{ air}}{\text{lb fuel}} = (\%\text{C} \times 1.514) + (\%\text{H} \times 4.54) + (\%\text{S} \times 0.568) - (\%\text{O} \times 0.568)$$

where all percentages are by weight. The cubic feet of air obtained from formula 3/4 must be measured at 60 F (15.6 C) and 14.7 psia (760 mm Hg) pressure. For other temperatures and pressures apply the correction factors as in the second paragraph of Example 3-1. For fuel oils containing negligible amounts of sulfur, oxygen, and inerts, formulas 2/5 and 2/10 may be combined with formula 3/4 to give the approximate expression

[3/5] ft³ air/gal oil $= (1906 \times \text{sg}) - [379 \times (\text{sg})^2]$ when sg is between 0.825 and 0.876
ft³ air/gal oil $= (1900 \times \text{sg}) - [379 \times (\text{sg})^2]$ when sg is between 0.876 and 0.934
ft³ air/gal oil $= (1895 \times \text{sg}) - [379 \times (\text{sg})^2]$ when sg is between 0.934 and 1.007
ft³ air/gal oil $= (1878 \times \text{sg}) - [379 \times (\text{sg})^2]$ when sg is between 1.007 and 1.076

where sg is the specific gravity (60/60 F)* of the fuel oil. (The term "inerts" refers to non-combustible substances in the fuel, such as CO_2, N_2, ash, and water.) The cubic feet of air obtained from this formula must be measured at 60 F and 14.7 psia pressure. For other temperatures and pressures, apply correction factors as in the second paragraph of Example 3-1. Results from formula 3/5 may be read on Table 2.3. A *rule of thumb* is: 25 cfm of air are required for each gallon per hour of oil.

Example 3-2. Find the air required to burn a fuel oil that weighs 6.99 lb per gallon (sg = 0.838) and has the following ultimate analysis: 86.14% C, 13.24% H, 0.22% S, 0.02% N, 0.00% ash, and 0.38% O.

Substituting in formula 3/4, $\dfrac{\text{ft}^3\text{ air}}{\text{lb fuel}} = (86.14 \times 1.514) + (13.24 \times 4.54) + (0.22 \times 0.568) - (0.38 \times 0.568) = 190.4$ ft³/lb or $6.99 \times (190.4) = 1331$ ft³/gal.

---

* See Part 2 for a discussion of specific gravities of oils.

Using formula 3/5, we obtain $(1906 \times 0.838) - [379 \times (0.838)^2] = 1331$ ft^3/gal. The rule of thumb is based on 25 cfm/gph × 60 min/hr = 1500 ft^3/gal.

All the above data have specified the air requirements for *perfect* combustion. In some instances it is desirable to burn fuels with a deficiency of air in order to obtain a reducing (non-oxidizing) atmosphere. In other instances an excess of air is intentionally supplied. This condition is usually described by specifying the *percent excess air*. Thus, if 1331 ft^3 of air are required for perfect combustion of one gallon of a fuel oil, but ten percent excess air is to be supplied, then the air supply should be $1331 + (0.10 \times 1331)$ or simply $1.10 \times 1331 = 1464$ ft^3/gal.

PRODUCTS OF COMBUSTION (poc)

It is often desirable to predict the quantity and analysis of the products of combustion of a fuel in order to determine proper flue sizes and furnace pressure, and to predict the magnitude of stack or flue gas losses. Table 3.1 lists the products resulting from perfect combustion of several chemical compounds. Formulas 3/6 through 3/17 permit calculation of the quantities of gases in the combustion products of *gaseous fuels* either by volume or by weight. The percentages to be substituted in **all** of these formulas are percentages by volume. Formulas 3/18 through 3/29 permit calculation of the quantities of gases (by weight or by volume) in the combustion products of *liquid and solid fuels*. The percentages to be substituted in these formulas are **all** percentages by weight.

Care should be exercised in the use of formulas 3/11 through 3/16 and 3/23 through 3/29 because they give the volume of the various flue gases at 60 F and 14.7 psia pressure (15.6 C and 760 mm Hg). These volumes must be corrected to the actual temperature and pressure conditions by use of formulas 3/2 and 3/3 or Tables A.2 and A.3 in the same manner as previously illustrated for correcting air volumes. At temperatures below 250 F the water vapor in the flue gases no longer behaves as a gas and may even condense. Therefore volumes calculated from formulas 3/11, 3/15, 3/23, and 3/27 are hypothetical at 60 F and are meaningless unless corrected to some temperature above 250 F.

For approximate calculations, a *rule of thumb* would say that the volume of combustion products equals the sum of air and gas (fuel) volumes. A quick scan of Table 2.12c shows this to be close for natural gases and some manufactured gases. For LP gases, ft^3 cp/ft^3 fuel ≈ ft^3 air/ft^3 fuel + 2. For oils, the ft^3 cp/gal = ft^3 air/gal + 85.

For cases in which an excess of air is supplied, it is merely necessary to add the weight or volume of the excess nitrogen and excess oxygen to the other combustion products. This procedure is illustrated in Example 3-4.

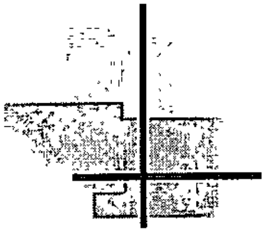


Table 3.2. Formulas for determining products of complete combustion of gaseous fuels. (All percentages are percents by volume, all volumes at stp — 60 F and 29.92 in. Hg.)

[3/6] $$\frac{\text{lb comb prod}}{\text{ft}^3\text{ fuel}} = (\%\mathrm{CO} \times 0.002\,558) + (\%\mathrm{H_2} \times 0.001\,872) + (\%\mathrm{CH_4} \times 0.007\,70) + (\%\mathrm{C_2H_6} \times 0.013\,53) + (\%\mathrm{C_3H_8} \times 0.019\,36) + (\%\mathrm{C_4H_{10}} \times 0.025\,18) + (\%\mathrm{CO_2} \times 0.001\,161) + (\%\mathrm{N_2} \times 0.000\,739) + (\%\mathrm{SO_2} \times 0.001\,690) + (\%\mathrm{H_2O} \times 0.000\,475) - (\%\mathrm{O_2} \times 0.002\,794) + (\%\mathrm{XSA}/100) \times 0.001\,819 \times \Theta$$

[3/7] $$\frac{\text{lb CO}_2}{\text{ft}^3\text{ fuel}} = (\%\mathrm{CO} \times 0.001\,161) + (\%\mathrm{CH_4} \times 0.001\,161) + (\%\mathrm{C_2H_6} \times 0.002\,322) + (\%\mathrm{C_3H_8} \times 0.003\,483) + (\%\mathrm{C_4H_{10}} \times 0.004\,644) + (\%\mathrm{CO_2} \times 0.001\,161)$$

[3/8] $$\frac{\text{lb H}_2\text{O}}{\text{ft}^3\text{ fuel}} = (\%\mathrm{H_2} \times 0.000\,475) + (\%\mathrm{CH_4} \times 0.000\,950) + (\%\mathrm{C_2H_6} \times 0.001\,425) + (\%\mathrm{C_3H_8} \times 0.001\,900) + (\%\mathrm{C_4H_{10}} \times 0.002\,375) + (\%\mathrm{H_2O} \times 0.000\,475)$$

[3/9a] $$\frac{\text{lb N}_2}{\text{ft}^3\text{ fuel}} = (\%\mathrm{N_2} \times 0.000\,739) + [(1 + \%\mathrm{XSA}/100) \times 0.001\,397 \times \Theta]$$

[3/9b] $$\frac{\text{lb O}_2}{\text{ft}^3\text{ fuel}} = (\%\mathrm{XSA}/100) \times (0.000\,422) \times \Theta$$

[3/10] $$\frac{\mu\text{g SO}_2}{\text{m}^3\text{ fuel}} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 45\,760$$

[3/11] $$\frac{\text{volume cp}^\dagger}{\text{volume fuel}} = (\%\mathrm{CO} \times 0.028\,9) + (\%\mathrm{H_2} \times 0.028\,9) + (\%\mathrm{CH_4} \times 0.105\,6) + (\%\mathrm{C_2H_6} \times 0.182\,3) + (\%\mathrm{C_3H_8} \times 0.259\,0) + (\%\mathrm{C_4H_{10}} \times 0.335\,7) + (\%\text{inerts}^* \times 0.01) - (\%\mathrm{O_2} \times 0.037\,8) + (\%\mathrm{XSA}/100) \times 0.023\,9 \times \Theta$$

[3/12] $$\frac{\text{volume dcp}^\dagger}{\text{volume fuel}} = (\%\mathrm{CO} \times 0.028\,9) + (\%\mathrm{H_2} \times 0.018\,9) + (\%\mathrm{CH_4} \times 0.085\,6) + (\%\mathrm{C_2H_6} \times 0.152\,3) + \%\mathrm{C_3H_8} \times 0.219\,0) + (\%\mathrm{C_4H_{10}} \times 0.285\,7) + (\%\text{inerts}^* \times 0.01) - (\%\mathrm{O_2} \times 0.037\,8) + (\%\mathrm{XSA}/100) \times 0.023\,9 \times \Theta$$

[3/13] $$\frac{\text{volume CO}_2}{\text{volume fuel}} = (\%\mathrm{CO} \times 0.01) + (\%\mathrm{CH_4} \times 0.01) + (\%\mathrm{C_2H_6} \times 0.02) + (\%\mathrm{C_3H_8} \times 0.03) + (\%\mathrm{C_4H_{10}} \times 0.04) + (\%\mathrm{CO_2} \times 0.01)$$

[3/14] $$\underset{\text{(ultimate \%CO}_2\text{)}}{\%\text{CO}_2\text{ in dcp}^\dagger} = 100 \times \frac{\text{volume of CO}_2}{\text{volume of fuel}} \div \left(\frac{\text{volume of dcp}}{\text{volume of fuel}}\text{ from formula 3/12}\right)$$

[3/15] $$\frac{\text{volume H}_2\text{O}}{\text{volume fuel}} = (\%\mathrm{H_2} \times 0.01) + (\%\mathrm{CH_4} \times 0.02) + (\%\mathrm{C_2H_6} \times 0.03) + (\%\mathrm{C_3H_8} \times 0.04) + (\%\mathrm{C_4H_{10}} \times 0.05) + (\%\mathrm{H_2O} \times 0.01)$$

[3/16a] $$\frac{\text{volume N}_2}{\text{volume fuel}} = (\%\mathrm{N_2} \times 0.01) + [(1 + \%\mathrm{XSA}/100) \times 0.018\,9 \times \Theta]$$

[3/16b] $$\frac{\text{volume O}_2}{\text{volume fuel}} = (\%\mathrm{XSA}/100) \times 0.005 \times \Theta$$

[3/17a] $$\frac{\mu\text{g SO}_2}{\text{m}^3\text{ cp}^\ddagger} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 45\,760 \div \left(\frac{\text{vol cp}^\ddagger}{\text{vol fuel}}\text{ from formula 3/11}\right)$$

[3/17b] $$\underset{\text{(by volume)}}{\text{ppm SO}_2} = \frac{\text{grains S}}{100\text{ ft}^3\text{ fuel}} \times 16.92 \div \left(\frac{\text{vol cp}^\ddagger}{\text{vol fuel}}\text{ from formula 3/11}\right)$$

---

* "Inerts" include CO_2, N_2, SO_2, SO_3, argon, helium, and other non-combustibles.

