FACULTAD DE INGENIERIA U.N.A.M.
DIVISION DE EDUCACION CONTINUA

CURSOS INSTITUCIONALES

DIPLOMADO

en

MANTENIMIENTO II

MODULO:II MANEJO DE GAS

MATERIAL DIDACTICO

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Villahermosa, Tab.

14-18 octubre de 1996

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MANEJO DE GAS.
PARTE I.

TEMARIO.

1.1. ORIGEN Y OCURRENCIA GEOLOGICA.

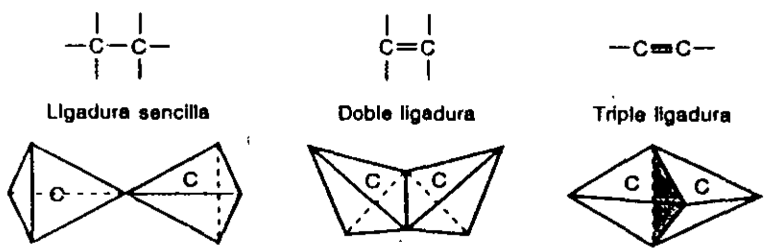
DEFINICION HIDROCARBUROS.

SON COMPUESTOS FORMADOS UNICAMENTE POR HIDROGENO Y CARBONO.

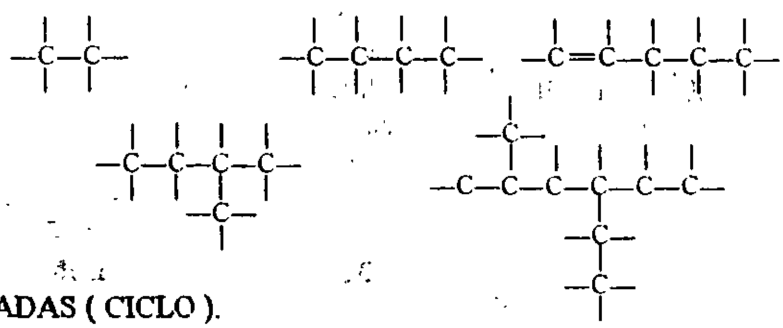
CARBONO.

EL CARBONO SE LOCALIZA EN EL GRUPO IVA DE LA TABLA PERIODICA.

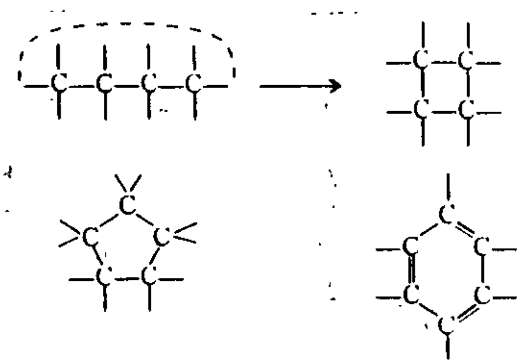
LOS ATOMOS DE CARBONO PUEDEN UNIRSE MEDIANTE ENLACES, SENCILLOS, DOBLES O TRIPLES.
EL ENLACE ES SATURADO CUANDO LA UNION ES SENCILLA Y NO SATURADO CUANDO ES DOBLE O TRIPLE.



LA CONCATENACION (CADENAS) PUEDEN SER ABIERTAS (EN FORMA LINEAL O TENER RAMIFICACIONES).



O SER CERRADAS (CICLO).



EN GENERAL, LOS HIDROCARBUROS SE PUEDEN CLASIFICAR COMO SE INDICA EN LA TABLA.

Hidrocarburos	Acíclicos (Cadena abierta)	Saturados	Ligadura sencilla (Alcanos)	Normales o lineales Arborescentes
		No saturados	Doble ligadura (Alquenos)	Normales o lineales Arborescentes
			Triple ligadura (Alquinos)	Normales o lineales Arborescentes
	Cíclicos (Cadena cerrada)	Saturados	Ciclanos o alicíclicos	
		No saturados	Bencénicos o aromáticos	

ALCANOS O PARAFINAS.

NO SON ACTIVOS QUIMICAMENTE Y POR ELLO SE LES LLAMA PARAFINAS, DEL LATIN PARUM (POCA), AFFINIS (AFINIDAD), POCA AFINIDAD.
EJEMPLOS: METANO, ETANO, PROPANO, n BUTANO, ETC.

PROPIEDADES FISICAS.
SON INCOLOROS, TIENEN OLOR CARACTERISTICO, SU DENSIDAD, PUNTO DE FUSION Y EL DE EBULLICION AUMENTA CONFORME SE INCREMENTA EL NUMERO DE ATOMOS DE CARBON.

PROPIEDADES QUIMICAS.
SON BASTANTE INERTES, BAJO COMBUSTION PRODUCEN CO_2 Y H_2O, LIBERAN GRAN CANTIDAD DE ENERGIA TERMICA Y LUMINOSA.

ALQUENOS O OLEFINAS (ASPECTO ACIETOSO)

LOS ALQUENOS SON HIDROCARBUROS NO SATURADOS CON DOBLE LIGADURA, SU TERMINACION ES "ENO", ETENO, PROPENO, BUTENO, ETC.
LA FORMULA GENERAL DE LOS ALQUENOS ES C_nH_{2n}, DONDE n ES EL NUMERO DE ATOMOS DE CARBONO.

PROPIEDADES FISICAS.
LOS PRIMEROS TRES COMPUESTOS SON GASEOSOS A PRESION Y TEMPERATURA AMBIENTE, LOS SIGUIENTES SON LIQUIDOS, LOS ALQUENOS CON MAS DE 16 ATOMOS DE CARBONO EN SU MOLECULA, SON SOLIDO.
SON INSOLUBLES EN AGUA, SU DENSIDAD, PUNTO DE FUSION Y DE EBULLICION SE ELEVAN CONFORME AUMENTA SU PESO MOLECULAR.

PROPIEDADES QUIMICAS.
LOS ALQUENOS PRESENTAN REACCIONES DE ADICION RELATIVAMENTE SENCILLAS.
CON HIDROGENO, EN PRESENCIA DE CATALIZADORES, FORMAN ALCANOS.

ALQUINOS O ACETILENICOS.

SON HIDROCARBUROS NO SATURADOS CON TRIPLE LIGADURA, SU TERMINACION ES "INO".
LA FORMULA GENERAL DE LOS ALQUINOS ES C_nH_{2n-2}.

PROPIEDADES FISICAS.
LOS TRES PRIMEROS SON GASEOSOS EN CONDICIONEES NORMALES, EL CUARTO AL DECIMO SON LIQUIDOS Y SOLIDOS A PARTIR QUE TIENE 16 ATOMOS DE CARBONO.

PROPIEDADES QUIMICAS.
PRESENTAN REACIONES DE ADICION.CON HIDROGENO Y SEGUN LAS CONDICIONES DE LA REACCION, FORMAN ALQUENOS O ALCANOS.

DEFINICION DE PETROLEO.

LA PALABRA "PETROLEO" SIGNIFICA ACIETE DE PIEDRA, SUS RAICES ETIMOLOGICAS SON PETRA (PIEDRA) Y OLEUM (ACEITE).
EL PETROLEO ES UN MEZCLA DE HIDROCARBUROS Y OTROS COMPUESTOS (AZUFRE, NITROGENO, ETC.)

LA PALABRA "CHAPOPOTE" PROVIENE DEL NAHUALT CHAPOPOCTLI, QUE SE DERIVA DE CHIAHUATL (GRASA) Y POCTLI (HUMO).

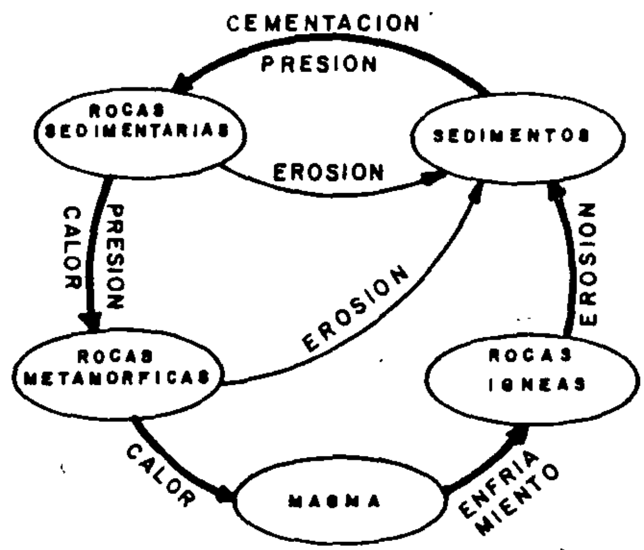
EL PETROLEO AMERICANO APROXIMADAMENTE EN UN 90 % SON ALCANOS, EN EL CASO EUROPEO, PREDOMINA LOS CICLANOS (CICLOPENTANO, CICLOHEXANO, ETC).

CLASIFICACION DE LAS ROCAS.

LAS ROCAS PUEDEN DIVIDIRSE EN TRES GRANDES GRUPOS, DE ACUERDO A SU ORIGEN:

A) ROCAS IGNEAS.
B) ROCAS SEDIMENTARIAS.
C) ROCAS METAMORFICAS.

LA FIGURA SIGUIENTE MUESTRA EL CICLO EVOLUTIVO DE LAS ROCAS.



A) ROCAS IGNEAS.

CUANDO OCURRE UNA ERUPCION, EL MAGMA LANZADO A LA SUPERFICIE, AL SER ENFRIADO FORMA LAS ROCAS IGNEAS.

B) ROCAS SEDIMENTARIAS.

COMO PRODUCCION DE LOS PROCESOS EROSIVOS, Y POR LA ACCION DE AGENTES DE TRANSPORTE COMO VIENTOS, RIOS Y MARES, ASI COMO LA PROPIA ACCION DE LA VIDA GENERADORA DE SEDIMENTOS ORGANICOS, DA ORIGEN A LAS ROCAS SEDIMENTARIAS.

PARA LA INDUSTRIA DEL PETROLEO, ESTAS ROCAS SON LAS MAS IMPORTANTES, YA QUE DE EN ELLAS OCURRE EL ORIGEN, MIGRACION Y ACUMULACION DE DEPOSITOS DE HIDROCARBUROS.
ESTAS ROCAS SE CLASIFICAN A SU VEZ EN:

* CLASTICAS..
* QUIMICAS.
* ORGANICAS.

LAS ROCAS SEDIMENTARIAS CLASTICAS. SON AQUELLAS FORMADAS A PARTIR DE LOS FRAGMENTOS DE OTRAS ROCAS. QUE YA EXISTIAN O COMPUESTOS DE MINERALES.

LAS ROCAS SEDIMENTARIAS QUIMICAS. SON LAS QUE SE FORMAN POR LA PRECIPITACION, EVAPORIZACION DE AGUAS SALOBRES Y REACCIONES QUIMICAS DE SALES DISUELTAS.

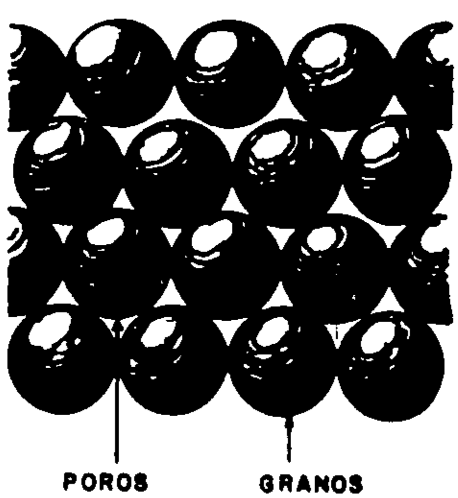
LAS ROCAS SEDIMENTARIAS ORGANICAS. SON LAS QUE SE FORMAN POR DESECHOS ORGANICOS DE PLANTAS Y ANIMALES.

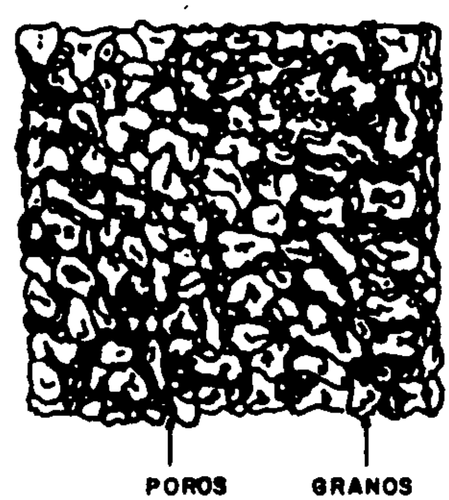
ESTAS ROCAS POSEEN DOS PROPIEDADES IMPORTANES QUE SON:

POROSIDAD
PERMEABILIDAD.

POROSIDAD.
LOS ESPACIOS ENTRE LAS PARTICULAS DE UNA ROCA SE DENOMINAN POROS, ESTOS PUEDEN OCUPARSE POR FLUIDOS COMO AGUA, ACEITE O GAS. EN ALGUNAS ROCAS ESTOS ESPACIOS PUEDEN O NO ESTAR COMUNICADOS, LO CUAL ES MUY IMPORTANTE, YA QUE DE ESTO DEPENDE QUE PUEDA EXISTIR FLUJO A TRAVES DE LA ROCA.