† cp = combustion products (flue gases); dcp = dry combustion products.

‡ To get an answer per volume of dry combustion products, use vol dcp/vol fuel from formula 3/12.

$\Theta = \%\mathrm{CO} + \%\mathrm{H_2} + (4 \times \%\mathrm{CH_4}) + (7 \times \%\mathrm{C_2H_6}) + (10 \times \%\mathrm{C_3H_8}) + (13 \times \%\mathrm{C_4H_{10}}) - (2 \times \%\mathrm{O_2})$

When there is a deficiency of air it is difficult to predict the volume or the analysis of the combustion products, but the total weight of the products will be equal to the weight of the fuel plus the weight of the air supplied.

Example 3-3. A furnace is fired with 1000 ft^3/hr of a natural gas having 0.2 grains of sulfur per 100 ft^3, and the following volumetric analysis: 80% CH_4, 16% C_2H_6, 2% O_2, 1% N_2, 1% CO_2.

Determine the volume of CO_2, water vapor, and nitrogen in the flue gases when the correct amount of air is supplied. Calculate the SO_2 concentration in the flue products. Also find the volume flow rate of the combustion products at the point where their temperature is 800 F and the pressure is 3.45 inches of water column (abbreviated "wc) positive (above atmospheric pressure).

From formula 3/13, the amount of CO_2 in the flue gases will be $(80 \times 0.01) + (16 \times 0.02) + (1 \times 0.01) = 1.13$ volume CO_2/volume fuel. Similarly, formulas 3/15 and 3/16 yield 2.08 vol H_2O/vol fuel and 8.10 vol N_2/vol of fuel respectively.

Formula 3/11 gives the volume of the combustion products as: $(80 \times 0.1056) + (16 \times 0.1823) + (1 + 1) \times 0.01 - (2 \times 0.0378) = 11.31$ volumes of combustion products per volume of fuel. By formula 3/17a, the SO_2 concentration in the combustion products is $0.2 \times 45\,760 \div 11.31 = 809$ $\mu g/m^3$; or by formula 3/17b, $0.2 \times 16.92 \div 11.31 = 0.299$ ppm.

The above 11.31 vol cp/vol fuel is for combustion products at the same temperature and pressure as the fuel. If the fuel is presumed to be measured at stp (60 F and 14.7 psia), the volume of combustion products must be corrected to the specified 3.45"wc and 800 F as follows. From Table C.6 in the Appendix, 1 osi = 1.732"wc; therefore 3.45"wc/1.732 = 1.99 osi. From Table A.3, one cubic foot of gas at that pressure becomes 1.0085 ft^3 at standard atmospheric pressure. From Table A.2a the volume of a cubic foot of standard air or gas is increased 2.421 times when it is heated to 800 F. Applying these correction factors,

$$\frac{11.31\text{ ft}^3\text{ cp at stp}}{\text{ft}^3\text{ of fuel}} \times \frac{1.0\text{ ft}^3\text{ at }3.45''\text{wc}}{1.0085\text{ ft}^3\text{ at stp}} \times \frac{2.421\text{ ft}^3\text{ at }800\text{ F}}{1.0\text{ ft}^3\text{ at stp}} = 27.15\text{ ft}^3$$

of combustion products per cubic foot of fuel. At a firing rate of 1000 cfh, the volume flow rate of the flue gases will be $1000 \times 27.15 = 27\,150$ cfh.

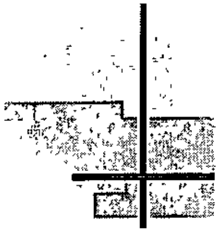
Example 3-4. Predict the analysis by volume of products of combustion of the fuel described in Example 3-3 when 15% excess air is supplied.

It is first necessary to use formula 3/1 to determine the volume of air required for perfect combustion. Thus $(80 \times 0.0956) + (16 \times 0.1673) - (2 \times 0.0478) = 10.23$.

Therefore 15% excess (XS) air will amount to $10.23 \times \frac{15}{100} = 1.534 \frac{\text{ft}^3\text{ XSair}}{\text{ft}^3\text{ fuel}}$.

Air is 20.99% oxygen and 78.03% nitrogen by volume. Therefore the excess air will be made up of 1.534×0.322 vol O_2/vol fuel and $1.534 \times 0.7803 = 1.197$ vol N_2/vol fuel. Adding these quantities to the flue gas analysis found in Example 3-3 above, combustion of one volume of fuel with 15% excess air will produce 1.13 vol CO_2, 2.08 vol H_2O, 0.322 vol O_2, and $8.10 + 1.197 = 9.30$ volumes of N_2.

Table 3.3. Formulas for determining products of complete combustion of liquid and solid fuels. (All percentages are percents by weight.)$^{\square}$



[3/18] $$\frac{\text{wt cp}^{\dagger}}{\text{wt fuel}} = (\%C \times 0.124\,8) + (\%H \times 0.352\,0) + (\%S \times 0.053\,0) + (\%\text{inerts}^{*} \times 0.01) - (\%O^{\square} \times 0.033\,1) + [\%XSA/100] \times [(\%H \times 0.342\,0) + (\%C \times 0.114\,8) + (\%S \times 0.043\,0) - (\%O \times 0.043\,1)]$$

[3/19] $$\text{wt } CO_2/\text{wt fuel} = (\%C \times 0.036\,6) + (\%CO_2^{\oplus} \times 0.01)$$

[3/20] $$\text{wt } H_2O/\text{wt fuel} = (\%H \times 0.089\,4) + (\%H_2O^{\circ} \times 0.01)$$

[3/21] $$\frac{\text{wt } SO_2}{\text{wt fuel}} = (\%S \times 0.020\,0) + (\%SO_2^{\triangle} \times 0.01)$$

[3/22a] $$\frac{\text{wt } N_2}{\text{wt fuel}} = [(\%C \times 0.088\,2) + (\%H \times 0.262\,6) + (\%S \times 0.033\,0) - (\%O^{\square} \times 0.033\,1)] \times [1 + \%XSA/100] + (\%N \times 0.01)$$

[3/22b] $$\frac{\text{wt } O_2}{\text{wt fuel}} = [(\%C \times 0.026\,6) + (\%H \times 0.079\,4) + (\%S \times 0.099\,79) - (\%O^{\square} \times 0.01)] \times [\%XSA/100]$$

[3/23] $$\frac{\text{ft}^3 \text{ cp}^{\dagger}}{\text{lb fuel}} = (\%C \times 1.508) + (\%H \times 5.433) + (\%S \times 0.565\,0) + (\%CO_2^{\oplus} \times 0.086\,1) + (\%H_2O^{\circ} \times 0.210\,4) + (\%N \times 0.135\,3) - (\%O^{\square} \times 0.447\,7) + [\%XSA/100] \times [(\%C \times 1.508) + (\%H \times 4.493) + (\%S \times 0.565\,0) - (\%O^{\square} \times 0.566\,2)]$$

[3/24] $$\frac{\text{ft}^3 \text{ dcp}^{\dagger}}{\text{lb fuel}} = (\%C \times 1.508) + (\%H \times 3.553) + (\%S \times 0.565\,0) + (\%CO_2^{\oplus} \times 0.086\,1) + (\%N \times 0.135\,3) - (\%O^{\square} \times 0.447\,7) + [\%XSA/100] \times [(\%C \times 1.508) + (\%H \times 4.493) + \%S \times 0.565\,0) - (\%O^{\square} \times 0.566\,2)]$$

[3/25] $$\text{ft}^3 \; CO_2/\text{lb fuel} = (\%C \times 0.315\,5) + (\%CO_2^{\oplus} \times 0{,}086\,1)$$

[3/26] $$\%CO_2 \text{ in dcp}^{\dagger} = 100 \times \frac{\text{ft}^3 \; CO_2}{\text{lb fuel}} \div \frac{\text{ft}^3 \text{ dcp}}{\text{lb fuel}}$$

[3/27] $$\text{ft}^3 \; H_2O/\text{lb fuel} = (\%H \times 1.880) + (\%H_2O^{\circ} \times 0.210\,4)$$

[3/28a] $$\text{ft}^3 \; SO_2/\text{lb fuel} = (\%S \times 0.118\,2) + (\%SO_2^{\triangle} \times 0.059\,2)$$

[3/28b] $$\frac{\mu g \; SO_2}{m^3 \text{ cp}^{\ddagger}} = \left(\frac{\text{wt } SO_2}{\text{wt fuel}} \text{ from formula 3/21}\right) \times 1.602 \times 10^{10} \div \left(\frac{\text{ft}^3 \text{ cp}^{\ddagger}}{\text{lb fuel}} \text{ from formula 3/23}\right)$$

[3/28c] $$\begin{array}{l}\text{ppm } SO_2\\ \text{(by volume)}\end{array} = \left(\frac{\text{ft}^3 \; SO_2}{\text{lb fuel}} \text{ from formula 3/28a}\right) \times 1 \times 10^{6} \div \left(\frac{\text{ft}^3 \text{ cp}^{\ddagger}}{\text{lb fuel}} \text{ from formula 3/23}\right)$$

[3/29a] $$\frac{\text{ft}^3 \; N_2}{\text{lb fuel}} = [(\%C \times 1.193) + (\%H \times 3.553) + (\%S \times 0.446\,8) - (\%O^{\square} \times 0.447\,7)] \times [1 + \%XSA/100] + (\%N \times 0.135\,3)$$

[3/29b] $$\frac{\text{ft}^3 \; O_2}{\text{lb fuel}} = [(\%C \times 0.315\,5) + (\%H \times 0.940\,0) + (\%S \times 0.118\,2) - (\%O^{\square} \times 0.118\,4)] \times [\%XSA/100]$$

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* "Inerts" include CO_2, N_2, SO_2, SO_3, argon, helium, and other non-combustibles.

† cp = combustion products (flue gases); dcp = dry combustion products.

‡ To get an answer per ft³ of dry combustion products, use ft³ dcp/lb fuel from formula 3/24.

$^{\square}$ These equations may be used for gaseous fuels containing no CO. If the values substituted in the above equations for %C, %H, and %S are the percentages of total carbon, hydrogen, and sulfur, (available plus unavailable), then the %O should be the total (free and combined) oxygen. If the values substituted in the above equations for %C, %H, and %S are the percentages of available carbon, hydrogen, and sulfur respectively, then the %O should be the free oxygen only.