PERMEABILIDAD.
LA PERMEABILIDAD DE UNA ROCA, ES LA MEDIDA DE SU CAPACIDAD ESPECIFICA PARA QUE EXISTA FLUJO A TRAVES DE ELLA.





C) ROCAS METAMORFICAS.

CUANDO LAS ROCAS DE LA CORTEZA TERRESTRE, SE ENCUENTRAN BAJO LA INFLUENCIA DE PRESION POR COLUMNAS DE SEDIMENTOS, TRACCION POR MOVIMIENTOS TELURICOS, ELEVACION DE TEMPERATURA POR ACTIVIDADES IGNEAS, ETC. LLEGAN A TRANSFORMARSE EN ROCAS METAMORFICAS, Y COMO SE APRECIA EN EL CILO DE LA ROCAS, ESTAS PUEDEN FUNDIRSE Y VOLVERSE MAGMA.

TEORIAS SOBRE EL ORIGEN DEL PETROLEO.

BASICAMENTE SE MANEJAN DOS TEORIAS: LA INORGANICA Y LA ORGANICA.

TEORIA INORGANICA.

ESTA TEORIA ESTABLECE QUE EL ACEITE SE FORMO. AL REACCIONAR EL AGUA, CON CARBUROS METALICOS INCRUSTADOS EN EL MAGMA. DESPLAZANDOSE POSTERIORMENTE A TRAVES DE LAS ROCAS POROZAS. HASTA ACUMULARSE EN TRAMPAS NATURALES.

TEORIA ORGANICA.

ES LA MAS ACEPTADA POR LOS CIENTIFICOS, AFIRMA QUE EL CARBONO E HIDROGENO QUE FORMAN EL PETROLEO, PROVIENEN DE RESTOS DE PLANTAS Y ANIMALES ACUMULADOS A TRAVES DEL TIEMPO GEOLOGICO.(CRETACICO, JURASICO, TRIASICO, CAMBRICO, SILURICO, ETC.).

A MEDIDA QUE SE ACOMODARON LOS SEDIMENTOS, LA ACCION DE LAS BACTERIAS. JUNTO CON LAS CONDICIONES DE PRESION Y TEMPERATURA DIERON LUGAR A LA FORMACION DE HIDROCARBUROS.

MIGRACION DEL PETROLEO.

POR MIGRACION SE ENTIENDE EL MOVIMIENTO DE LIQUIDOS O GASES DEL AREA DONDE SE FORMARON (ROCA MADRE) Y QUE VAN HACIA LA ROCA DONDE SE PUEDEN ACUMULAR (ROCA ALMACEN. LA MIGRACION ES UN PROCESO CONTINUO.

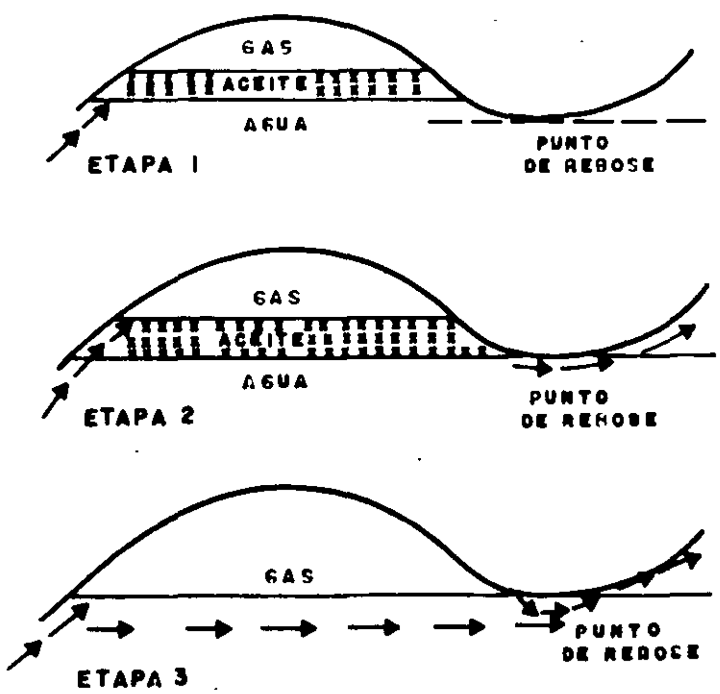
LOS ESQUEMAS QUE A CONTINUACION SE PRESENTAN MUESTRAN EL MOVIMIENTO DE ELLOS.

ETAPA 1. SE MUESTRA LA ESTRATIFICACION DEL GAS. ACEITE Y AGUA ARRIBA DEL PUNTO DE REBOSE DE LA TRAMPA.

ETAPA 2. SE MUESTRA COMO LOS HIDROCARBUROS LLENAN LA TRAMPA HASTA EL PUNTO DE REBOSE. CAUSANDO QUE EL ACIETE MIGRE.

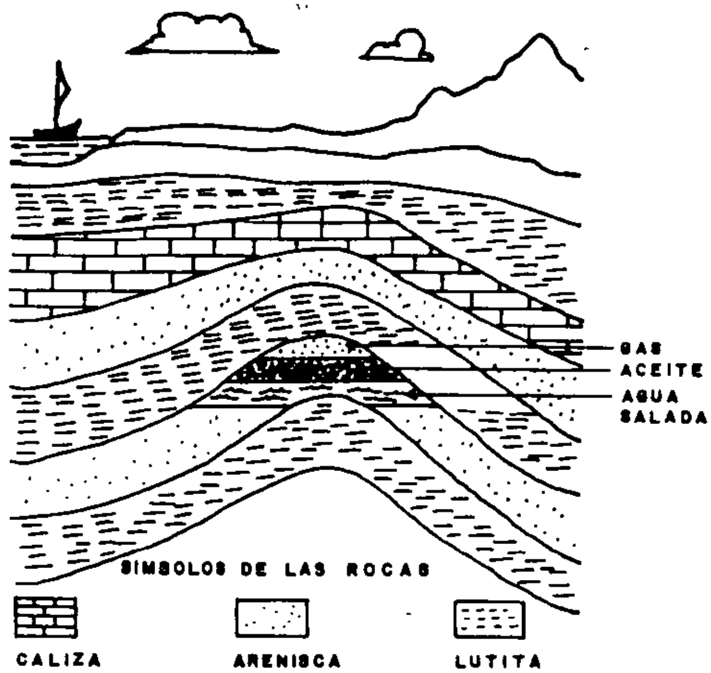
ETAPA 3. SE SEÑALA QUE LA TRAMPA ESTA LLENA DE GAS, ESTE SE MUEVE DESDE ABAJO, ENTRANDO A LA TRAMPA. PERO UN VOLUMEN IGUAL SE REBASA AL MISMO TIEMPO Y EL ACEITE SE DESVIA COMPLETAMENTE DE LA TRAMPA.

DE LA INTERPRETACION ANTERIOR, SE DEDUCE QUE DEBERA EXISTIR, UNA BARRERA NECESARIA PARA IMPEDIR UNA MIGRACION. CON OBJETO DE TENER UNA ACUMULACION DE HIDROCARBUROS.



ALMACENAMIENTO DE HIDROCARBUROS.

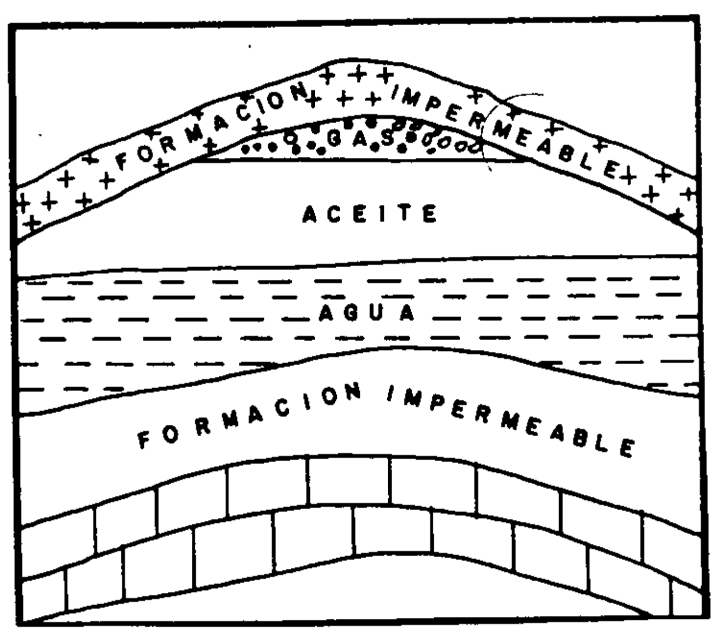
LAS ROCAS DE DEPOSITO (ARENISCAS Y CALIZAS SON LAS COMUNES) SON ROCAS POROSAS CAPACES DE ALMACENAR GAS, ACEITE Y AGUA.
LA FIGURA SIGUIENTE MUESTRA UN YACIMIENTO TIPICO.



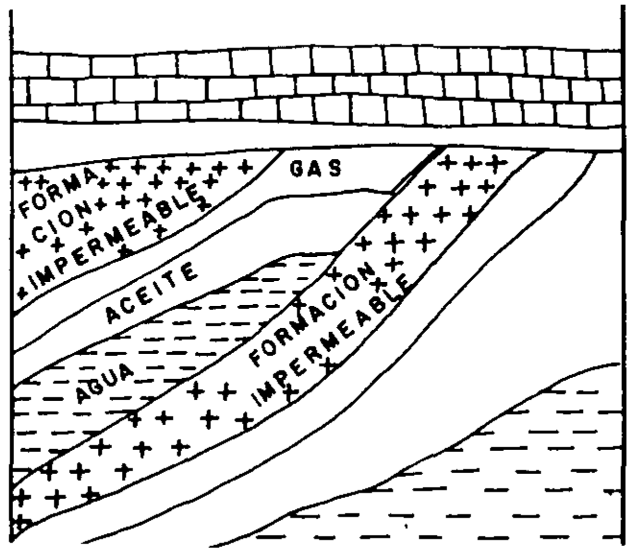
AL TENER LOS TRES FLUIDOS (GAS, ACEITE Y AGUA) DIFERENTES DENSIDADES, OCUPAN DETERMINADOS ESPACIOS EN LA TRAMPA.
DE ESTA FORMA LOS HIDROCARBUROS MIGRAN HACIA ARRIBA A TRAVES DE LA ROCAS Y A LO LARGO DE VARIOS KILOMETROS.

ESTRUCTURAS GEOLOGICAS (CAPACES DE CONTENER H.)

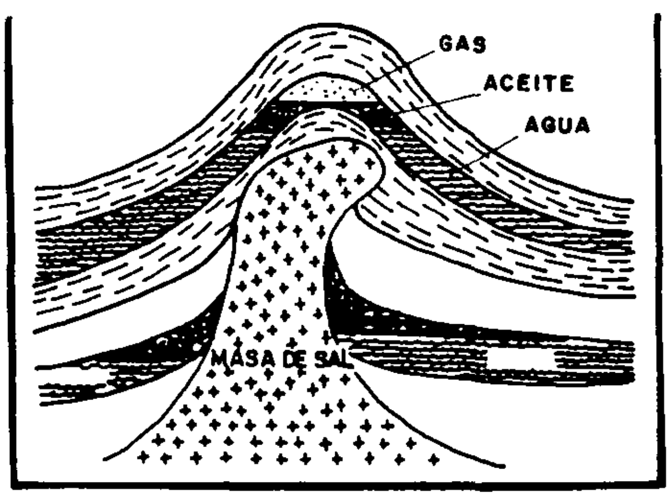
A) ANTICLINAL.
B) TRAMPAS POR FALLAS.
C) ESTRATIGRAFICA
D) ESTRUCTURA SALINAS.



ESTRATIGRAFICA.
ESTRUCTURA O TRAMPA QUE TIENE UN ACUÑAMIENTO DE UNA ARENA PRODUCTIVA, ATRAPADA POR CAPAS IMPERMEABLES. ESTAS DISCORDANCIAS O PERIODOS DE EROSION SEGUIDOS DE DEPOSITACION. LLEGAN A FORMAR TRAMPAS RICAS EN HIDROCARBUROS.



ESTRUCTURA SALINAS.
EN ESTE TIPO DE ESTRUCTURAS, EL NUCLEO O TAPON SALINO, SALIO POR ENTRE SEDIMENTOS SUPRAYACENTES.



CLASIFICACION DE YACIMIENTOS.

POR EL TIPO DE EMPUJE.

- **EMPUJE HIDRAULICO.**
- **EMPUJE VOLUMETRICO POR EXPANSION DE GAS.**
- **EMPUJE MIXTO.**

1.4. COMPOSICION DEL GAS NATURAL.

Table 2 3 Constituents of Wellhead Natural Gas

Class	Component	Formula	Shorthand
Hydrocarbons	Methane	CH_4	C1
	Ethane	C_2H_6	C2
	Propane	C_3H_8	C3
	i Butane	iC_4H_{10}	iC4
	n Butane	nC_4H_{10}	nC4
	i Pentane	iC_5H_{12}	iC5
	n Pentane	nC_5H_{12}	nC5
	Cyclopentane	C_5H_{10}	
	Hexanes and heavier		C6+
Inert Gases	Nitrogen	N_2	N2
	Helium	He	
	Argon	A	
	Hydrogen	H_2	H2
	Oxygen	O_2	O2
Acid Gases	Hydrogen Sulfide	H_2S	H2S
	Carbon Dioxide	CO_2	CO2
Sulfur Compounds	Mercaptans	R-SH	
	Sulfides	R-S-R'	
	Disulfides	R-S-S-R'	
Water Vapor		H_2O	
Liquid Slugs	Free water or brine		
	Corrosion inhibitors		
	Methanol	CH_3OH	
Solids	Millscale and rust		
	Iron sulfide	FeS	
	Reservoir fines		

Table 2–5 Typical Gas Analyses (Mol Percent)

Component	Natural Gas	Natural Gas	Condensate Fluid	Separator Gas
N2	0.51	4.85	—	—
CO2	0.67	0.24	0.47	—
C1	91.94	83.74	82.13	59.01
C2	3.11	5.68	6.37	10.42
C3	1.26	3.47	4.09	15.12
i-C4	0.37	0.30	0.50	2.39
n-C4	0.34	1.01	1.85	7.33
i-C5	0.18	0.18	0.55	2.00
n-C5	0.11	0.19	0.67	1.72
C6	0.16	0.09	1.03	1.18
C7+	1.35	0.25	2.34	0.80
	100.00	100.00	100.00	100.00
C7+ Mol.Wt.	172	115	114	—
C7+ Sp Gr.	0.803	0.744	0.765	—
C2+ GPM	2.5	3.2	5.5	12.3[a]

Source. Kaasa (1978) Kaasa (1978) Allen (1952) Unknown
a Used properties of n C8 for C7+ to calculate GPM C2+

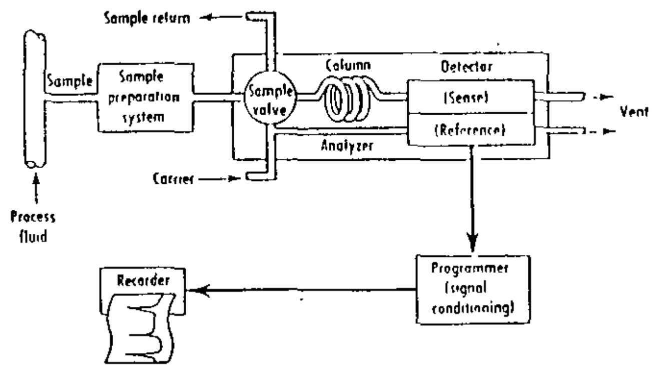


Figure 2–3. Basic chromatography system (Leisey *et al.* 1977).

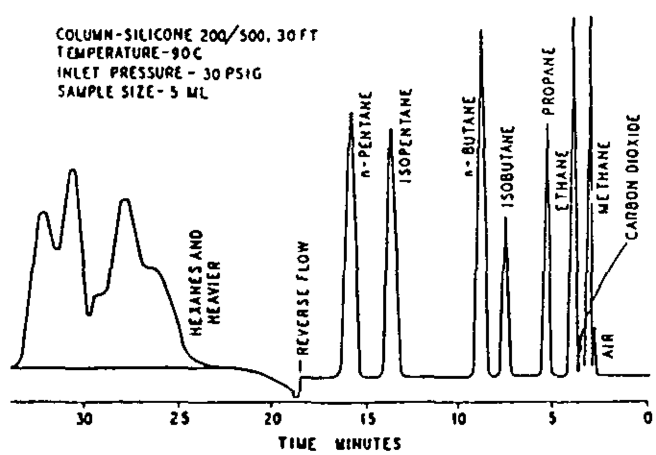


Figure 2–4. Chromatogram of natural gas (Silicone 200/500) (GPA, 1986, Std 2261–86).

DEFINICIONES.

GAS NATURAL. GAS QUE PROVIENE DE YACIMIENTO Y NO HA TENIDO ALGUN PROCESO DE SEPARACION, COMPUESTO PRINCIPALMENTE DE METANO Y ETANO (COMPUESTOS NO LICUABLE A BAJAS PRESIONES Y TEMPERATURA AMBIENTE).

GAS LICUABLE DEL PETROLEO (LP): COMPUESTO DE PROPANO, PROPILENO, BUTANO (INSOBUTANO) Y BUTILENOS, LICUABLE A BAJAS PRESIONES Y TEMPERATURA. A PRESION ATMOSFERICA Y A TEMPERATURA AMBIENTE, SE EVAPORA Y PUEDE SER USADO COMO GAS (PLANTAS DE ESTABILIZADORAS DE GASOLINA).

GAS AMARGO. ES EL QUE CONTIENE H_2S (ACIDO SULFHIDRICO) EN MAS DE 14 PPM Y CO_2 (DIOXIDO DE CARBONO) EN MAS DE 4 PPM.

GAS DULCE. GAS AMARGO TRATADO CON SOLUCION ACUOSA DE DIETANOL AMINA PARA DISMINUIR AL MINIMO EL H_2S (ACIDO) Y CO_2.

GAS HUMEDO. GAS QUE CONTIENE HIDROCARBUROS MAS PESADOS QUE EL METANO Y ETANO.

GAS SECO. GAS QUE SE ENCUENTRA EN UNA FASE Y LAS CANTIDADES DE LIQUIDO QUE LLEVA SON DESPRECIABLES Y PARA SU USO NO REQUIERE SEPARACION.

PUNTO CRITICO. ESTADO DONDE LA FASE VAPOR PURA, TIENE IDENTICAS PROPIEDADES DE LA FASE DE LIQUIDO PURO A LA MISMA PRESION Y TEMPERATURA.

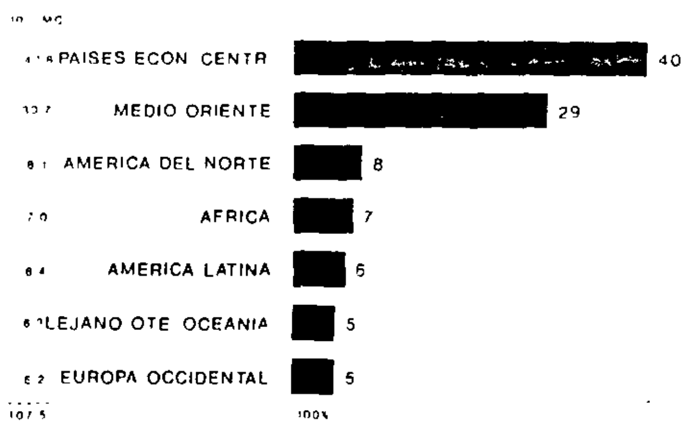
PUNTO TRIPLE. ESTADO EN EL CUAL ES POSIBLE MANTENER UNA MEZCLA DE LAS TRES FASE EN EQUILIBRIO.

TEMPERATURA CRITICA. TEMPERATURA SOBRE LA CUAL ES IMPOSIBLE LICUAR UN GAS MEDIANTE LA APLICACION DE PRESION.

1.2. RESERVAS Y PRODUCCION DE GAS NATURAL.

RESERVAS PROBADAS DE GAS NATURAL A NIVEL MUNDIAL SON DE 107.5 BILLONES DE METROS CUBICOS.