$^{\oplus}$ If %C includes the unavailable carbon already in the form of CO_2, this CO_2 term should be omitted and note $^{\square}$ observed. $^{\circ}$ If %H includes the unavailable hydrogen already in the form of H_2O, this H_2O term should be omitted and note $^{\square}$ observed. $^{\triangle}$ If %S includes the unavailable sulfur already in the form of SO_2, this SO_2 term should be omitted and note $^{\square}$ observed.

Example 3-5. Predict the gravimetric (weight) analysis of the flue gases resulting from the perfect combustion of a 15°API oil having the following gravimetric analysis: 88.50% C, 10.50% H, 0.10% N, 0.80% S, 0.06% O. Find $\%CO_2$ in the dry flue gas.

When the correct amount of air is supplied, the quantity of CO_2 in the flue gas (by formula 3/19) will be $(88.5 \times 0.0366) = 3.24$ wt CO_2/wt fuel. Similarly, formulas 3/20, 3/21, and 3/22 give 0.94 wt H_2O/wt fuel, 0.016 wt SO_2/wt fuel, and 10.59 wt N_2/wt fuel. These total $3.24 + 0.94 + 0.016 + 10.59 = 14.79$ wt cp/wt fuel. The $\%CO_2$ by weight is therefore $(3.24/14.79) \times 100 = 21.9$. Similarly for the other combustion products, the gravimetric flue gas analysis is 21.9% CO_2, 6.4% H_2O, 0.1% SO_2, 71.6% N_2.

To predict the volumetric $\%CO_2$ in the dry flue gases, formulas 3/24, 3/25, and 3/26 may be used as follows: $(88.50 \times 1.508) + (10.50 \times 3.553) + (0.80 \times 0.5650) + (0.10 \times 0.1353) - (0.06 \times 0.477) = 171.2$ ft^3 dry flue gases/lb fuel; $(88.50 \times 0.3155) = 27.92$ ft^3 CO_2/lb fuel; so $100 \times (27.92/171.2) = 16.3\%$ CO_2 in dry flue gases. This is the so-called "ultimate $\%CO_2$" which is discussed in the following section.

FLUE GAS ANALYSES

Flue gas analyses are used to indicate the air/fuel ratio and to indicate the degree of completeness of combustion. If the mixing is poor, an excess of air must be supplied so that every particle of fuel will contact some air and burn. Figure 3.4 shows the effects of poor mixing or quenching. If the flame or hot intermediate combustion gases contact a cold surface or meet a blast of cold air, gas, or water, they may be suddenly chilled to a temperature level at which the combustion reaction cannot promptly go to completion. This quenching action may result in incomplete combustion with gases such as O_2, CO, H_2, and aldehydes in the flue products, as with cases of poor mixing.

Significance of $\%CO_2$, O_2, and combustibles. With good mixing, perfect combustion is obtained when the flue gas analysis shows no CO, H_2, or O_2 and when the $\%CO_2$ is at a maximum. The theoretical maximum $\%CO_2$ in the dry flue gases is termed the *ultimate* $\%CO_2$. By adjusting the air/fuel ratio until the maximum $\%CO_2$ is obtained, and until the minimum $\%O_2$ and combustibles are indicated, an operator can set a burner close to the point of best fuel efficiency. This permits approximate setting of the air/fuel ratio on single-burner furnaces without metering the fuel and the air flow. For applications requiring either reducing or oxidizing combustion, the flue gas analysis may be used as a means of duplicating certain desired conditions if all other conditions are exactly the same.

With poor mixing such as results when coal is burned on grates or when gas or oil is burned in a delayed mixing type of burner, the manner in which the flue gas analysis varies with changes in the air/fuel ratio is a function of the physical arrangement of the burner and combustion chamber. The poor-mixing curves of Figure 3.4 represent only one of many possibilities for this case. These curves demonstrate, however, that the flue gas analysis may be used as an indication of the air/fuel ratio or of the relative completeness of combustion. Table 3.5 shows the %CO_2 readings that should be obtained with perfect mixing of various amounts of air with some of the specific fuels described in Tables 2.1 and 2.12 of Part 2.

Figure 3.4. Effect of air/fuel ratio on flue gas analysis for 1108 Btu/ft³ natural gas (0.63 gas gravity) containing 83% CH_4 and 16% C_2H_6. Values for rich mixtures depend somewhat on combustion chamber design. The average values shown are within ½% of correct for H_2, CO, and CO_2, but may be as much as 2% low for other constituents. Some external heat is usually required for mixtures with less than 70% aeration (dotted lines). Dashed lines show the trends with poor mixing or quenching. Gas constituent percentages are on a dry basis to allow comparison with gas analyzer readings, that measure the gas volumes after water vapor has condensed out of the sample. With the correct amount of air (10.56 ft³), each cubic foot of this fuel gas produces 2.14 ft³ H_2O, 1.15 ft³ CO_2, 8.39 ft³ N_2; so %CO_2 = 100 × 1.15 ft³ CO_2 + (1.15 + 8.39) ft³ dry flue gas = 12.1%. See also Figure 3.13.

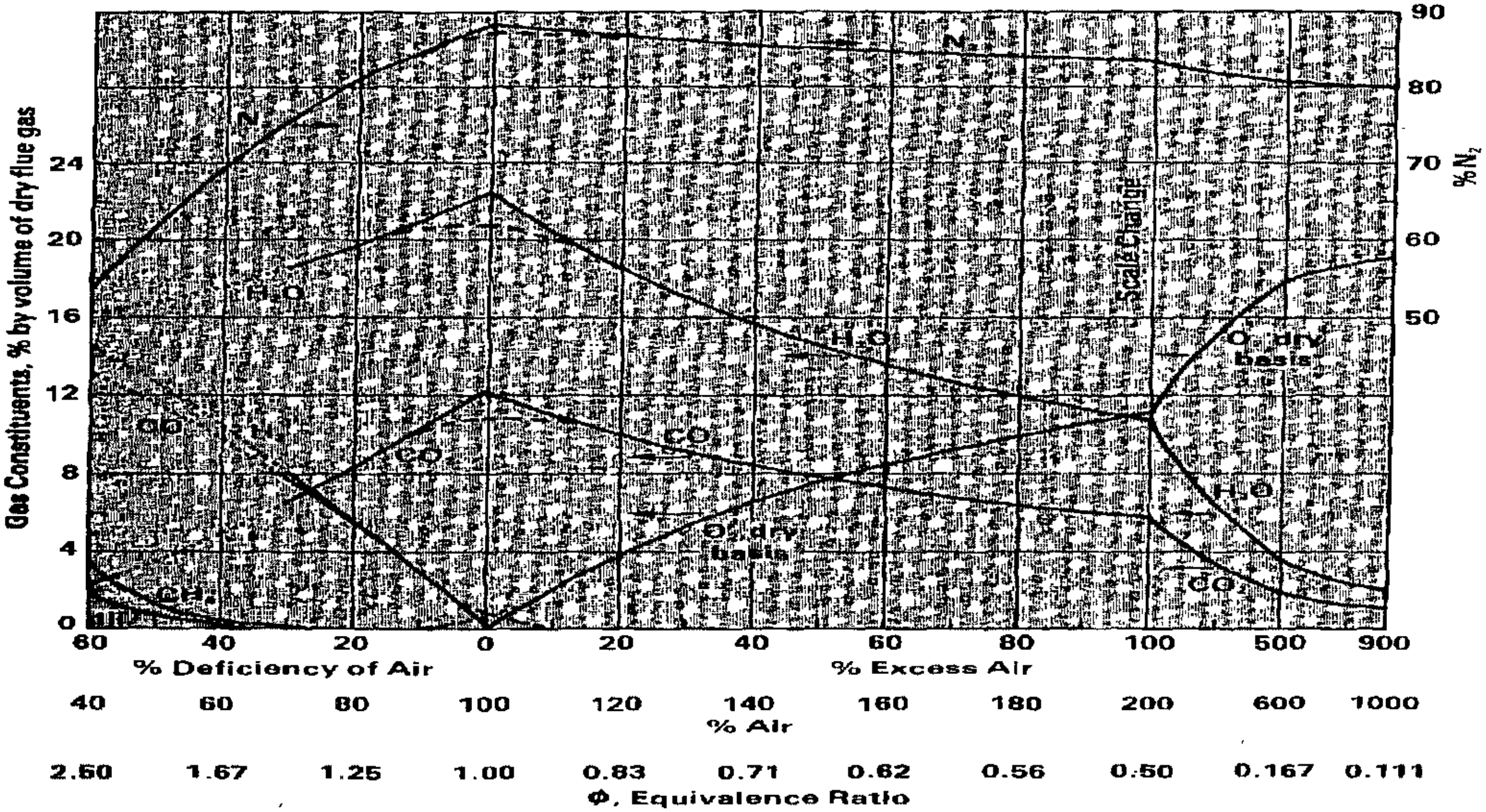

Table 3.5a. Effect of excess air on %O_2 and %CO_2 in combustion products of fuels from Tables 2.1a and b

Fuels		%Excess air									
		0	10	20	40	60	80	100	200	400	1000
		ϕ, Equivalence ratio									
	%O_2 wet %O_2 dry %CO_2 dry a/f ratio*	1.00	0.91	0.83	0.71	0.62	0.56	0.50	0.33	0.20	0.09
Natural gas (Birmingham)		0	1.73	3.20	5.55	7.35	8.77	9.92	13.5	16.4	18.8
		0	2.09	3.80	6.43	8.36	9.83	11.0	14.4	17.1	19.2
		11.7‡	10.6	9.61	8.14	7.05	6.22	5.57	3.65	2.16	0.97
		9.44	10.4	11.3	13.2	15.1	17.0	18.9	28.3	47.2	104
Blast furnace gas		0	0.89	1.70	3.15	4.39	5.47	6.42	9.82	13.4	17.1
		0	0.89	1.71	3.17	4.41	5.50	6.45	9.86	13.4	17.1
		25.5‡	24.4	23.4	21.7	20.1	18.8	17.6	13.5	9.17	4.68
		0.68	0.75	0.82	0.95	1.09	1.23	1.36	2.04	3.41	7.49
Producer gas (W-G, bituminous)		0	1.23	2.32	4.18	5.70	6.97	8.04	11.6	14.9	18.0
		0	1.35	2.54	4.54	6.14	7.46	8.56	12.1	15.4	18.3
		18.5‡	17.3	16.2	14.5	13.1	11.9	10.9	7.75	4.90	2.33
		1.30	1.43	1.56	1.82	2.08	2.34	2.60	3.90	6.50	14.3
Coke oven gas (by-product)		0	1.69	3.12	5.43	7.21	8.63	9.78	13.3	16.3	18.8
		0	2.10	3.82	6.46	8.39	9.87	11.0	14.4	17.1	19.2
		10.8‡	9.71	8.82	7.46	6.46	5.70	5.10	3.34	1.98	0.89
		5.44	5.98	6.53	7.62	8.70	9.79	10.9	16.3	27.2	59.8
Propane (natural)		0	1.77	3.26	5.64	7.46	8.89	10.0	13.6	16.5	18.9
		0	2.06	3.75	6.36	8.28	9.75	10.9	14.3	17.0	19.2
		13.7‡	12.3	11.2	9.53	8.27	7.31	6.55	4.30	2.55	1.15
		23.8	26.2	28.5	33.3	38.0	42.8	47.6	71.3	119	262
Butane (natural)		0	1.77	3.27	5.65	7.47	8.90	10.1	13.6	16.5	18.9
		0	2.05	3.74	6.34	8.26	9.73	10.9	14.3	17.0	19.2
		14.0‡	12.6	11.5	9.75	8.46	7.48	6.70	4.41	2.61	1.18
		30.6	33.7	36.8	42.9	49.0	55.2	61.3	91.9	153	337

* ft^3 air/ft^3 fuel, m^3 air/m^3 fuel, or any ratio of volumes in consistent units.