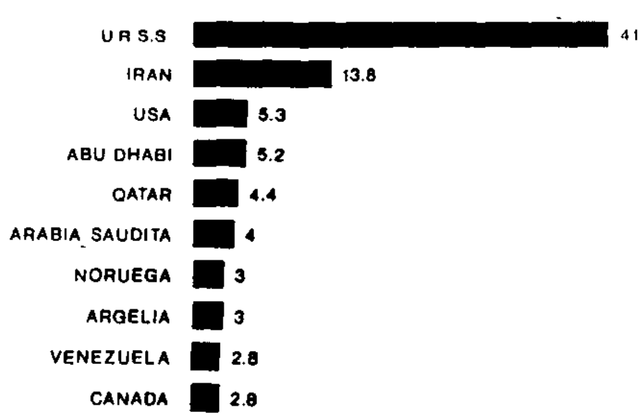
MUNDO
RESERVAS PROBADAS DE GAS NATURAL / 1987



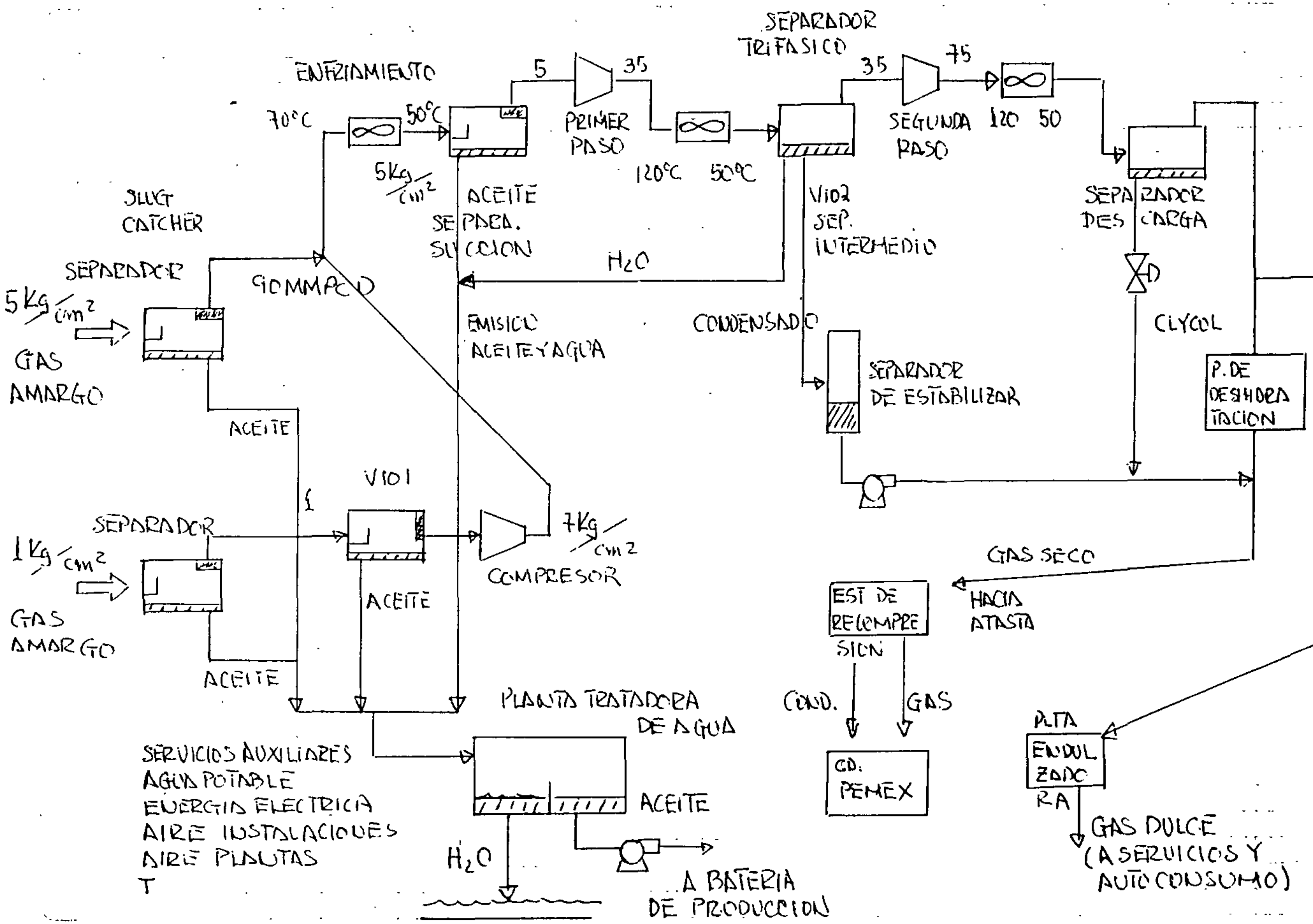
Fuente BP Statiscal Review 1988

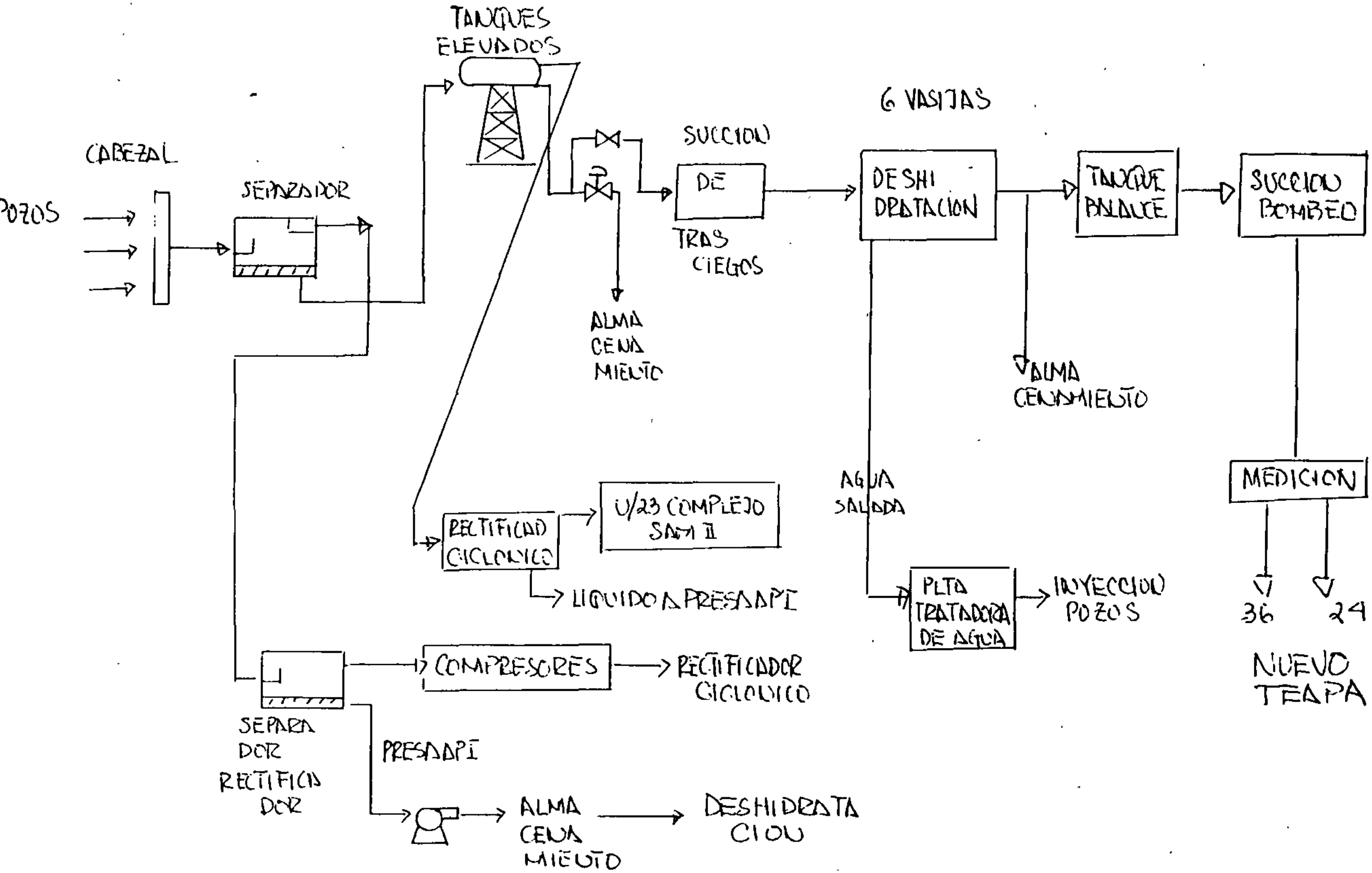
LOS DIEZ PRIMEROS SON:

LOS DIEZ PRIMEROS
RESERVAS PROBADAS GAS NATURAL 1987 10 MC



Fuente, BP Statiscal Review 1988


SEPARADOR TRIFASICO
ENFRIAMIENTO
5
35
35
75
70°C
50°C
PRIMER PASO
120°C
50°C
SEGUNDA PASO
120
50
5Kg/cm2
ACEITE
SEPARA. SUCCION
SLUG CATCHER
V102 SEP. INTERMEDIO
SEPARADOR DESCARGA
SEPARADOR
90 MMPCD
H2O
5 Kg/cm2
GAS AMARGO
EMISION ACEITE Y AGUA
CONDENSADO
CLYCOL
SEPARADOR DE ESTABILIZAR
P. DE DESHIDRATACION
ACEITE
V101
SEPARADOR
1 Kg/cm2
GAS AMARGO
7Kg/cm2
COMPRESOR
ACEITE
GAS SECO
HACIA ATASTA
EST DE RECOMPRESION
ACEITE
PLANTA TRATADORA DE AGUA
COND.
GAS
PLTA ENDULZADORA
SERVICIOS AUXILIARES
AGUA POTABLE
ENERGIA ELECTRICA
AIRE INSTALACIONES
AIRE PLANTAS
T
CD. PEMEX
ACEITE
H2O
A BATERIA DE PRODUCCION
GAS DULCE (A SERVICIOS Y AUTOCONSUMO)


TANQUES
ELEVADOS
CABEZAL
POZOS
SEPARADOR
ALMA
CENA
MIENTO
SUCCION
DE
TRAS
CIEGOS
6 VASIJAS
DESHI
DRATACION
TANQUE
BALANCE
SUCCION
BOMBEO
ALMA
CENAMIENTO
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SALADA
MEDICION
36
24
NUEVO
TEAPA
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DE AGUA
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CION

CONCEPTOS BASICOS DE MEDICION

1. INTRODUCCION

La medición es una actividad básica para la ciencia y la ingeniería, así como para la vida diaria de las personas. Para poder decir algo concreto acerca de una cosa es indispensable poder describir cuantitativamente sus propiedades, lo cual se logra sólo a través de la medición de las mismas.

Podemos pensar en la *medición* como el proceso de *asignar números*, en forma empírica y objetiva, a *las propiedades* de objetos o fenómenos en el mundo real, con el propósito de describirlos. La acción de medir implica la comparación de una *cantidad física* con un patrón de referencia apropiado, a fin de cuantificarla con un *número*.

En la práctica la medición es de primordial importancia en el mundo moderno, ya que es fundamental en toda transacción comercial, y es la base para poder ejercer un control real en cualquier proceso u organización, estando íntimamente ligada a los sistemas de control y aseguramiento de calidad.

A continuación se presentan algunos conceptos básicos relacionados con la medición.

2. ERROR DE MEDICION

El *error absoluto de medición* o simplemente *error de medición* es, por definición, la diferencia entre el *valor medido*, q_m, y el *valor real*, q_r, de la cantidad considerada:

$$\varepsilon = q_m - q_r \tag{1}$$

En esta definición, el valor medido, q_m, es simplemente el valor indicado por el instrumento de medición. Por otro lado, el valor real o verdadero, q_r, esto es, el número que corresponde a esa - cantidad suponiendo una medición perfecta, es un concepto -

idealizado que no puede ser determinado empíricamente. Sin embargo, el valor verdadero puede ser *estimado*, generalmente por medio de métodos estadísticos.

En ocasiones en la práctica se utiliza un *valor verdadero convencional*, que es una aproximación del *valor verdadero* lo suficientemente cercana para que la diferencia entre ambos valores pueda ser despreciada, según la aplicación de que se trate. Es común que se use como *valor verdadero convencional* la indicación de un instrumento de alta exactitud.

A veces es más útil considerar el *error relativo de medición*, que se define como el *error absoluto* dividido entre el *valor real*:

$$\varepsilon_{rel}(\%) = \frac{q_m - q_r}{q_r} \times 100 \qquad (2)$$

El error de medición puede ser *sistemático*, *aleatorio* o una combinación de ambos. El error *sistemático* es el que no cambia con el tiempo, o sea, es constante al realizar varias mediciones sucesivas. Por otro lado, el error es *aleatorio* cuando cambia con el tiempo en forma aleatoria.

3. EXACTITUD

Exactitud es la habilidad de indicar valores muy cercanos al valor real de la variable medida. Se debe considerar como un concepto *cualitativo* asociado al instrumento o procedimiento de medición. Mientras más exacto sea un instrumento, menor será el error de las mediciones efectuadas con él.

Sin embargo, en la práctica es frecuente encontrar la palabra *exactitud* en lugar de *incertidumbre*. La *incertidumbre*, uno de los términos más importantes en metrología como veremos más adelante, nos da un intervalo dentro del cual es probable que se encuentre el valor real; es un concepto *cuantitativo* que acompaña siempre al resultado de toda medición y normalmente forma parte de las especificaciones de los instrumentos de medición.

4. INCERTIDUMBRE

4.1 DEFINICION DEL CONCEPTO DE INCERTIDUMBRE

Cada vez que realizamos una medición estamos haciendo una *estimación* del valor real de alguna cantidad física que no conocemos y nos interesa conocer. Nótese que aunque se presupone la existencia de un valor real, al mismo tiempo se acepta que éste nunca podrá ser determinado empíricamente con total certeza y se trata de un concepto idealizado. Al reportar el resultado de la medición, no es suficiente con proporcionar el *valor medido* o estimado, se requiere contar con alguna indicación de su confiabilidad o de la calidad de la estimación hecha. Para ello es necesario establecer un *intervalo de incertidumbre*, que es un intervalo de valores dentro del cual existe una probabilidad determinada de que esté contenido el valor real. A la probabilidad de que el intervalo de incertidumbre contenga al valor real se le llama *nivel de confianza* (simbolizado por α). y normalmente es de al menos 95%. Al intervalo de incertidumbre también se le llama *intervalo de confianza*.

La manera usual de reportar el resultado de una medición por medio de un intervalo de confianza es como sigue:

$$\text{"Cantidad"} = q_m \pm \delta \ , \quad \alpha = 95\%$$

lo anterior nos dice que hay una probabilidad de 95% de que el intervalo $(q_m - \delta, q_m + \delta)$ contenga al valor real de la cantidad medida, q_r.

En la práctica, generalmente se expresa la *incertidumbre de la medición* diciendo simplemente que es igual a $\pm\delta$. De acuerdo con esto, podríamos decir que la incertidumbre de medición es igual a la mitad de la magnitud del intervalo de incertidumbre. Por otro lado, vale la pena señalar también que cuando hablamos de la incertidumbre de algún instrumento, en realidad nos estamos refiriendo a la incertidumbre de las *mediciones* realizadas con dicho instrumento.

Cuando se realiza una medición directa, utilizando un solo instrumento de medición, q_m estará dado la indicación o lectura del instrumento, mientras que δ y α estarán dadas por las especificaciones del instrumento (proporcionadas por el fabricante).

Cuando se realiza una medición indirecta, en la cual el valor medido q_m se calcula por medio de alguna expresión matemática partir de la medición de otras cantidades, es necesario obtener la incertidumbre total de la medición combinando las incertidumbres asociadas a las diferentes mediciones directas involucradas. A continuación presentaremos las distintas formas de combinar la incertidumbre para encontrar la incertidumbre total de una medición indirecta.

4.2 COMBINACION DE INCERTIDUMBRES

El primer requisito para poder combinar correctamente las incertidumbres es que todas tengan el *mismo* nivel de confianza α. En caso contrario es necesario aplicar técnicas de la teoría de probabilidad y estadística a fin de ajustar los intervalos de confianza de modo que todos tengan el mismo nivel de confianza.

4.2.1 METODO DE LA RAIZ CUADRADA DE LA SUMA DE LOS CUADRADOS (RSC)

Supongamos que tenemos una cantidad z que es función de x y y:

$$z = f(x,y)$$

Si x y y son estadísticamente *independientes*, como ocurre usualmente en la práctica, la incertidumbre de z se puede obtener a partir de las de x y y por medio de la siguiente expresión general:

$$\delta z = \sqrt{\left(\frac{\partial z}{\partial x}\delta x\right)^2 + \left(\frac{\partial z}{\partial y}\delta y\right)^2} \qquad (3)$$

Esta expresión es para una función de dos variables (x y y), pero se puede aplicar a funciones de un número mayor de variables, simplemente aumentando el número de términos en la raíz cuadrada.

Desarrollando la ecuacion 3 (o sea, efectuando el proceso de diferenciación parcial de la función) podemos llegar a fórmulas particulares aplicables a diferentes casos específicos, algunas de las cuales se muestran a continuación.

a) Suma o resta de variables, $z=x+y$, $z=x-y$:

$$\delta z = \sqrt{(\delta x)^2 + (\delta y)^2} \tag{4}$$

b) Producto o cociente de variables, $z=x\cdot y$, $z=x\div y$:

$$\frac{\delta z}{z} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2} \tag{5}$$

c) Caso general de potencias y productos, $z=x^a\cdot y^b$:

$$\frac{\delta z}{z} = \sqrt{\left(\frac{a\,\delta x}{x}\right)^2 + \left(\frac{b\,\delta y}{y}\right)^2} \tag{6}$$

4.2.2 METODO DE LA SUMA ARITMETICA

En los casos en que no es posible asegurar que las cantidades que intervienen en la medición indirecta de la cantidad $z=f(x,y)$ sean independientes, se deben combinar las incertidumbres por medio de la suma aritmética de las mismas, de acuerdo con la siguiente expresión:

$$\delta z = \left|\frac{\partial z}{\partial x}\delta x\right| + \left|\frac{\partial z}{\partial y}\delta y\right| \tag{7}$$

Igual que con el método RSC, a partir de la ecuación 7 podemos desarrollar fórmulas particulares para los casos más comunes, como las que se muestran a continuación.

a) Suma o resta de variables, $z=x+y$, $z=x-y$:

$$\delta z = \delta x + \delta y \tag{8}$$

b) Producto o cociente de variables, $z=x\cdot y$, $z=x\div y$:

$$\frac{\delta z}{z} = \frac{\delta x}{x} + \frac{\delta y}{y} \tag{9}$$

c) Caso general de potencias y productos, $z=x^a\cdot y^b$:

$$\frac{\delta z}{z} = a\frac{\delta x}{x} + b\frac{\delta y}{y} \tag{10}$$

A diferencia de lo que ocurre con el método RSC, la incertidumbre obtenida con el método de la suma aritmética ya no se apega al concepto probabilístico de incertidumbre presentado en la sección 4.1, en el sentido de que ya no es posible decir cuál es la probabilidad de que el intervalo $(z-\delta z, z+\delta z)$ contenga al valor verdadero z_r. Este método es más conservador que el RSC en la evaluación de la incertidumbre combinada y proporciona los límites dentro de los cuales podría estar el valor real en *"el peor de los casos"*, esto es, suponiendo que los errores de medición involucrados fueran máximos y en el mismo sentido.