‡ Ultimate %CO_2.

Table 3.5b. Effect of excess air on %O_2 and %CO_2 in combustion products of fuels from Tables 2.1a and b

Fuels		%Excess air									
		0	10	20	40	60	80	100	200	400	1000
		φ, Equivalence ratio									
		1.00	0.91	0.83	0.71	0.62	0.56	0.50	0.33	0.20	0.09
#1 Distillate oil	%O_2 wet	0	1.79	3.31	5.71	7.54	8.97	10.1	13.6	16.5	18.9
	%O_2 dry	0	2.02	3.69	6.27	8.18	9.65	10.8	14.3	17.0	19.1
	%CO_2 dry	15.4‡	13.9	12.6	10.8	9.35	8.27	7.42	4.89	2.91	1.31
	a/f ratio†	190	209	228	267	305	343	381	571	952	2090
#2 Distillate oil	%O_2 wet	0	1.80	3.31	5.72	7.55	8.99	10.1	13.7	16.5	18.9
	%O_2 dry	0	2.02	3.68	6.26	8.16	9.63	10.8	14.2	16.9	19.1
	%CO_2 dry	15.6‡	14.1	12.9	11.0	9.53	8.44	7.57	4.99	2.97	1.34
	a/f ratio†	188	207	225	263	301	338	376	564	939	2070
#5 Residual oil	%O_2 wet	0	1.81	3.33	5.75	7.58	9.02	10.2	13.7	16.6	18.9
	%O_2 dry	0	2.00	3.65	6.22	8.13	9.59	10.8	14.2	16.9	19.1
	%CO_2 dry	16.3‡	14.7	13.4	11.4	9.95	8.81	7.90	5.22	3.11	1.40
	a/f ratio†	182	200	219	255	291	328	364	546	911	2000
#6 Residual oil	%O_2 wet	0	1.82	3.35	5.77	7.61	9.04	10.2	13.7	16.6	18.9
	%O_2 dry	0	1.99	3.64	6.20	8.10	9.56	10.7	14.2	16.9	19.1
	%CO_2 dry	16.7‡	15.1	13.8	11.8	10.2	9.07	8.14	5.38	3.21	1.45
	a/f ratio†	175	193	210	246	281	316	351	526	877	1930
Bituminous coal	%O_2 wet	0	1.83	3.37	5.80	7.64	9.08	10.2	13.8	16.6	18.9
	%O_2 dry	0	1.95	3.57	6.10	7.99	9.45	10.6	14.1	16.8	19.1
	%CO_2 dry	18.5‡	16.8	15.3	13.1	11.4	10.1	9.10	6.04	3.61	1.64
	a/f ratio†	141	155	169	197	225	254	282	423	704	1550
Coke	%O_2 wet	0	1.89	3.46	5.94	7.80	9.25	10.4	13.9	16.7	19.0
	%O_2 dry	0	1.91	3.50	5.99	7.86	9.32	10.5	14.0	16.7	19.0
	%CO_2 dry	20.4‡	18.6	17.0	14.6	12.8	11.3	10.2	6.80	4.08	1.85
	a/f ratio†	132	145	158	184	211	237	263	395	658	1450

† ft^3 air/lb fuel.
‡ Ultimate %CO_2.

Instruments. Many types of instruments are available for analyzing flue gases. Most indicate the percent by volume of the various compounds in the dry flue gas. One of the most common instruments is the Orsat apparatus, which works on the principle of selective *absorption* of the gases by chemical solutions. The Orsat apparatus indicates percentages of CO_2, O_2, and CO. The percent CO_2 is often the only analysis made. *Conductivity* type analyzers, which sense the difference in the cooling effect of different gases, can be very accurate if calibrated properly and frequently. Analysis of *combustibles* in the flue gases (CO, H_2, and hydrocarbons) may be accomplished by burning the combustibles with a measured volume of air or oxygen, usually in the presence of a catalyst. The percentage of combustibles in the flue gas is then proportional to the measured heat released.

Oxygen analysis can be determined continuously and without time delay by use of a solid electrolyte, zirconium oxide. The galvanic action yields an output signal in the form of a variable electromotive force that can be used for automatic air/fuel ratio control. Note in Table 3.5 that $\%O_2$ changes very little with changes in fuel analysis.

COMBUSTION EFFICIENCY

For any furnace, oven, kiln, or boiler, the overall combustion efficiency, or fuel *efficiency, is 100% minus the summation of all losses.* As illustrated by the Sankey diagram of Figure 3.6,

$$[3/30] \qquad \text{efficiency, \%} = \left(\frac{\text{useful output}}{\text{gross input}}\right) \times 100, \text{ or } \left(\frac{\text{gross input} - \text{total losses}}{\text{gross input}}\right) \times 100$$

where the input, the output, and the losses are all measured in consistent units such as Btu/hr, kcal/s, joules/kg of fuel, or gallons of fuel per ton of product.

The **losses** to conveyors, fixtures, walls, and openings can be calculated using specific heat data from the Appendix and heat transfer data from Part 4. The *flue gas losses (stack loss)* are described and evaluated in this section. They include the heat carried away by the dry flue gases (such as CO_2, N_2, O_2, and CO) and the heat carried away by the moisture (H_2O) in the flue gases. This moisture loss is the latent and sensible heat in water formed by combustion of hydrogen in the fuel.

Dry flue gas loss (dfg loss) is equal to the amount of heat given up by the dry combustion products as they cool from the final exit temperature (after all heat recovery devices) to the base temperature used in evaluating the gross calorific value of the fuel (usually 60 F or 15.6 C). This loss can be calculated by the following formulas.

[3/31] dfg loss = dfg flow rate × (dfg heat content at flue temperature − dfg heat content at base temperature)

or, in American weight units, Btu/hr = lb dfg/hr × (Btu/lb from Table 3.7a − 0)

or, in American volume units, Btu/hr = cfh dfg × (Btu/scf from Table 3.7b − 0)

or, in Metric weight units, kcal/hr = kg dfg/hr × (kcal/kg from Table 3.7c − 0)

or, in Metric volume units, kcal/hr = m^3 dfg/hr × (kcal/m^3 from Table 3.7d − 0)

For flue gases consisting of mixtures of gases, the losses due to each of the flue gas constituents should be added:

[3/32] dfg loss = CO_2 flow rate × CO_2 heat content + N_2 flow rate × N_2 heat content + O_2 flow rate × O_2 heat content + etc.

Tables 3.7a, b, c, d list heat contents (enthalpies) measured above a base of 60 F or 15.6 C.

Figure 3.6. Sankey diagram for a furnace heat balance. Gross input − moist flue gas loss = net input; net input − dry flue gas loss = available heat input. These terms can be evaluated in any consistent heat or energy units per unit of time per unit of fuel, or per unit of production output. A diagram such as this makes it easier to visualize areas of possible improvement in furnace efficiency.

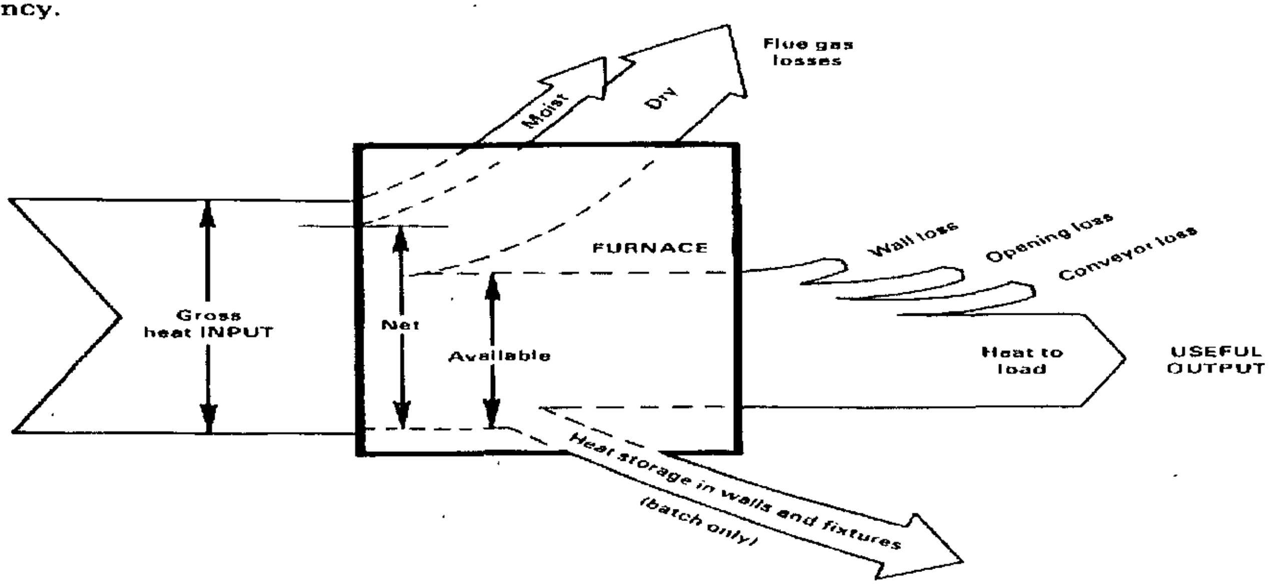

Table 3.7a. Heat contents of combustion gases,* in Btu/lb

Gas temperature, F / Btu/lb	Air†	CO	CO_2	H_2	H_2O‡	N_2	O_2	SO_2
60	0	0	0	0	0	0	0	0
100	9.7	9.8	8.3	139.1	17.7	9.8	8.7	6.0
200	34.0	34.7	29.6	486.8	62.4	34.6	30.9	21.5
300	58.4	59.8	52.0	834.9	108.0	59.7	53.5	37.7
400	79.7	85.3	75.2	1 183.6	154.4	85.0	76.5	54.4
500	106	111.1	99.4	1 533.0	201.7	110.6	99.9	71.7
600	128	137.1	124.3	1 883.2	249.7	136.4	123.6	89.5
800	179	190.2	176.5	2 586.9	348.4	188.8	172.1	126.5
1000	233	244.3	231.4	3 295.9	450.4	242.3	221.8	165.2
1200	288	299.6	288.7	4 011.2	555.8	296.8	272.0	205.2
1400	342	356.0	347.9	4 734.1	664.5	352.3	324.3	246.2
1600	397	413.3	408.6	5 465.8	776.6	408.8	376.8	288.0
1800	452	471.6	470.5	6 207.5	892.2	466.3	429.9	330.3
2000	510	530.8	533.2	6 960.3	1011.1	524.7	483.4	372.7
2200	568	590.8	596.3	7 725.3	1133.4	584.1	537.2	415.0
2400	626	651.7	659.5	8 503.9	1259.2	644.4	591.2	456.9
2600	685	713.3	722.3	9 297.1	1388.5	705.7	645.1	498.1
2800	742	775.6	784.3	10 106.1	1521.2	767.9	698.9	538.3
3000	801	838.6	845.2	10 932.2	1657.4	831.0	752.3	577.1
3200	859	902.3	904.6	11 776.4	1797.0	895.0	805.2	614.4
3400	918	966.5	962.1	12 640.0	1940.2	959.8	857.5	649.8
3600	975	1031.2	1017.4	13 524.2	2086.8	1025.6	909.1	683.0
3800	1048	1096.4	1069.9	14 430.0	2237.0	1092.2	959.6	713.8