5. PRECISION Y RESOLUCION

La *precisión* es una característica de los instrumentos de medición que indica el grado de variación en el resultado proporcionado por el instrumento al realizar varias mediciones de una misma cantidad. En otras palabras, se relaciona con la repetibilidad del instrumento.

Aquí cabe señalar que un instrumento puede ser muy preciso, en el sentido de que el resultado de sus mediciones sucesivas de una misma cantidad no varia mucho, y al mismo tiempo ser inexacto, ya que no sabemos si los resultados obtenidos, a pesar de presentar poca variación, son cercanos al valor real. O sea, exactitud implica precisión pero precisión no implica exactitud.

La resolución de un instrumento es el mínimo cambio en la variable medida que éste es capaz de detectar. En instrumentos de indicación analógica, la resolución es igual a la magnitud de la división mínima de la escala, y en instrumentos digitales está determinada por el dígito menos significativo. Aqui también un instrumento puede tener una muy alta resolución mas no por ello será exacto.

Se debe tratar de evitar confundir los términos *precisión* y *resolución* con *exactitud*, ya que cada uno tiene un significado propio diferente y bien definido.

6. ALCANCE E INTERVALOS DE MEDICION

El *alcance* de un instrumento nos da toda la gama de valores que es posible medir con él, y va desde el valor mínimo (normalmente cero) al máximo.

El alcance total del instrumento puede estar dividido en varios *intervalos* de medición, cada uno con sus propias especificaciones de exactitud, resolución, etcétera. Cabe aquí señalar la frecuente e incorrecta utilización de la palabra *rango* (que en castellano significa jerarquía social o grado militar) en lugar de *alcance* o *intervalo*; esta practica común deriva de la incorrecta traducción del vocablo inglés *"range"*.

7. CALIBRACION

La *calibración* es el proceso de determinar o estimar el error de medición de un instrumento con el fin de saber si se encuentra dentro de límites aceptables, normalmente dados por las especificaciones del fabricante o por alguna norma técnica.

Dependiendo del instrumento, el proceso de calibración puede terminar con la determinación del error o puede incluir ajustes al equipo para disminuir dicho error, o la determinación de factores de corrección para compensarlo.

Todos los instrumentos de medición deben ser calibrados, al momento de ser fabricados y después a intervalos regulares para asegurar la exactitud y confiabilidad de sus mediciones.

La calibración es un proceso especial y altamente refinado por medio del cual se establece la relación entre los valores indicados por un instrumento o sistema de medición y los valores - correspondientes proporcionados por un patrón de referencia de incertidumbre conocida. La incertidumbre del patrón debe ser - mucho menor que la del instrumento que se calibra.

No se puede exagerar la importancia, dentro de cualquier empresa, de un adecuado programa de calibración, ya que es la única garantía de la integridad y validez de la medición. Por otra parte, contar con plan establecido de calibración es un requisito importante en cualquier sistema de aseguramiento de calidad y es una exigencia de las nuevas normas de la serie ISO-9000.

8. "TRAZABILIDAD" O RASTREABILIDAD

La definición formal de "trazabilidad" o rastreabilidad dada en el Vocabulario de Términos Básicos y Generales en Metrología de la ISO es "*La propiedad del resultado de una medición por la cual puede ser relacionado con los patrones apropiados, generalmente patrones internacionales o nacionales, a través de una cadena ininterrumpida de comparaciones*". La palabra "*trazabilidad*" es una traducción incorrecta del término en inglés "*traceability*" y una traducción más apropiada sería *rastreabilidad*, sin embargo dado que "*trazabilidad*" es ampliamente usada, será la que emplearemos aquí para evitar confusiones.

La cadena ininterrumpida de comparaciones consiste, por lo general, en una serie de calibraciones que comienzan con el instrumento usado en la medición y llegan hasta el patrón nacional o internacional correspondiente. Por lo tanto, la evidencia de la trazabilidad de la medición está en los *certificados de calibración* de los instrumentos y patrones involucrados, emitidos por laboratorios acreditados por el organismo nacional rector correspondiente.

La existencia de trazabilidad en las mediciones es también, al igual que el plan de calibración, un requisito para cumplir con las normas sobre sistemas de aseguramiento de calidad como las de la serie ISO-9000.

9. NORMALIZACION

Con el fin de establecer criterios y procedimientos de medición uniformes que favorezcan la armonía en las mediciones efectuadas por diferentes personas y sirvan para evitar discrepancias en las transacciones comerciales, las distintas asociaciones profesionales y los organismos de normalización elaboran y publican normas para la medición de las cantidades mas diversas.

En lo que se refiere a la industria petrolera en particular, el *American Petroleum Institute* (API) publica su *"Manual of Petroleum Measurement Standards"*, que contiene los métodos y pautas de medición recomendados para efectuar las mediciones que se requieren en esta industria.

Otras organizaciones que publican normas de medición aplicables en la industria petrolera son:

- American Petroleum Institute (API)
- American Gas Association (AGA)
- Gas Processors Association (GPA)
- Instrument Society of America (ISA)
- American Society of Mechanical Engineers (ASME)
- American Society for Testing and Materials (ASTM)
- Institute of Petroleum (IP)
- British Standards Institute (BSI)
- International Organisation for Standardization (ISO)

Por otra parte, como se mencionó en la sección 7, la calibración es un aspecto fundamental en cualquier sistema de medición, y existen distintas normas, publicadas por organizaciones competentes, que establecen los requisitos que debe cumplir un sistema de calibración.

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Manual of Petroleum Measurement Standards Chapter 13—Statistical Aspects of Measuring and Sampling

Section 1—Statistical Concepts and Procedures in Measurement

Measurement Coordination Department

FIRST EDITION, JUNE 1985

American
Petroleum
Institute

CONTENTS

SECTION 1—STATISTICAL CONCEPTS AND PROCEDURES IN MEASUREMENT

Chapter 13—Statistical Aspects of Measuring and Sampling

SECTION 1—STATISTICAL CONCEPTS AND PROCEDURES IN MEASUREMENT

13.1.0 Introduction

The nature of physical measurements makes it impossible to measure a physical variable without error. Absolute accuracy is only achievable when it is possible to count the objects or events; even then, when large numbers are involved, it may be necessary to approximate. With the best equipment and directions, the potential for errors in fluid volume measurements involving large amounts of material is large.

Minimizing errors, estimating the remaining errors, and keeping all parties informed of errors is increasingly important to the petroleum industry. Equally important is an understanding of the size and significance of errors. Providing estimates of errors and statements concerning errors in a standard form can help avoid disputes and dispel delusions of accuracy in statements of quantity.

Chapter 13 of the *Manual of Petroleum Measurement Standards* is designed to help those who make measurements of bulk oil quantities improve the value of their result statement by making proper estimates of the uncertainty or probable error involved in measurements. During the development of Chapter 13 I, reference was made to Part XIV, Section I (Tentative) of the *Petroleum Measurement Manual* published by the Institute of Petroleum, London, England.

13.1.1 Scope

This chapter covers the basic concepts involved in estimating errors by statistical techniques and ensuring that results are quoted in the most meaningful way. The statistical procedures that should be followed in estimating a true quantity from one or more measurements and in deriving the range of uncertainty of the results are discussed. Sources of error are examined and examples are provided showing how a statement of the overall uncertainty in completed measurements is derived.

The subsequent sections (in preparation at the time this section was published) of Chapter 13 will deal with the application of the concepts discussed in Section 1 to various methods for bulk oil measurement widely used in the petroleum industry. Chapter 13.1 is a reference document explaining theory and the application of statistical procedures whereas subsequent sections will provide statistical equations and typical examples for various types of measurement.

13.1.2 Definitions

The following terms are used throughout Chapter 13.

Accuracy is the ability to indicate values closely approximating the true value of the measured variable

Bias is any influence on a result that produces an incorrect approximation of the true value of the variable being measured. Bias is the result of a predictable systematic error.

Confidence interval or range of uncertainty, C, is the range or interval within which the true value is expected to lie with a stated degree of confidence.

Confidence level is the degree of confidence that may be placed on an estimated range of uncertainty.

Degrees of freedom is the number of independent results used in estimating the standard deviation.

Direct measurement is a measurement that produces a final result directly from the scale on an instrument.

Error is the difference between true and observed values.

Indirect measurement is a measurement that produces a final result by calculation using results from one or more direct measurements.

Mean, $\bar{x}$, is the average of two or more observed values.

Measurement is a procedure for determining a value for a physical variable.

Normal (Gaussian) distribution (see Appendix A).

The *observed value* is the result obtained from a measurement.

An *outlier* is a result that differs considerably from the main body of results in a set.

Parameters are the values that characterize and summarize the essential features of measurements.

Precision is the degree to which data within a set cluster together.

A *random error* is an error that varies in an unpredictable manner when a large number of measurements of the same variable are made under effectively identical conditions.

Range, w, is the region between the limits within which a quantity is measured.

Repeatability, r, is a measure of the agreement between the results of successive measurements of the same variable carried out by the same method, with the same instrument, at the same location, and within a short period of time.

Reproducibility is a measure of the agreement between the results of measurements of the same variable where individual measurements are carried out by the same methods with the same type of instruments, but by different observers, at different locations, and after a long period of time.

A *result* is the observed value of a variable determined by a single measurement.

A *spurious error* is a gross error in procedure (for example, human errors or machine malfunctions).

Standard deviation, *s*, is the root mean square deviation of the observed value from the average.

Standard normal deviate (see Appendix A).

Student's t is a statistical function that varies in magnitude with degrees of freedom.

A *systematic error*, *e*, is one that, in the course of a number of measurements made under the same conditions, on material having the same true value of a variable, either remains constant in absolute value and sign or varies in a predictable manner. Systematic errors result in a bias.

True value, *X*, is the correct value of a variable.

Variance, *V or v*, is the measure of the dispersion or scatter of the values of the random variable about the mean μ.

13.1.3 Nomenclature

The following algebraic symbols are used throughout Chapter 13.

- A True limit of range of uncertainty for random errors.
- a Estimate of A.
- B True limit of range of uncertainty for systematic errors.
- b Estimate of B.
- C True total limit of range of uncertainty.
- c Estimate of C.
- D Conversion factor (used to derive s from w).
- e Estimate of systematic error.
- n Number of repeated measurements.
- m Number of quantities incorporated in a final indirect quantity measurement.
- p Number of independent sources of systematic error.
- P, Q Constants
- r Estimate of repeatability.
- S True value of standard deviation
- s Estimate of standard deviation.
- t Value of Student's t distribution
- V True variance, S^2.
- v Estimate of variance, s^2.
- w Range of a set of data.
- X True value of a variable.
- $\bar{x}$ Observed mean value of a set of data
- x Observed value of a variable.
- $\bar{y}$ Observed mean value corrected for bias.
- y Observed value of a variable corrected for bias.
- μ Mean of Gaussian normal distribution.
- σ Standard deviation of a Gaussian normal distribution.
- ϕ Degrees of freedom.

13.1.4 Statistical Control

Proper use of statistical techniques requires that the measurement process be in a state of statistical control. Unless this is achieved, any statement concerning the estimate of the true value of the quantity being measured, and the statistical uncertainty associated with it, is not strictly valid and may even be meaningless. A measurement process that is under statistical control will; if measurements on the same quantity are repeated by the same method and under essentially the same conditions, show stability of the mean value and regular scatter of individual results (see also 13.1.7).

Repeatability and reproducibility, when properly established, can be used to monitor statistical control on a routine basis (see 13.1.7.1 and 13.1.7.2).

Strict statistical control is usually very difficult to ensure. An important step in establishing any measurement procedure is to decide which variables should be used to monitor statistical control and to establish target values required to maintain an appropriate degree of consistency. Some essential elements in statistical control are listed here.

1. The entire measurement procedure and instructions must be clearly defined and closely followed.
2. Independent procedures for checking and maintaining equipment must be available.
3. Means for detecting and eliminating equipment malfunctions and human mistakes (leading to spurious errors) should be incorporated (see 13.1.6.1).

These features of the measurement procedure must be adhered to at all times. Furthermore, control charts and other records of equipment performance, maintenance, and calibration checks must be used as an integral part of statistical control procedures.

13.1.5 Measurements

13.1.5.1 TRUE VALUE

One primary assumption is made; that is, an exact or true value exists for any variable, valid for the conditions that exist at the moment when the result is determined Generally, the true value X cannot be determined, but a valid estimate $\bar{x}$ can be obtained by rigorous application of the appropriate method of measurement using the specified instruments By statistical analysis of the various errors involved, it is possible to use observed values to obtain an estimate of the true value and to quantify the reliability of that estimate In any set of measurements, the best estimate of X will be the mean $\bar{x}$ after rejecting outliers and correcting for systematic errors.

13.1.5.2 UNCERTAINTY OF MEASUREMENT

The usefulness of a result is greatly increased when it is accompanied by a statement of its reliability. The statistical calculations provided in this chapter give a range or interval within which the true value of the variable can be expected to lie with a stated degree of confidence The statistical term for such an interval is the *confidence interval* (also referred to as the *range of uncertainty* of the measurement) The limits of a confidence interval about an estimate $\bar{x}$ are expressed as $\bar{x} \pm C(\bar{x})$; the magnitude of $\pm C(\bar{x})$ depends on the random variability of the measurements, unknown systematic errors, and the confidence level. As an example, consider the following statement: 10° ±1°C. In this statement, the estimate $\bar{x}$ is 10° and the confidence interval is ±1°.

13.1.5.3 CONFIDENCE LEVEL

Setting absolute limits to a range of uncertainty is rarely possible. It is more practical to give an indication of the degree of confidence that may be placed on an estimated range of uncertainty. This degree of confidence, or confidence level, indicates the probability that the range quoted will include the true value of the quantity being measured. The most common statistical practice is to use the 95 percent confidence level. This level implies that there is a 95 percent probability (19 chances in 20) that the true value will lie within the stated range. The 95 percent level is recommended for all commercial applications in petroleum measurement and will be used throughout this chapter. In certain limited circumstances, a different degree of confidence may be required.

NOTE Strictly, a confidence level or confidence interval can only be used to account for Gaussian random errors or errors that may be so treated. Systematic errors must be accounted for before the confidence level and interval are applied, and substantial contributions to the total uncertainty should be separately recorded

13.1.5.4 REPORTING RESULTS

All results should be reported so that the estimate of the true value, and the limits within which the true value is expected to lie with a given level of confidence, can be seen at a glance. Results should be written as follows: $\bar{x} \pm C(\bar{x})$ 95, n (95 percent confidence level, n measurements) from which the following relevant information can be obtained:

1 $\bar{x}$ is a mean value of n measurements, is corrected for all known systematic errors, and is the estimate of the true value

2 There is 95 percent probability that the true value lies between $\bar{x} - C(\bar{x})$ and $\bar{x} + C(\bar{x})$

3 There is 95 percent probability that any further single measurement will lie within $\bar{x} \pm = C(\bar{x})/n^{0.5}$

Expanding on the example, assume that the following temperature measurements were taken for a delivery batch of crude oil: 10, 8, 11, 9, and 12°C; and the confidence interval was determined to be ± 2°C. Then $\bar{y}$ = 10, n = 5 and the result statement would be: 10° ± 2°C (95 percent confidence level, 5 measurements)

13.1.6 Types of Errors

The difference between the observed value of a variable and its true value includes all errors associated with the person actually taking and recording the results, instrument errors, procedure errors, and errors resulting from sampling procedures or changes in conditions during the period of measurement. There are three basic types of errors that must be considered: spurious errors, systematic errors, and random errors.

13.1.6.1 SPURIOUS ERRORS

Spurious errors are gross errors, such as misapplication of method, incorrect reading or recording, and instrument malfunction. These errors cannot be incorporated into any statistical analysis and the results must be discarded.

There are statistical methods of testing for outliers (see Appendix B), but these methods should only be applied if there is good reason to believe that spurious errors exist. Data should not be discarded lightly, and the observer should record what information has been discarded and state the reasons.

13.1.6.2 SYSTEMATIC ERRORS

A systematic error is one that, in the course of a number of measurements made under the same conditions on the same variable, remains constant or varies predictably. Thus, systematic errors cause bias in the results. The bias can be positive or negative, leading to over- or underestimation of the true value of the variable being measured. In many liquid measurement applications, systematic errors may make a larger contribution to the overall uncertainty of a result than random errors (see 13.1.6.3) Systematic errors must be identified and either eliminated or compensated for before interpreting overall results statistically (see note in 13.1.5.3).

Ideally, bias could be considered as constant for all measurements made by the same operator and equipment. Unfortunately, assessment of bias is complicated by the fact that some contributions to bias do vary with time. For example, knowledge and control of test conditions may be inadequate or an instrument may wear progressively. Such factors will probably not change significantly during the course of one set of measurements but could change both in magnitude and sign over a longer period.

Assessment of systematic errors by experimental means is difficult, especially when variation with time is involved. Errors introduced by the observer or by changes in operating conditions are probably easiest to identify, but any experimental evaluation of systematic error may involve a complete change of equipment, which is often not feasible. The alternative to experimentation is to make a subjective assessment on the basis of experience and knowledge of the instruments involved.

In any event, if the conditions of measurement are unchanged, increasing the number of measurements will not reduce the effects of systematic error.

All conceivable sources of error must be identified, examined methodically, and assessed quantitatively to establish whether they make a significant contribution to bias.

13.1.6.3 RANDOM ERRORS

Random errors are caused by small independent influences that prevent a repeated measurement from giving an identical result, although the true value of the variable involved remains the same. Results that contain only random errors are amenable to statistical analysis. Random errors are assumed to follow a normal (Gaussian) distribution, described in Appendix A. Provided that all systematic errors can be accounted for, the corrected mean value $\bar{y}$ and the range of uncertainty $\pm C(\bar{y})$ can be calculated. Increasing the number of measurements reduces the value of $C(\bar{y})$ and hence improves the reliability of the final estimate $\bar{y}$.

13.1.7 Accuracy and Precision

A set of measurements subject to the smallest systematic errors will be expected to have their mean closest to the true value, and this is said to give the most accurate set. It is also evident that the set of measurements subject to the smallest random errors will be expected to be clustered closest together, and so form the most precise set. Within these rather narrow statistical definitions, precise measurements are not necessarily accurate, since they could cluster about a point that is not the true value. Conversely, it is possible to have a set of measurements that are accurate taken as a group although widely scattered and of doubtful reliability when taken singly.

This distinction is important since any statement concerning reliability must account for both systematic errors and random errors, as statistically defined. In practice, accuracy in measurement cannot exist without precision, so every effort must be made to satisfy both criteria of reliability.

The precision of a method of measurement can be determined quantitatively and is conventionally expressed as repeatability and reproducibility.

13.1.7.1 REPEATABILITY

The repeatability of a method of bulk measurement is a quantitative measure of the random error associated with a single operator at a given location, obtaining successive measurements on the same body of material over a short time interval, with the same measuring devices, and under constant operating conditions. Repeatability is defined as the difference between two such measurements that would be exceeded in the long run in 1 case in 20 in the normal and correct operation of the method of measurement. Repeatability is the range of uncertainty (95 percent confidence level) for the difference between two measurements obtained under the same conditions.

The short time interval between measurements is essential to ensure that external conditions are kept as nearly constant as practicable. The time interval should be of the same order of magnitude as the duration of a single measurement. For example, if a measurement takes 5 minutes to carry out, the interval before a second measurement should not exceed 10 minutes.

13.1.7.2 REPRODUCIBILITY

The reproducibility of a bulk measurement method is a quantitative expression of the random error associated with different operators working in different locations with different instruments, with each operator obtaining single measurements on the same body of material by using the same method and the same types of measuring devices. It is defined as the difference between two such single and independent measurements that would be exceeded in the long run in only 1 case in 20 in the normal and correct operation of the method of measurement. Reproducibility is the range of uncertainty (95 percent confidence level) for the difference between two measurements obtained under the same conditions.

Good reproducibility indicates that random errors are acceptably small (good repeatability) and that systematic errors other than those inherent in the method are probably also very limited in size and number. Reproducibility conditions as defined, can rarely be met in quantitative bulk oil measurement because the identity of a body of oil is almost invariably lost during its movement from one place to another (the only possible exception being measurement by gage or weighing of a vehicle or ship). However, a close approximation to reproducibility conditions could be achieved for measurements such as gaging a storage tank if two operators each set up their own apparatus for the prescribed method of measurement at the same location.

13.1.7.3 APPLICATION OF PRECISION TO A SINGLE MEASUREMENT

As stated previously, reproducibility of a measurement method, strictly defined, is not a concept that can often be utilized. The application of repeatability is also limited in normal commercial transfer measurement, since the second measurement required to establish a difference between two results is not a practical proposition in everyday work using meters.

In practice it is necessary to conduct a special exercise and obtain repeated determinations of the result with the apparatus that is to be used at a given site and to use these determinations to estimate the random error of a single measurement. This random error is expressed as the range of uncertainty about a single measurement rather than the range for the difference between two measurements as would be the case for repeatability and reproducibility. This estimate of the range of uncertainty is then used for all routine measurements until such time as a complete re-check of the apparatus and method is undertaken (usually at prescribed regular intervals).

The estimated range of uncertainty so obtained would cover errors both from the instruments used and from the calibration system employed. It should also be noted that, without repeated measurements, it is impossible to use the range of uncertainty as a means of monitoring statistical control on a short-term basis, as was the case with repeatability (see 13.1.7.1).

13.1.8 Statistical Procedures

True value and range of uncertainty are two important characteristics describing the measurement of any physical variable. There are characteristics that describe other features of the results, such as random error, standard deviation, and bias, and these are called the parameters of the population of observed variables. Parameters are all assumed to have true values. The procedures described in this section are used to derive estimates of the parameters, known as statistics, from the set of measurements obtained. Parameters will be represented algebraically either by Greek letters (for example, μ and σ) or true values by capital Roman letters, and observed values will be represented by lowercase Roman letters.

In general, the result in question will be a function of one or more intermediate results, each of which could contribute to both the final result estimate and its range of uncertainty. The statistics for each intermediate result should be established first. Intermediate results will be combined to give the statistics that relate to the final result.

13.1.8.1 STATISTICAL PROCEDURE FOR A SINGLE SET OF DATA

Statistics are derived from a single set of n repeated measurements x_i, for i = 1 to n. Each measurement will be an estimate of X, the true value of the variable but will be subject to both systematic and random errors (see 13.1.6). All known sources of systematic error should be accounted for before the true value and range of uncertainty are estimated. In the interest of clarity, it is good practice to record the source and magnitude of each error separately.

Random errors are assumed to follow the normal (Gaussian) distribution (see 13.1 6.3 and Appendix A), which is fully determined if its parameters μ (mean) and σ (standard deviation) are determined. These two parameters are estimated from the measurements obtained. The possible sources and magnitudes of the systematic errors to be found in measuring systems are given in detail in 13.1.8.1.1 through 13.1.8.1.7.

13.1.8.1.1 Number of Repeated Measurements Required

There is no fixed value for the optimum number of measurements required to establish a true value and a range of uncertainty. On the one hand, n, the number of repeated measurements, has no bearing on the determination of systematic errors that are present to the same extent in all measurements made under the same operating conditions (see 13.1.7.2). On the other hand, the statistics relating to random errors (for example, mean and standard deviation) are not independent of n, since the larger n becomes, the closer estimates will approach their true values and the smaller will be the range of uncertainty (see 13.1.7.3).

Very often it is only practical to obtain from five to ten measurements in the field. This is perfectly acceptable for the day-to-day estimate of a mean value, but greater reliability is required for a statistic that is to be used as a standard measure. This is the case for repeatability (see 13.1.7.1), which should be estimated from at least 20 and preferably 30 or more repeated measurements. A similar argument applies when estimating the range of uncertainty for single measurements (see 13.1.7.3)

13.1.8.1.2 Outlying Results

Results that are subject to spurious errors (see 13.1.6.1) may differ considerably from the remaining results in the set. These are called outlying results. If a result is suspected to be an outlier but is not easily identifiable, then the set of results should be tested for outliers according to the procedures given in Appendix B. The suspect result should be discarded if the test proves significant. It should be stressed, however, that a good reason is required before a result is rejected, and that reason should be clearly stated.

When the repeatability of the method of measurement has been established, it is possible to make a preliminary check for outliers by the range test illustrated in 13.1.8.1.7. Note that constant systematic errors cannot be detected in an outlier test because they are present to the same extent in all results of the quantity in question (see 13.1.6.2)

13.1.8.1.3 Correcting for Bias

If a constant systematic error e is known to exist, for example, a depth gage is known to give a consistent bias 1 millimeter above the true reading due to faulty calibration, then each of the measurements x_i should be adjusted accordingly. The adjusted results, y_i, will then be the most accurate available (see 13.1.7) and are given by the expression:

$$y_i = x_i - e \quad (1)$$

Note that the systematic error could be level dependent, that is, a constant function (for example, percentage) of the measurement itself:

$$e = f(x) \quad (2)$$

An example of this would be a direct reading meter known from experience to give a consistent bias 1 percent above the true value. In that case, Equation 1 becomes:

$$y_i = x_i - f(x_i) \quad (3)$$

There are times, however, when the systematic error is unknown in magnitude and/or sign, usually due to variations in operating conditions over a long interval (see 13.1.6.2) In that case, the average systematic error $\bar{e}$ should be estimated, taking into account the conditions that affect the measurements at the time. Very often the only way to estimate the average is to calculate the mean range in which the errors could lie. If the errors were estimated to range from e_1 to e_2, the average systematic error would be:

$$\bar{e} = (e_1 + e_2)/2 \quad (4)$$

Individual measurements should then be adjusted by the mean value $\bar{e}$ as in Equation 5:

$$y_i = x_i - \bar{e} \quad (5)$$

Note that when the systematic error takes positive or negative values up to the same maximum ($e_1 = -e_2$) no correction will be made. Note also that unknown systematic errors will contribute to the range of uncertainty for the true value estimate (see 13.1.8.1.6.3).