Table 3.7b. Heat contents of combustion gases,* in Btu/scf△

Gas temperature, F / Btu/scf	Air†	CO	CO_2	H_2	H_2O‡	N_2	O_2	SO_2
60	0	0	0	0	0	0	0	0
100	0.74	0.73	0.96	0.73	0.84	0.73	0.74	1.02
200	2.60	2.56	3.44	2.57	2.96	2.56	2.61	3.63
300	4.47	4.42	6.04	4.41	5.13	4.41	4.52	6.36
400	6.1	6.30	8.74	6.25	7.33	6.28	6.46	9.18
500	8.1	8.20	11.54	8.09	9.58	8.17	8.43	12.10
600	9.8	10.13	14.44	9.94	11.86	10.08	10.44	15.11
800	13.7	14.05	20.49	13.65	16.55	13.95	14.53	21.36
1000	17.8	18.05	26.87	17.39	21.39	17.90	18.73	27.89
1200	22.0	22.14	33.51	21.17	26.40	21.93	23.02	34.64
1400	26.2	26.30	40.38	24.98	31.56	26.03	27.39	41.58
1600	30.4	30.53	47.44	28.84	36.89	30.20	31.82	48.63
1800	34.6	34.84	54.62	32.76	42.37	34.45	36.30	55.77
2000	39.0	39.21	61.91	36.73	48.02	38.77	40.82	62.94
2200	43.5	43.65	69.23	40.77	53.83	43.15	45.38	70.08
2400	47.9	48.14	76.56	44.88	59.81	47.61	49.91	77.16
2600	52.4	52.70	83.85	49.06	65.94	52.14	54.47	84.11
2800	56.8	57.30	91.06	53.33	72.25	56.73	59.01	90.89
3000	61.3	61.96	98.13	57.69	78.71	61.39	63.52	97.46
3200	65.7	66.66	105.02	62.14	85.35	66.12	67.99	103.75
3400	70.2	71.40	111.70	66.70	92.15	70.91	72.40	109.73
3600	74.6	76.19	118.11	71.37	99.11	75.77	76.75	115.34
3800	80.2	81.00	124.21	76.15	106.24	80.69	81.02	120.53

* Computer-calculated data based on formulae from Reference 3.a listed at end of Part 3, except †. None of the values in Table 3.7 are corrected for dissociation.

† From Reference 3.b.

Table 3.7c. Heat contents of combustion gases,* in kcal/kg

kcal/kg Gas temperature, C	Air †	CO	CO_2	H_2	H_2O ‡	N_2	O_2	SO_2
15.6	0	0	0	0	0	0	0	0
100	20.5	20.9	17.9	292.9	37.6	20.8	18.6	13.0
200	43.3	46.1	40.6	640.3	83.5	46.0	41.4	29.4
300	68.1	71.9	65.0	989.1	130.9	71.5	64.8	46.8
400	92.8	98.3	90.7	1339.6	179.8	97.6	88.8	65.1
500	119	125.1	117.7	1692.3	230.1	124.1	113.5	84.1
600	146	152.5	145.8	2047.7	282.0	151.1	138.8	103.8
700	174	180.3	174.9	2406.3	335.4	178.5	164.2	124.1
800	201	208.6	204.8	2768.5	390.3	206.4	190.1	144.7
900	229	237.3	235.3	3134.9	446.8	234.7	216.4	165.7
1000	256	266.5	268.2	3505.8	504.7	263.5	242.9	186.8
1100	285	296.1	297.5	3881.8	564.2	292.7	269.6	207.9
1200	314	326.0	329.0	4263.4	625.3	322.3	296.5	229.0
1300	343	356.3	360.5	4651.0	687.8	352.4	323.4	249.9
1400	373	387.0	391.9	5045.2	752.0	382.8	350.3	270.6
1500	401	418.0	422.9	5446.3	817.6	413.7	377.1	290.7
1600	431	449.3	453.6	5854.8	884.9	445.0	403.8	310.4
1700	460	480.9	483.6	6271.3	953.7	476.7	430.4	329.4
1800	489	512.7	512.8	6698.2	1024.0	508.8	456.6	347.6
1900	518	544.8	541.2	7130.0	1095.9	541.3	482.6	365.0
2000	548	577.2	568.5	7573.1	1169.5	574.1	508.2	381.3
2100	585	609.7	594.5	8026.0	1244.5	607.4	533.4	396.5

Table 3.7d. Heat contents of combustion gases,* in kcal/m^3 △

kcal/m^3 Gas temperature, C	Air †	CO	CO_2	H_2	H_2O ‡	N_2	O_2	SO_2
15.6	0	0	0	0	0	0	0	0
100	25.0	24.7	33.2	24.7	28.6	24.6	25.2	35.1
200	52.9	54.5	75.5	54.1	63.5	54.3	55.9	79.4
300	83.2	85.0	120.7	83.5	98.5	84.6	87.6	126.5
400	113	116.2	168.6	113.1	136.6	115.4	120.1	175.9
500	145	147.9	218.8	142.8	174.8	146.8	153.3	227.4
600	178	180.3	271.0	172.9	214.4	178.7	187.3	280.6
700	212	213.2	325.0	203.2	255.0	211.1	221.9	335.3
800	245	246.7	380.5	233.8	296.7	244.1	256.9	391.1
900	280	280.6	437.1	264.8	339.6	277.6	292.4	447.7
1000	313	315.1	494.7	296.1	383.7	311.6	328.3	504.7
1100	348	350.1	552.9	327.8	428.9	346.1	364.4	561.9
1200	383	385.5	611.4	360.1	475.3	381.1	400.6	619.0
1300	419	421.3	669.9	392.8	522.8	416.6	437.0	675.5
1400	456	457.6	728.2	426.1	571.6	452.7	473.3	731.2
1500	490	494.2	785.9	460.0	621.5	489.2	509.6	785.8
1600	528	531.2	842.8	494.5	672.6	526.2	545.7	838.9
1700	562	568.6	898.5	529.7	724.9	563.8	581.6	890.3
1800	597	606.2	952.9	565.5	778.4	601.8	617.1	939.5
1900	633	644.2	1005.6	602.2	833.1	640.0	652.2	986.4
2000	669	682.4	1056.3	639.6	888.9	678.9	686.8	1030.5
2100	714	720.9	1104.7	677.9	946.0	718.2	720.8	1071.5

‡ Water vapor. Does not include latent heat of vaporization. See Tables A.5a and A.5b.

△ The standard cubic foot (scf) and the cubic metre (m^3) are measured at a temperature of 60 F (15.6 C) and at an atmospheric pressure of 29.92″Hg (760 mm Hg).

Moisture loss is equal to the amount of heat that is given up by the water vapor in the flue gases as it cools from the furnace exit temperature to the base temperature used in evaluating the calorific value of the fuel. Most of the moisture loss is the latent heat of condensation of the water vapor formed by combustion of hydrogen in the fuel. As illustrated in Figure 3.6, the *gross heating value minus the moisture loss per unit of fuel is equal to the net heating value* per unit of fuel.

$$[3/33] \quad \text{moisture loss} = \text{lb } H_2O/\text{hr}^* \times (\text{vapor enthalpy at flue temperature} - \text{liquid enthalpy at base temperature})$$

where the liquid enthalpy is [base temperature (F) − 32], and the vapor enthalpy can be obtained from Table A.5 in the Appendix. As an alternate, the following approximate formula may be used:

$$[3/34] \quad \text{moisture loss, in Btu/hr} = \text{lb } H_2O/\text{hr}^* \times [1088 + 0.46 \times (t_2 - 60)]$$

where t_2 is the furnace exit temperature (F) and 60 is the base temperature (F) used to evaluate the gross heating value of the fuel.

Available heat is the gross quantity of heat released within a combustion chamber, minus both the dry flue gas loss and the moisture loss. It represents the amount of heat remaining for useful heating, plus wall, conveyor, (storage) and opening losses. Figure 3.8 shows how the concept of available heat is used to simplify analyses of furnace losses. Figure 3.9 shows the variation in available heat with exit gas temperature for several typical fuels under conditions of perfect combustion. Figure 3.10 is a generalization for all fuels giving *percent* available heat with various flue temperatures and various amounts of excess air.† The percent additional loss due to a *deficiency of air* (excess fuel) will be approximately equal to the percent deficiency of air or $\frac{\%\text{ excess fuel}}{100 + \%\text{ excess fuel}}$.

Either excess air or excess fuel reduces the % available heat. The *perfect combustion* or *0% excess air* line on Figure 3.10 represents the best possible efficiency, as for a perfect furnace with no losses through walls, openings, fixtures, conveyors, or storage.

Example 3-6. *Determine the efficiency of a boiler* using 70 gal/hr of #2 fuel oil (137 080 Btu/gal, 7.22 lb/gal) if the temperature of the flue gases after the last pass is 500 F. The radiation and convection losses from the walls have been estimated as 3% of the gross input. (Calculation of wall losses is explained in Part 4, page 100.)

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* If moisture in the flue gas has been expressed in scf H_2O, as from formula 3/15, such figures can be converted to lb H_2O by multiplying by 0.0476.

† See footnote (†) on page 71.