13.1.8.1.4 Estimating True Value

The results y_i (x_i corrected for bias) are now subject to random errors and unknown systematic errors. As previously stated, the measurements y_i are assumed to follow the normal distribution with mean μ and standard deviation σ. The estimate of the mean that is most likely to be correct, or the "maximum likelihood" estimate of μ, is the average $\bar{y}$ of the set of corrected measurements:

$$\bar{y} = \frac{1}{n}(y_1 + y_2 + \ldots + y_n) = \frac{1}{n}\sum_{i=1}^{n} y_i \quad (6)$$

If only one result is available, the result is the estimate of the true value.

13.1.8.1.5 Estimating Standard Deviation

The standard deviation $\sigma(y)$ describes the random error of a single measurement.

The maximum likelihood estimate $s(y)$ of the standard deviation is calculated from the set of corrected results (y_i) as follows:

$$s(y) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

or

$$s(y) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} y_i^2 - \frac{n\bar{y}^2}{n-1}} \quad (7)$$

A less complicated but more approximate estimate is:

$$s(y) = \frac{w}{D(n)} \quad (8)$$

Where

w = the range of the set of measurements (for n < 12).

$D(n)$ = a conversion factor (see Table 1).

A further approximation can be made by replacing $D(n)$ by $(n)^{0.5}$. It should be stressed, however, that Equation 8 is approximate since it should theoretically apply to the average range $\bar{w}$ of a number of sets of n measurements. A more reliable estimate would be obtained from the average range of six pairs of results than from the range of a single set of twelve repeated results. For this reason, the equation should only be used as a quick check to monitor statistical control and not for data interpretation (see 13.1.4).

The standard deviation of the average of n repeated results can be calculated as:

$$\sigma(\bar{y}) = \frac{\sigma(y)}{n^{0.5}} \quad (9)$$

In terms of estimates, the standard deviation, or as it is more commonly called, the standard error, of the average becomes:

$$s(\bar{y}) = \frac{s(y)}{n^{0.5}} \quad (10)$$

As the number of measurements increases, the standard error of the average will decrease. Therefore, an average based on a large number of measurements would in this sense be more reliable than one based on a small number of measurements (see 13.1.8.1.1). Furthermore, since the distribution of any average tends toward the normal as n becomes larger, Equation 10 would still hold true if the distribution of individual results deviated from the normal distribution.

13.1.8.1.6 Estimating Range of Uncertainty

For a measurement function, here called G, the limit $C(G)$ of the range of uncertainty (see 13.1.5.2) consists of two parts, the limit $A(G)$ due to random errors and the limit $B(G)$ due to unknown systematic errors (see 13.1.8.1.3). The estimation of A, B, and C depends to a large extent on the nature of G, be it a single measurement or an average, and on the nature of the errors present. (In this section, the expression "limit of the range of uncertainty" will often be referred to in shortened form as "limit of uncertainty" or "uncertainty limit.")

Table 1—Range Conversion Factor

Number of Measurements, n	Conversion Factor, D(n)	Number of Measurements n	Conversion Factor D(n)
2	1.128	8	2.847
3	1.693	9	2.970
4	2.059	10	3.078
5	2.326	11	3.173
6	2.534	12	3.258
7	2.704		

SOURCE: Davies, O. L., *Statistical Methods in Research and Production*, 2nd Edition, Longman, 1984

13.1.8.1.6.1 Uncertainty Due to Random Errors

The limit $A(y)$ of the range of uncertainty due to random errors about a single measurement y is simply the product of the standard deviation $\sigma(y)$ and the standard normal deviate (see Appendix A). For 95 percent probability, the standard normal deviate has a value of 1.96, that is,

$$A(y) = 1.96\,\sigma(y) \quad (11)$$

In general, the standard deviation will be estimated from Equation 7 as $s(y)$. To take this into account, the limit of random uncertainty calculated from $s(y)$ should be based not on the standard normal deviate, but on a value known as Student's t, which varies in magnitude with the degree of freedom. For the purpose of this document, degrees of freedom may be regarded as the number of independent measurements used in estimating the standard deviation, which for n measurements will be $n - 1$ (1 degree of freedom having been used in calculating the average). The limit of the range of uncertainty for single measurements (see 13.1.7.3), will, in this case, be estimated as:

$$a(y) = (t_{95,\,n-1})\,s(y) \quad (12)$$

Where:

$t_{95,\,n-1}$ = the value of the t-distribution for $(n-1)$ degrees of freedom and for a two-sided probability of 95 percent (two-sided since the range of uncertainty covers both sides of the true quantity estimate).

Values of the t-function are given in Table 2. Once again, by using Equation 10, the limit for an average will become:

$$a(\bar{y}) = (t_{95,\,n-1}) \times s(\bar{y})$$
$$= (t_{95,\,n-1}) \times \frac{s(y)}{n^{0.5}} \quad (13)$$

Table 2—*t*-Distribution Values for 95 Percent Probability (Double-Sided)

Degrees of Freedom ϕ	$t_{.95}$ ϕ	Degrees of Freedom ϕ	$t_{.95}$ ϕ
1	12 706	18	2.101
2	4 303	19	2 093
3	3 182	20	2.086
4	2 776	21	2.080
5	2.571	22	2.074
6	2.447	23	2.069
7	2 365	24	2.064
8	2 306	25	2.060
9	2 262	26	2.056
10	2 228	27	2 052
11	2 201	28	2.048
12	2 179	29	2 045
13	2 160	30	2.042
14	2.145	40	2 021
15	2 131	60	2 000
16	2 120	120	1 980
17	2 110	--	1.960

SOURCE. Fisher and Yates, *Statistical Tables for Biological, Agricultural, and Medical Research.*

Thus, combining Equations 12 and 13:

$$a(\bar{y}) = \frac{a(y)}{n^{0.5}} \tag{14}$$

It is worth noting that as n becomes very large, so the t-value approaches the standard normal deviate, and the standard deviation estimate $s(y)$ approaches the true value $\sigma\ (y)$.

13.1.8.1.6.2 Uncertainty Due to Systematic Errors

Systematic errors can affect results by creating a bias, an uncertainty, or both (see 13.1.6.2). When the errors are known, be they level dependent or not, the bias can be removed according to 13.1.8.1.3 and no uncertainty will exist. On the other hand, when the errors are unknown in sign and/or magnitude and even though bias can be allowed for according to Equation 4, there will still be an uncertainty as to the true value of the variable. Nor is it theoretically possible, due to the very nature of systematic errors, to express the true limit B in terms of the measurements obtained. It is necessary, therefore, to estimate the limit for each source of systematic error by calculating the absolute value by which the corrected results could deviate from their true value with 95 percent confidence. Assuming that systematic errors are uniformly distributed and using the symbols defined in 13.1.8.1.3, this means that:

$$h(y) = 0.95 \left| \frac{(e_1 - e_2)}{2} \right| \tag{15}$$

Note that $h(y)$ is the limit of a range of uncertainty, and should not be confused with the maximum value (e_1 or e_2) that a systematic error could take If the error takes positive or negative values up to the same maximum ($e_1 = e_2$) then

$$h(y) = 0.95\,|e_1| = 0.95\,|e_2| \tag{16}$$

Note also that since systematic errors are present to the same extent for all measurements made under the same conditions (see 13 1.6.2), the limit of the range of uncertainty about an average result $\bar{y}$ will be identical, that is:

$$h(\bar{y}) = h(y) \tag{17}$$

Although it is difficult to handle systematic errors with theoretical justification, this should not detract from their importance in measuring systems. In many cases, systematic errors create greater uncertainty than random errors, and for this reason, great care should be taken in their identification and estimation.

13.1.8.1.6.3 Combining Random and Systematic Uncertainties

In attempting to allow for systematic uncertainties, difficulties will arise because systematic errors are often variable with time and cannot be identified from a single set of measurements obtained under constant operating conditions (see 13.1.6.2). This is not to say that systematic errors cannot be estimated at all since good estimates can be derived from calibration exercises or from experience with and knowledge of the measuring system involved. A combination of uncertainties is required because it is of great value to state the range in which a true value is expected to lie.

There are two schools of thought on how uncertainty limits should be combined: (1) by simple addition or (2) by a method called root sum square. The latter method is theoretically correct if only random uncertainty limits are to be combined (see 13.1.8.2.2), but gives a narrower range and, therefore, a more optimistic view than the former method. In choosing between the two methods, consideration must be given not only to theoretical implications, but also to the manner in which errors are found to behave in practice.

Consider first a set of measurements of the same quantity subject to p independent sources of systematic error, all of which are unknown but have been estimated according to 13.1 8 1.3. Since the errors affect the same measurement, they tend to cancel each other out, at least to a certain extent. With this in mind, it would be sensible to take the more optimistic view and combine the systematic uncertainty limits by the root sum square method. Assuming that systematic errors follow a uniform distribution—that there is an equal probability that the error lies anywhere throughout its full range—there would be a theoretical justification for this choice. As a general rule, the total limit of the range of uncertainty due to systematic errors should be calculated as.

$$b(y) = \sqrt{b_1^2(y) + b_2^2(y) + \ldots + b_p^2(y)} \qquad (18)$$

In this equation, the systematic uncertainties have been combined in exactly the same manner as random uncertainties (see 13.1.8.2.2). On a theoretical basis, systematic and random uncertainties should be combined in the same fashion. There is further justification for this approach in practical terms, since systematic and random errors would be expected to average each other out to a certain extent This leads to the root sum square method for combining systematic and random uncertainties, which, in terms of average measurements, is:

$$c(\bar{y}) = \sqrt{a^2(\bar{y}) + b^2(\bar{y})} \qquad (19)$$

Note that $a(\bar{y})$ becomes smaller as n becomes larger (see 13.1 8.1.1), whereas $b(\bar{y})$ will remain unchanged The total limit $c(\bar{y})$ will approach the limit $b(\bar{y})$ as n increases. This shows the need for care in estimating systematic errors, regardless of the number of repeated measurements obtained (see 13.1.6.2). Note also that by using Equations 14 and 17, the limit of the range of uncertainty for any further single measurement (see 13.1.5.4) becomes:

$$c(y) = \sqrt{na^2(y) + b^2(y)} \qquad (20)$$

13.1.8.1.7 Estimating Repeatability

Since repeatability is defined as the range of uncertainty due to random errors for the difference between two measurements (see 13.1.7.1), it can be estimated directly from Equation 12. In this case, the standard deviation relates to the absolute difference between two repeated measurements, y_1 and y_2, and for a normal distribution of errors this is:

$$\sigma(|y_1 - y_2|) = \sqrt{2}\,\sigma(y_1) = \sqrt{2}\,\sigma(y_2) = \sqrt{2}\sigma(y) \qquad (21)$$

In terms of estimates this becomes:

$$s(y_1 - y_2) = \sqrt{2}s\,(y) \qquad (22)$$

Substituting Equation 22 into Equation 12, the estimate r of repeatability will be given by:

$$r = (t_{\alpha,\, n-1})\,[\sqrt{2}\, s(y)] \qquad (23)$$

$t_{\alpha,\, n-1}$ is described in 13.1.8.1 6. This estimate can be compared with a predetermined repeatability value for control purposes. If r were excessively great, it would imply that measurements were subject to unusually large errors. Note that a repeatability estimate that is to be used as a standard measure should be based on as many results as possible, at least 20 and preferably 30 or more (see 13.1.8.1.1) and would normally be calculated at the end of a carefully controlled study.

Repeatability is most commonly used as a range test of the difference between two repeated measurements (see 13.1 4 and 13 1.7.1). It can also be used to construct a test on the range of three or more measurements. By combining Equations 23 and 8, the range can be represented by:

$$w = \frac{d(n)r}{\sqrt{2}t_{\alpha,\, n-1}} \qquad (24)$$

By substituting a previously determined repeatability value into this expression, a critical value can be calculated for the range of a set of n measurements. However, it is advisable not to use this as a formal outlier test. Because the range represents only a part of the information on the variability within a set of measurements (that is, the smallest and largest values), the test will only be approximate. Nevertheless, it can be used to monitor statistical control within a set of measurements (see 13 1.4 and 13.1.6.2) and flag the need for rigorous analysis.

13.1.8.2 STATISTICAL PROCEDURE FOR TWO OR MORE SETS OF DATA

In some cases, the quantity in question is obtained indirectly from m intermediate and independent results, each of which will have been estimated from a separate set of data according to the procedures in 13.1.8.1. In this section, procedures are given in which the estimates for the intermediate quantities are combined to give those relating to the final quantity.