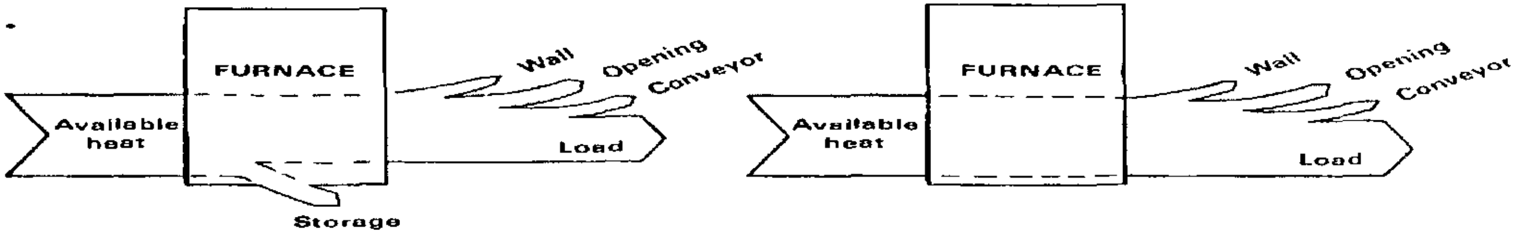
Simplified solution. From Figure 3.9, curve B, at 500 F, the available heat is 114 000 Btu/gal or (70 × 114 000) = 7 980 000 Btu/hr. The % available heat = 114 000/137 080 = 83%. The sum of the dry gas loss and the moisture loss is then 100 − 83 = 17%. There should be no loss due to incomplete combustion or due to radiation through furnace openings in this case. The total loss is therefore the sum of the dry flue gas loss, the moisture loss, and the wall loss or 17 + 3 = 20%. The percent of the gross input which goes into evaporating water in the boiler is then 100 − 20 = 80%, and this is the efficiency of the unit. If excess air is used, Figure 3.10 can be used to estimate the additional loss. From Figure 3.13 a 20% deficiency of air will result in about 60% available heat. This minus 3% wall loss will result in 57% efficiency.

Detailed solution. A more accurate calculation of the efficiency may be had by use of formula 3/32 to calculate the dry flue gas loss and formula 3/33 to calculate the moisture loss. To use these formulas, it is first necessary to determine the fuel analysis (from the supplier, Table 2.1, or Table 2.12) and then calculate constituents of the flue gas by formulas 3/25, 3/27, 3/28a, and 3/29a of Table 3.3 (or formulas 3/13, 3/15, and 3/16 of Table 3.2 for gaseous fuels)...using data from Table 2.1 in this case...

$\text{ft}^3\ CO_2/\text{lb fuel} = 87.3 \times 0.3155 = 27.54$
$\text{ft}^3\ H_2O/\text{lb fuel} = 12.5 \times 1.880 = 23.50$
$\text{ft}^3\ SO_2/\text{lb fuel} = 0.21 \times 0.1182 = 0.02$
$\text{ft}^3\ N_2/\text{lb fuel} = 87.3 \times 1.193 + 12.5 \times 3.553 + 0.21 \times 0.4468 = 148.7.$

Substituting in formula 3/32 and taking heat content values from Table 3.7b at 500 F, dfg loss = 27.54 × 11.54 + 148.7 × 8.17 + 0.02 × 12.10 = 1533 Btu/lb of fuel or 1533 × 7.22 lb/gal × 70 gal/hr = 774 700 Btu/hr, which is equivalent to 1533 × 7.22/137 080 = 8.07%. From formula 3/33*, the moisture loss = 23.50 × 0.0476 × [1287.3 − (60 − 32)] = 1408 Btu/lb of fuel or 711 800 Btu/hr, which is equivalent to 1408 × 7.22/137 080 = 7.42%. Therefore the percent available is 100 − 8.07 − 7.42 = 84.5%. (This compares with 83% by Figure 3.9.) The efficiency of the boiler is then 84.5 − 3 = 81.5%.

Figure 3.8. By starting with available heat instead of gross heat, furnace heat balances are greatly simplified. The Sankey diagram at left is for a batch-type furnace; the one at right, for a continuous furnace.



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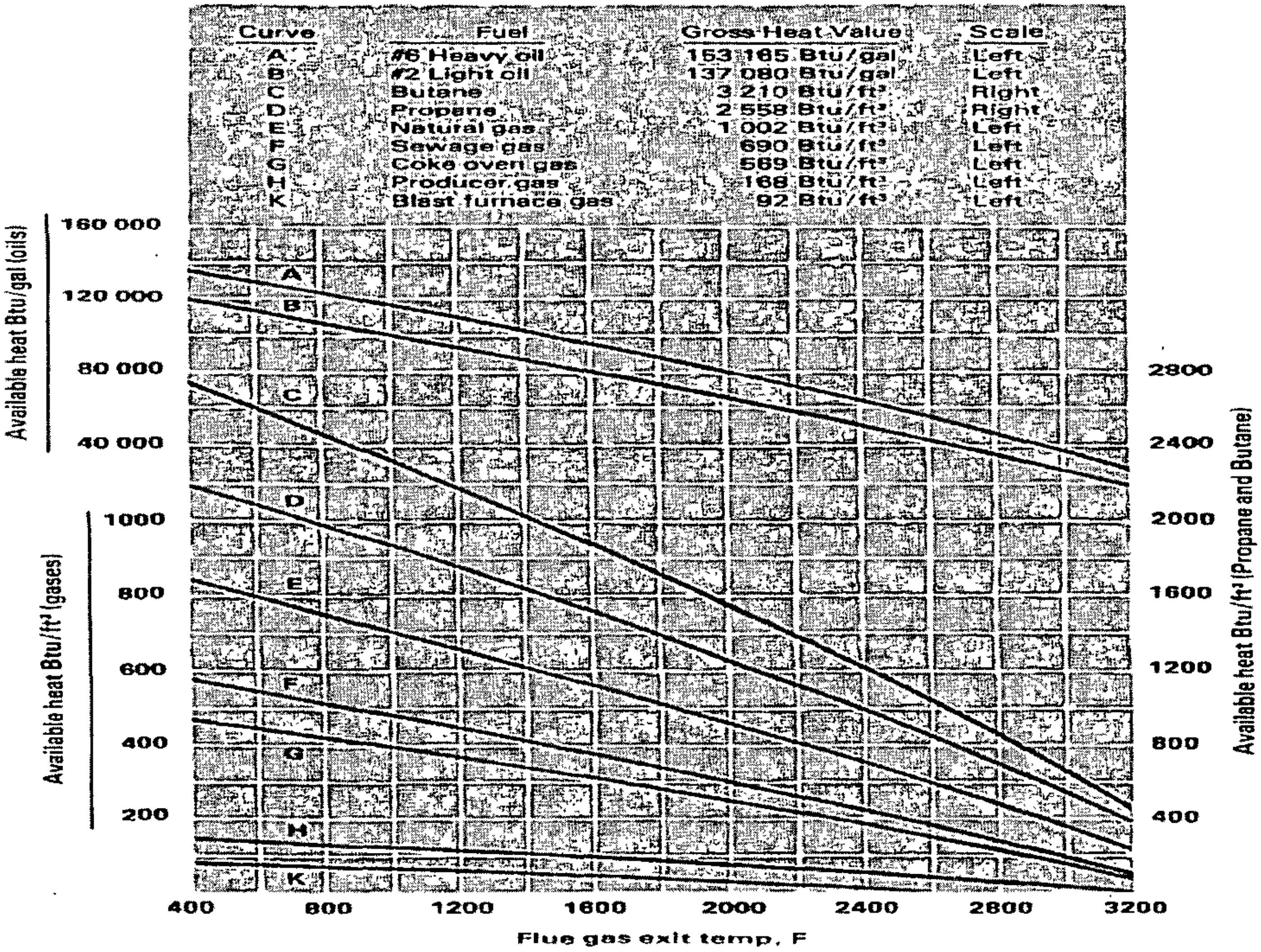
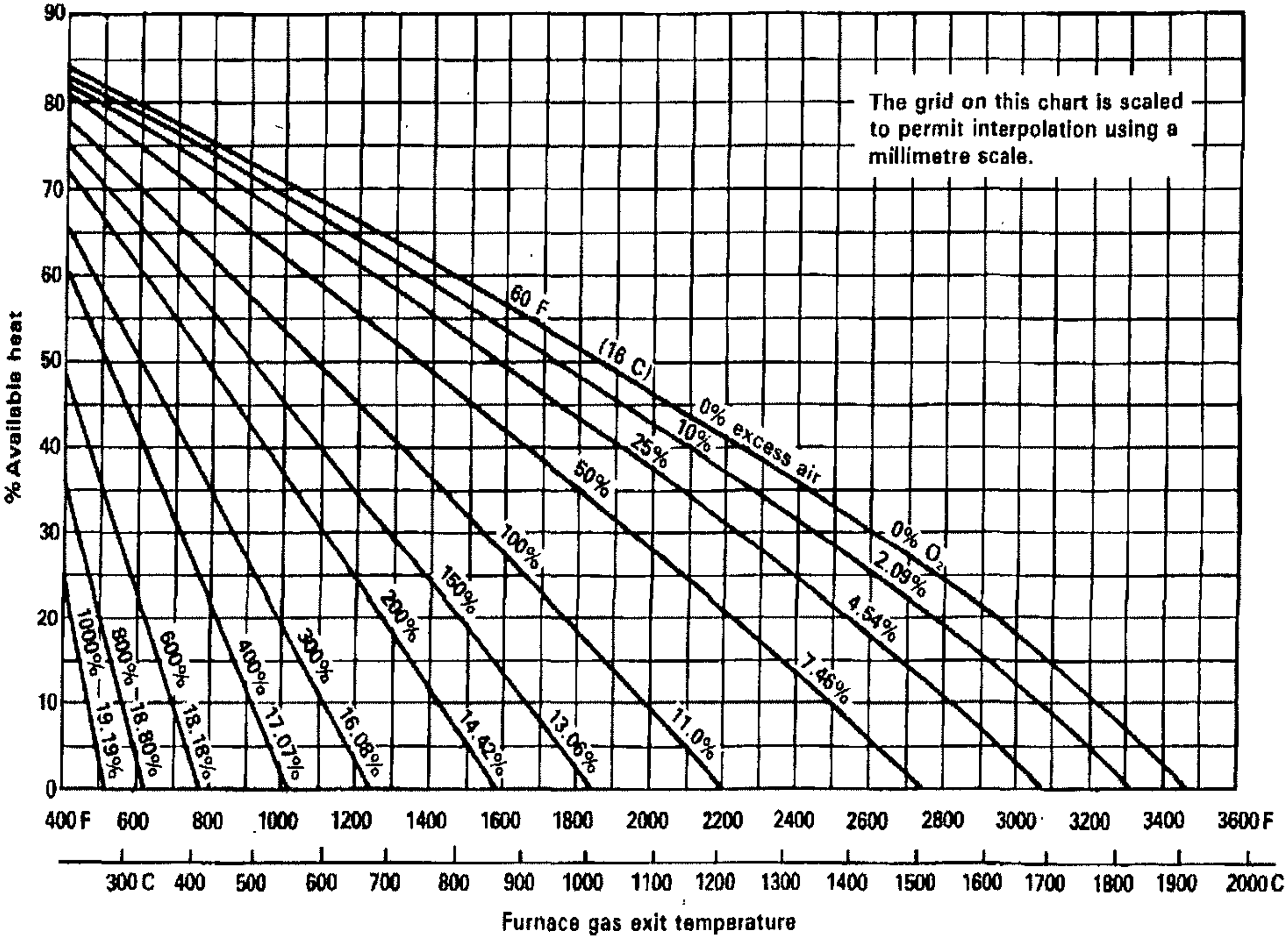
* Moisture loss must include latent heat, so Table 3.7 cannot be used.

Figure 3.9. Available heats for some typical fuels. The fuels listed below are identified by their gross heating values. Further information concerning these fuels may be found in Tables 2.1 and 2.12. (See Example 3-6.) All available heat figures are based upon perfect combustion and a fuel input temperature of 60 F.



Curve	Fuel	Gross Heat Value	Scale
A	#6 Heavy oil	153 165 Btu/gal	Left
B	#2 Light oil	137 080 Btu/gal	Left
C	Butane	3 210 Btu/ft³	Right
D	Propane	2 558 Btu/ft³	Right
E	Natural gas	1 002 Btu/ft³	Left
F	Sewage gas	690 Btu/ft³	Left
G	Coke oven gas	569 Btu/ft³	Left
H	Producer gas	168 Btu/ft³	Left
K	Blast furnace gas	92 Btu/ft³	Left

Figure 3.10. Available heat chart for 1000 Btu/ft^3 natural gas*, showing the effect of excess air upon available heat. Based on 60 F (16 C) air. Applicable only if there is no unburned fuel in the products of combustion. Corrected for dissociation of CO_2 and H_2O. See also Figures 3.11, 12, 15, 17. See Examples 3-6, 7, 8. See footnote (†) on page 71. The x-intercept is the adiabatic flame temperature (hot mix temperature) for that particular curve. Example: With 25% excess air with natural gas (4.54% O_2 in the furnace exit gas), the adiabatic flame temperature is 3070 F, or 1688 C.



The grid on this chart is scaled to permit interpolation using a millimetre scale.

*For other fuels, see Figure 3.9.

Example 3-7. *Find the air required* to maintain 25% excess air through 16 burners on a hardening furnace with 1000 C (1800 F) exit gas temperature if the available heat required is 0.81 million kcal/hr (3.2 million Btu/hr). The fuel is Algeria LNG (Table 2.12b) having 10 132 gross kcal/m^3 (1139 gross Btu/ft^3) and requiring 10.76 volumes of air per volume of fuel.

From Figure 3.10, at 1000 C and 25% excess air, read 43% available. Therefore the gross input required is 810 000/0.43 = 1 880 000 kcal/hr. Select 16 burners each with at least 1 880 000/16 = 117 700 kcal/hr capacity each.

The fuel gas input required will be 1 880 000/10 132 = 185.6 m^3/hr. The air required for stoichiometric combustion would be 185.6 × 10.76 = 1997 m^3/hr; but for the requested 25% excess air, the required burner air capacity will be 1.25 × 1997 = 2496 m^3/hr.

Operating experience with high velocity recirculating burners will probably show that the 25% excess air is not required; so fuel can be conserved by adjusting the fuel/air ratio closer to the stoichiometric ratio.

Example 3-8. *Select burners and a blower for a dual-purpose furnace* with the following specifications:

	Hardening	**Drawing**
Available Btu/hr required	4 200 000	92 000
Flue gas exit temp., F	1 900	1 000

Solution: For the hardening operation, Figure 3.10 gives 48% available heat with perfect combustion.

$$\text{Therefore } \frac{4\ 200\ 000}{0.48} = 8\ 750\ 000 \text{ gross Btu/hr.}$$

Burners selected: fourteen 6422-4 Burners, each rated 6300 cfh air (or 630 000 Btu/hr) with 16 osi air pressure at the burners, for a total gross input of 8 820 000 Btu/hr.

$$\text{Blower capacity required} = \frac{8\ 820\ 000 \text{ gross Btu/hr}}{100 \text{ gross Btu/ft}^3 \text{ air}} = 88\ 200 \text{ cfh.}$$

Blower selected: 2324-35/2-15 Turbo Blower (rated 96 000 cfh at 24 osi).

Example 3-9: *How much excess air for low fire?* For holding during the low temperature operation on the above furnace, the fuel flow will be reduced and the air left on at high fire rate, thus providing excess air. How much excess air should be used at low fire?

$$\textit{Solution:} \text{ First find the ratio, } \frac{\text{available Btu required at low fire}}{\text{cfh air supplied with air on full}} = \frac{92\ 000}{88\ 200} = 1.04.$$

Then, from Figure 3.11 (follow the dotted arrow) read 380% excess air and 4.8 to 1 required valve turndown. If no excess air were used, the required valve turndown would have been the same as the gross Btu turndown, or 8 240 000 ÷ (92 000/0.71) = 63.6 to 1. [0.71 is from 71% available at 1000 F, read from Figure 3.10.]

The 6422-4 Burner selected above is stable with more than the required 380% excess air; so it will still operate satisfactorily. However, a look at Figure 3.10 shows that the % available heat at 1000 F and 380% excess air is only about 6%; so the drawing

Example 3-10. *How much uniformity can be expected* from the combination selected in Example 3-9?

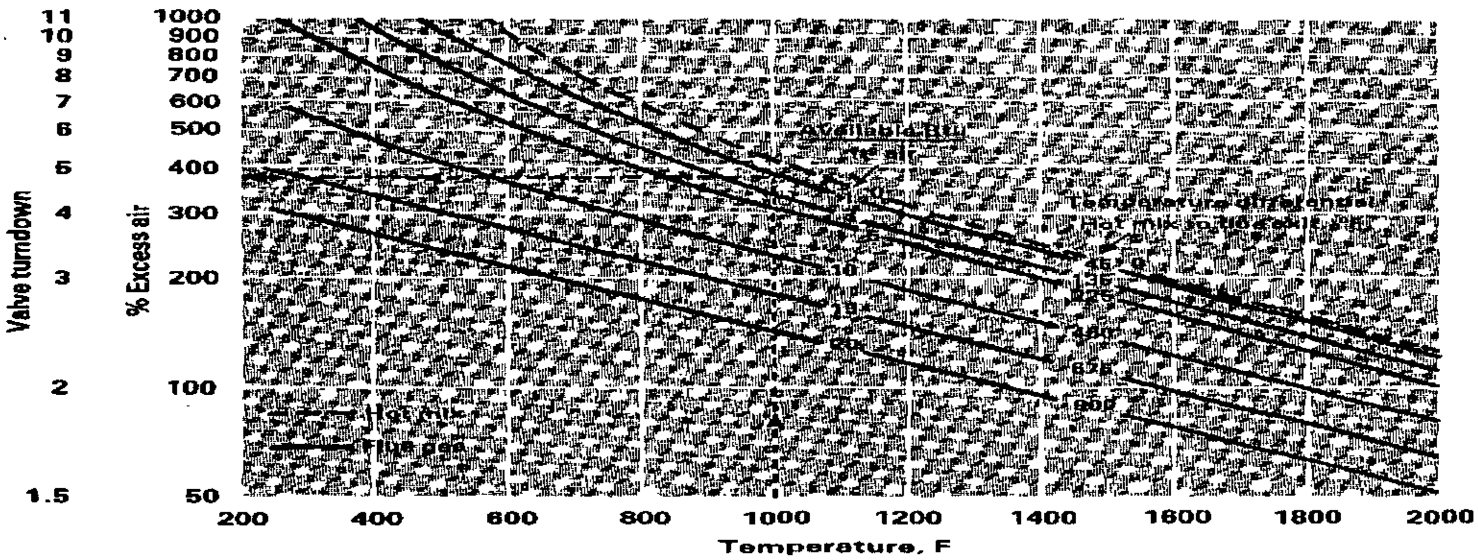
Solution: By interpolation from Figure 3.11, it is found that for 1.04 Btu available/ft³ of air supplied, the hot mixture issuing from the flame tip is only about 50° above the flue gas exit temperature. This can also be surmised from Figure 3.12 or from the x-intercept of Figure 3.10.

This is the maximum temperature differential within the furnace gases. The maximum temperature differential within the work would be a fraction of this. Just how small a fraction depends on placement of the work and is not a function of burner operation.

Example 3-11. A forge furnace is fired with heavy oil (13° API; 152 000 Btu/gallon) and operates at 2200 F. The flue gas exit temperature is approximately 2400 F. The radiation loss through openings has been estimated at 1 152 000 Btu/hr and the wall loss at 162 000 Btu/hr. The firing rate is 50 gallons per hour. What efficiency can be expected from this furnace, and how much steel can it heat per hour?

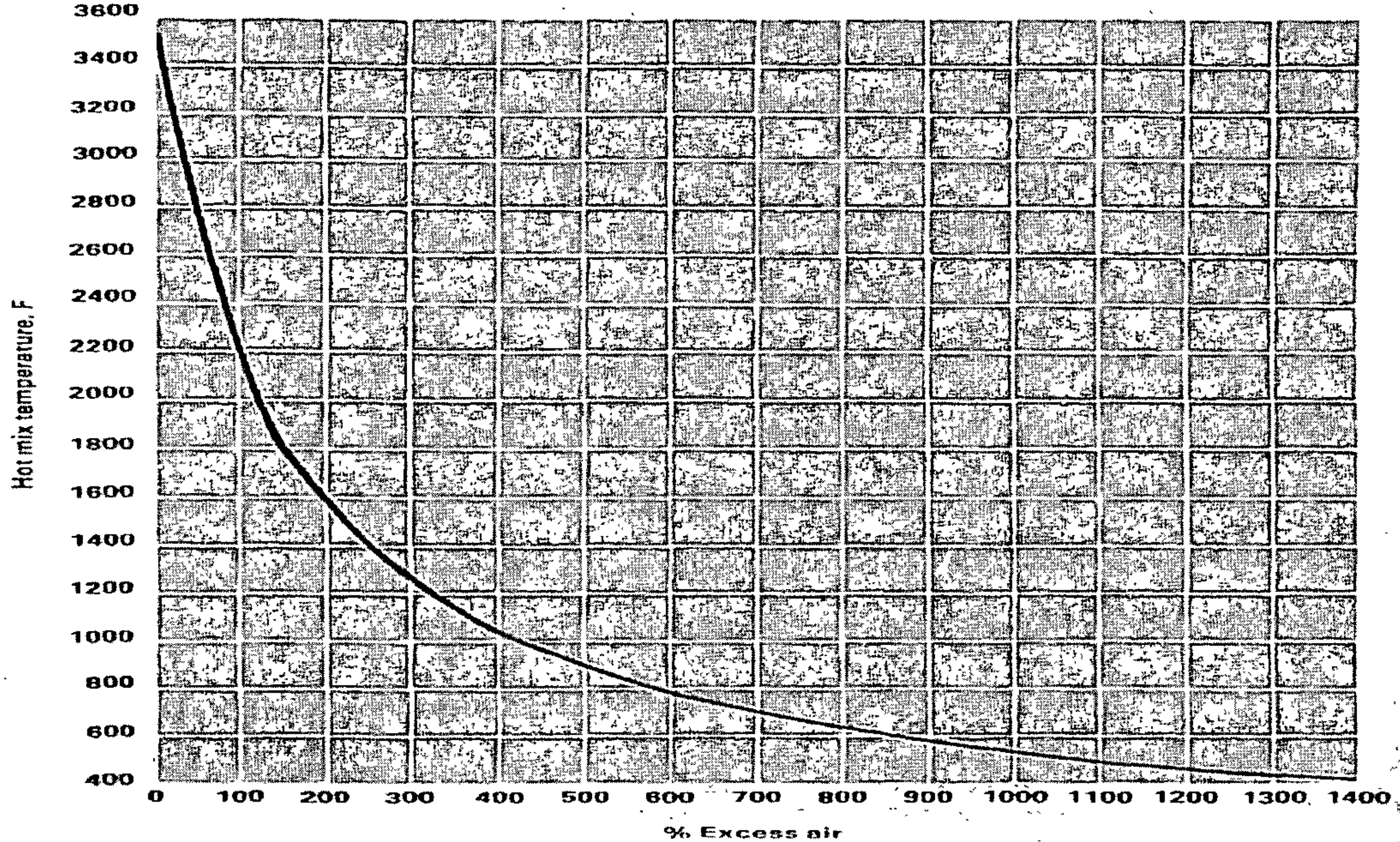
Simplified solution. The gross input rate is (50 gal/hr) × (152 000 Btu/gal) = 7 600 000 Btu/hr. From Figure 3.9 the available heat of a 152 000 Btu/gal oil is 65 000 Btu/gal. Subtracting the losses through openings and walls from the available heat, the heat left for heating the steel is (65 000 Btu/gal) × (50 gal/hr) − 1 152 000 Btu/hr − 162 000 Btu/hr = 1 936 000 Btu/hr. The efficiency is therefore $\frac{1\,936\,000}{7\,600\,000} = 25.5\%$.

Figure 3.11. Excess air required for various temperature differentials.



From Figure A.7 in the Appendix, the heat content of steel at 2200 F is 340 Btu/lb. Therefore the furnace can heat 1 936 000 ÷ 340 = 5690 pounds of steel per hour.

Figure 3.12. Effect of excess air on hot mix temperature. Points for this graph are derived from an available heat chart for distillate oil at the intersections of the excess air curves with the zero available heat line (x-intercepts). Similar "tempering" of the "flame" or hot mix temperature is achieved by use of high velocity burners, whose jet induces recirculation and mixing of furnace gases with the new combustion products.



Detailed solution. The gross input rate is (50 gal/hr) × (152 000 Btu/gal) = 7 600 000 Btu/hr. From formulas 2/5 and 2/8, 13°API is found to be equivalent to a specific gravity of 0.98 and a specific weight of 8.17 lb/gal. By formula 2/10, the %hydrogen is found to be $25 - \frac{2122.5}{13 + 131.5} = 10.3$. Assuming that about 98% of the fuel is combustible material (the remainder being water, sediment, oxygen, and nitrogen), the hydrogen will constitute 10.3 × 0.98 = 10.1% of the fuel. This leaves 98 − 10.1 = 87.9% carbon.

Determining the flue gas constituents from formulas 3/19, 3/20, and 3/22a,

lb CO_2/lb fuel = 87.9 × 0.0366 = 3.22; so lb CO_2/hr = 3.23 lb CO_2/lb fuel × 8.17 lb fuel/gal × 50 gal/hr = 1315.

lb H_2O/lb fuel = 10.1 × 0.0894 = 0.903; so lb H_2O/hr = 0.903 × 8.17 × 50 = 369.

lb N_2/lb fuel = 87.9 × 0.0882 + 10.1 × 0.2626 = 10.41; so lb N_2/hr = 10.41 × 8.17 × 50 = 4252.

Using formula 3/32 and Table 3.7a, dfg loss = 1315 × 659.5 + 4252 × 644.4 = 3 607 000 Btu/hr. From formula 3/34, moisture loss = 369 × [1088 + 0.46 × (2400 − 60)] = 799.000 Btu/hr. The total loss is the sum of the dry flue gas loss, the moisture loss, the opening loss, and the wall loss, or 3 607 000 + 799 000 + 1 152 000 + 162 000 = 5 720 000 Btu/hr, which is 5 720 000/7 600 000 = 75% of the gross input. The efficiency is therefore 100 − 75 = 25%. The heat left for heating the steel is 7 600 000 − 5 720 000 = 1 880 000 Btu/hr. From Figure A.7 in the Appendix, the heat content of steel at 2200 F is 340 Btu/lb. Therefore the furnace can heat 1 876 000/340 = 5529 pounds of steel per hour.

Losses due to incomplete combustion include the loss due to incomplete burning of carbon monoxide, hydrogen, and hydrocarbons (including aldehydes from poor mixing or quenching, as described in Figure 3.4), and the loss due to unburned solid fuel which becomes trapped in the refuse.

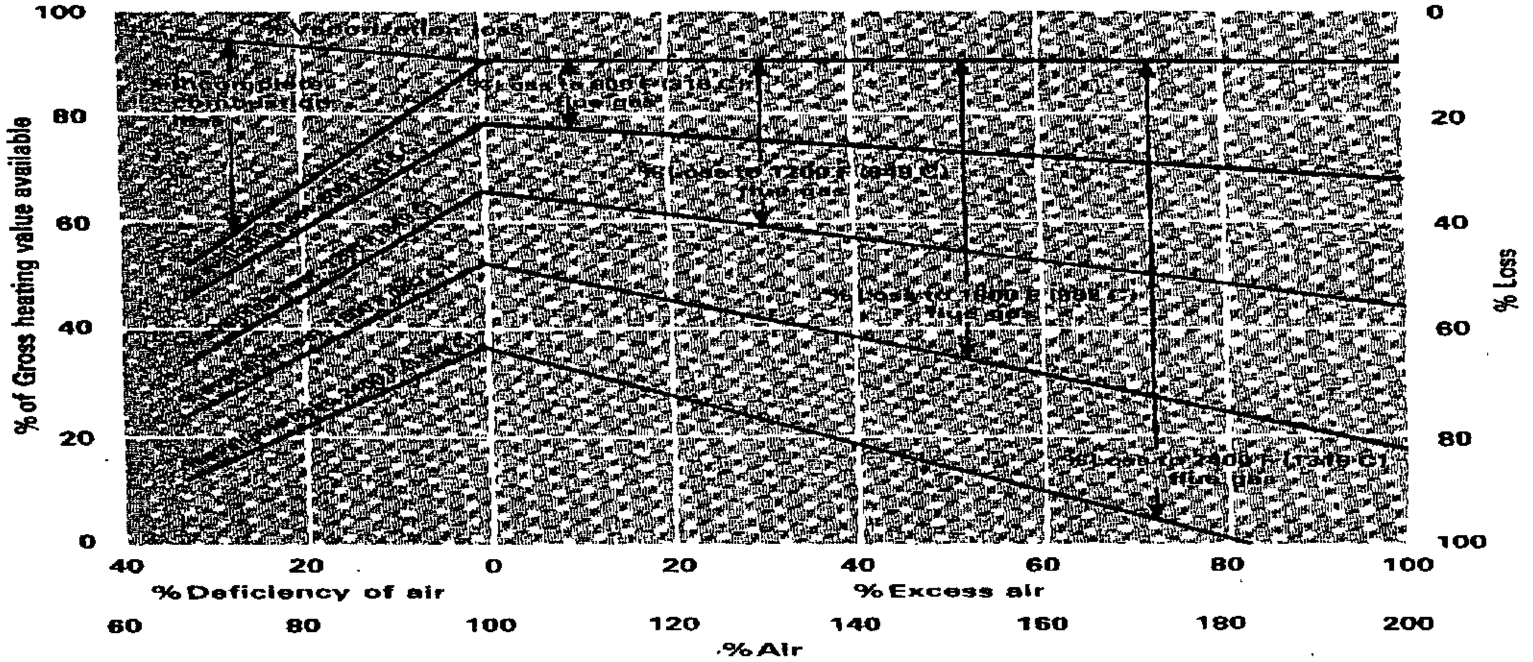
Incomplete combustion may be intentional, as in instances where the process requires a reducing atmosphere. The percent loss due to a deficiency of air is roughly equal to the percent deficiency. Figure 3.13 shows the loss due to incomplete combustion of natural gas, more precisely.

Example 3-12. If perfect combustion of a fuel requires 10 ft^3 of air per ft^3 of fuel, but only 9 ft^3 of air is supplied per ft^3 of fuel, then the percent deficiency of air is [(10 − 9)/10] × 100 = 10%. This 10% deficiency of air results in a loss due to incomplete combustion of about 10%.

Optimum Air Supply. The optimum air supply for best thermal efficiency in a furnace is that at which the sum of the loss due to incomplete combustion and the loss due to heat in the flue gases is a minimum. In cases where thorough high speed mixing is possible, the optimum air/fuel ratio is the chemically correct air/fuel ratio. This is usually the case when the fuel is gas or oil. When the mixing is poor, it is often necessary to add excess air to increase the completeness of combustion. This excess air then adds to the quantity of the flue gases. Accurate determination of the optimum point requires a series of furnace tests at a variety of air/fuel ratios, but the point may be approximated by finding the air/fuel ratio that produces the maximum $\%CO_2$.

Figure 3.13 illustrates the manner in which the various losses change with the air/fuel ratio. If the mixing were thorough, the incomplete combustion loss would be zero at the chemically correct air/fuel ratio, and the minimum total loss (maximum % available) would also occur at the chemically correct air/fuel ratio.

Figure 3.13. Variation of furnace losses and available heat with air/fuel ratio. This graph is based on 1108 Btu/ft³ natural gas (0.63 gas gravity, 83% CH_4, 16% C_2H_6). As an example, with 80% aeration (20% deficiency of air), reading down on the **right-side scale**, the loss to vaporization of water formed by combustion of hydrogen in the fuel is 7%, leaving 93% net. The incomplete combustion loss is (33 − 7) = 26%. If the flue gas leaves the furnace at 1800 F, the dry flue gas loss is (65 − 33) = 32%, leaving (100 − 65) = 35% available for useful heating and to balance losses through wall, openings, and conveyors.



- *TEORÍA*
- *DE LA*
- *COMBUSTIÓN*

- *Por Alfredo Sánchez Flores*
- *Abril de 2004*