13.1.8.2.1 Estimating True Value

The value X of the final result is assumed to be a function F of the m intermediate quantities $X_1, X_2 \ldots X_m$

Algebraically, this can be represented by:

$$X = F(X_1, X_2, \ldots X_m) \qquad (25)$$

The maximum estimate of X is obtained simply by substituting into Equation 25 the appropriate estimates for $X_1, X_2, \ldots X_m$ In terms of measurements corrected for bias (see 13 1.8 1.3), the estimate $\bar{y}$ of the true variable will become:

$$\bar{y} = F(\bar{y}_1, \bar{y}_2, \ldots \bar{y}_m) \qquad (26)$$

As an example, consider a relationship between quantities of the form

$$X = PX_1X_2 + QX_3 \qquad (27)$$

P and Q are known constants. The estimate of the final quantity, according to Equation 26, is then

$$\bar{y} = P\bar{y}_1 \bar{y}_2 + Q\bar{y}_3 \quad (28)$$

Note that the calculation resulting from such an equation could give rise to a further source of systematic error (see 13.1.8.2.3). This would be the case, for example, in estimating the volume of a tank from tables of liquid depth. The intermediate results would include assumed values for tank dimensions, with further assumptions on environmental conditions, and these could all contribute to unknown systematic errors.

13.1.8.2.2 Combining Random Uncertainties

Random error is represented statistically by the standard deviation (sometimes called standard error) associated with a particular measurement function (see 13.1.8.1.5). It is useful when combining random errors to consider another parameter called variance. Standard deviation σ is simply the square root of the variance V.

$$V(X) = \sigma^2(X) \quad (29)$$

In terms of estimates corrected for bias,

$$v(y) = s^2(y) \quad (30)$$

Any of the expressions dealing with standard deviation may be converted to the corresponding expressions for variance by substituting Equation 29 or 30.

Now consider the random errors associated with the m intermediate quantities. The variance of the indirect measurements of the final quantity is given approximately by the expression:

$$V(X) = \left(\frac{\sigma F}{\sigma X_1}\right)^2 V(X_1) + \left(\frac{\sigma F}{\sigma X_2}\right)^2 V(X_2) + \ldots + \left(\frac{\sigma F}{\sigma X_m}\right)^2 V(X_m) \quad (31)$$

$\sigma F/\sigma X_i$ represents the partial differential coefficient of F with respect to X_i, and F is Equation 25. $\sigma F/\sigma X_i$ may be regarded as the change in F brought about by unit change in X_i. Equation 31 only holds true, however, if the quantities $X_1, X_2, \ldots X_m$ are independent of each other. Furthermore, the equation leads to the root sum square method of combining random uncertainty limits (see 13.1.8.1.6.3), for by substituting into it Equations 11 and 29, it becomes:

$$A(X) = \sqrt{\left[\frac{\sigma F}{\sigma X_1} A(X_1)\right]^2 + \left[\frac{\sigma F}{\sigma X_2} A(X_2)\right]^2 + \ldots + \left[\frac{\sigma F}{\sigma X_m} A(X_m)\right]^2} \quad (32)$$

The corresponding equation in terms of estimates will be

$$a(\bar{y}) = \sqrt{\left[\frac{\sigma F}{\sigma X_1} a(\bar{x}_1)\right]^2 + \left[\frac{\sigma F}{\sigma X_2} a(\bar{x}_2)\right]^2 + \ldots + \left[\frac{\sigma F}{\sigma X_m} a(\bar{x}_m)\right]^2} \quad (33)$$

13.1.8.2.3 Combining Systematic Uncertainties

As previously stated, there are theoretical difficulties when attempting to combine systematic uncertainties (see 13.1.8.1.6). The choice is between the arithmetic and root sum square methods of combining and should take into account the manner in which the errors behave in practice. This is sometimes difficult to judge, particularly for the multiplicative terms in a relationship (see Equation 27). Assuming a uniform distribution of systematic errors, however, it is theoretically correct to combine the systematic errors in a multiplicative function by the root sum square method. This, coupled with the fact that systematic errors combined in an additive fashion are expected to cancel each other out to a certain extent, leads to the choice of the root sum square method as applicable in the general case. The appropriate formula is identical in form to Equation 33 but with random uncertainty limits replaced by the corresponding systematic limits:

$$b(\bar{y}) = \sqrt{\left[\frac{\sigma f}{\sigma X_1} b(\bar{x}_1)\right]^2 + \left[\frac{\sigma f}{\sigma X_2} b(\bar{x}_2)\right]^2 + \ldots + \left[\frac{\sigma f}{\sigma X_m} b(\bar{x}_m)\right]^2} \quad (34)$$

The point to remember when combining systematic uncertainties is that the relationship between quantities (see Equation 25) may only be approximate (see 13.1.8.2.1). In that case, a further unknown systematic error could be present, and the corresponding uncertainty limit should be estimated according to Equation 15. This should be included as another squared term in the uncertainty expression (Equation 34).

13.1.8.2.4 Estimating Total Uncertainty

For the reasons already explained in 13.1.8.1.6.3, the random and systematic components of the total uncertainty should be combined by quadrature according to Equation 19. In this case, however, $a(\bar{y})$ will be estimated from Equation 33 and $b(\bar{y})$ from Equation 34.

13.1.8.3 ROUNDING STATISTICAL ESTIMATES

When applying the procedures of 13.1.8.1 and 13.1.8.2, it is important to consider the effect of rounding on the statistical estimates derived. Rounding that is too coarse will become a significant source of error. Any particular result will be reported to the smallest unit of measure of the instrument involved, and the statistics that relate to that result should reflect this level of accuracy and should be rounded accordingly. For example, a gage reading would be reported to the nearest millimeter if that was the scale unit of the tape measure. Estimates of the mean gage, standard deviation, and the limit of the range of uncertainty should also be rounded to the nearest millimeter, and the calculations leading up to those estimates should include a sufficient number of digits to achieve this.

Particular care should be taken when considering more complicated functions, such as would be found in the indirect estimation of a parameter from a number of intermediate calculations. It is useful to relate the calculations to the units in which the final estimate is to be reported. In a root sum square estimate, for example, which is to be reported to two decimal places, the squared terms should be calculated to at least four decimal places to achieve the required level of accuracy. From the opposite viewpoint, in terms of a root sum square estimate, if one or more of the squared terms were calculated to only two decimal places, it would be incorrect to report the final estimate to any greater accuracy than one decimal place.

All estimates, except repeatability, should be rounded up or down to the smallest unit of measure (rounding unit). As a result of its definition (see 13.1.7.1), a repeatability estimate should always be rounded up to the nearest rounding unit.

13.1.8.4 EXAMPLE

Consider the indirect measurement of the volume at standard temperature of liquid in a tank. This is to be estimated from a set of repeated gage readings, a calibration table, a set of repeated temperature measurements, and a temperature correction formula. Each set of direct measurements (gage readings and temperatures) will be considered separately according to 13.1.8.1, and the appropriate statistics will be derived. These will then be combined to give estimates in terms of the liquid volume corrected for expansion in the tank resulting from nonstandard temperature.

For the purpose of this example, the procedures of 13.1.8.1 will only be described in detail with respect to the set of gage readings. Statistics for the set of temperature data will be given. Note that statistics that are to be used at a later stage in the calculations will be stated to a greater level of accuracy (one or two more decimal places) than that achieved in the corresponding measurements. This is to ensure that the final estimate of volume includes no rounding errors. Note also that the figures used in the example were chosen strictly for illustrative purposes, and are not necessarily typical of those to be found in practice.

13.1.8.4.1 Direct Measurements

In this section, the procedures of 13.1.8.1 will be applied to the single set of tank gage measurements. This can be considered as separate steps as follows.

Step 1—Information available.

Six gage measurements x_i, for $i = 1$ to 6 (see 13.1.8.1) were recorded to the nearest millimeter: 6534, 6544, 6542, 6540, 6543, and 6544. Unknown systematic errors were expected as a result of sludge at the bottom of the tank and inaccuracy in the tank gage tape. These errors (see 13.1.8.1.3) recorded in millimeters as:

Source of Systematic Error	Maximum Range of Error e_1	e_2
Sludge	−4	0
Tape	−1	+1

It is also known from an independent study that the repeatability for tank gaging was 7 millimeters.

Step 2—Outlying results.

The first gage reading differs from the others by what appears to be an appreciable amount. As a quick check on its validity, the critical range for the set of measurements, rounded to the nearest millimeter, is calculated from Equation 24 as:

$$w = \frac{D(n)r}{\sqrt{2} \times (t_{95,\, n-1})}$$

Where:

$n = 6.$
$D(6) = 2.543$ (see Table 1).
$r = 7.$
$t_{95,5} = 2.571$ (see Table 2).

Therefore:

$$w = \frac{D(6)r}{\sqrt{2}\, t_{95,5}} = \frac{2.534 \times 7}{2 \times 2.571} = 5 \text{ millimeters}$$

The observed range of 10 exceeds this value, so Dixon's outlier test was applied (see Appendix B). The appropriate Dixon ratio for six measurements and for testing a low value is:

$$R_{10} = \frac{6540 - 6534}{6544 - 6534} = 0.6$$

which exceeds the critical ratio at the 95 percent probability level. The first measurement was rejected as a faulty reading (outlier), and all following calculations disregard it.

Step 3—Correcting for bias.

According to Equation 4, the average systematic error due to tape inaccuracy is zero, but that for sludge is given by.

$$\bar{e} = \frac{(e_1 + e_2)}{2} = \frac{-4 + 0}{2} = -2 \text{ millimeters}$$

The results x_i must be adjusted according to Equation 1 to give the corrected measurements Y_i, for i = 1 to 5: 6546, 6544, 6542, 6545, and 6546.

Step 4—Estimating true gage reading.

This will be the average $\bar{y}$ of the results corrected for bias (Equation 5), that is:

$$\bar{y} = \frac{6546 + 6544 + ... + 6546}{5} = 6544.6 \text{ millimeters}$$

Step 5—Estimating standard deviation.

The standard deviation of corrected measurements can be estimated both from Equation 7 as:

$$s(y) = \tfrac{1}{4}\sqrt{(1.4^2 + 0.6^2 + 2.6^2 + 0.4^2 + 1.4^2)} = 1.67$$

and from Equation 8 as:

$$s(y) = \frac{w}{D(5)} = \frac{4}{2.326} = 1.72$$

Statistics derived from the second and more approximate estimate will be given in parentheses for comparative purposes.

Step 6—Estimating range of uncertainty.

By substituting the standard deviation estimates into Equation 13, the limit of the range of uncertainty due to random errors becomes:

$$a(\bar{y}) = \frac{[t_{n-1}][s(y)]}{\sqrt{5}} = \frac{2.776 \times 1.67}{\sqrt{5}} = 2.07\ (2.14) \text{ millimeters}$$

Since there are two unknown sources of systematic error, the corresponding limits of uncertainty will be estimated for each according to Equations 15 and 16, respectively, as:

$$\text{limit due to sludge } b_1(y) = 0.95 \times \left|\frac{(-4 - 0)}{2}\right| = 1.9 \text{ millimeters}$$

$$\text{limit due to tape } b_2(y) = 0.95 \times |-1| = 0.95 \text{ millimeter}$$

Combining the systematic limits by the root sum square method (Equation 18) gives the total limit for systematic errors:

$$b(y) = \sqrt{1.9^2 + 0.95^2} = 2.12 \text{ millimeters}$$

The limits for systematic and random uncertainties should be combined in a similar manner (Equation 19) to give:

$$c(\bar{y}) = \sqrt{a^2(\bar{y}) + b^2(\bar{y})} = \sqrt{2.07^2 = 2.12^2} = 2.96\ (3.01) \text{ millimeters}$$

Step 7—Estimating repeatability.

To compare the variability within the set of measurements to that expected in practice, the repeatability can be estimated from Equation 23 as:

$$r = (t_{n-1}) \times \sqrt{2} \times s(y) = 2.776 \times \sqrt{2} \times 1.67 = 6.6\ (6.7) \text{ millimeters}$$

Rounding up to the nearest unit of measure of 1 millimeter (see 13.1.8.3), the repeatability estimates would become 7 millimeters. This is identical to the value derived from the independent study.

Step 8—Stating the result.

The estimate of the true gage reading should be stated after rounding to the nearest unit of measure (see 13.1.5.4):

$$C(\bar{y}) = 2.96 \sim 3$$

The result statement thus becomes:

True gage reading = 6545 ± 3 millimeters (95 percent confidence level, 5 measurements)

NOTE. One further result is rejected as a faulty reading (outlier).

Table 3—Derived Statistics for Example

Value	Gage Reading, millimeters	Thermometer Reading, °C
n	5	9
$\bar{y}$	6544.6	23.38
$\sigma(\bar{y})$	2.07	1.362
$b(y)$	2.12	0.500

Table 4—Symbols for Example

Measurement	True Value	Estimate Corrected for Bias
Depth	X_1	y_1
Absolute volume	X_2	y_2
Temperature	X_3	y_3
Corrected volume	X_4	y_4

13.1.8.4.2 Measuring Volume

Next, the statistics derived from the two sets of direct measurements are combined according to the procedures of 13.1.8.2 as follows:

Step 1—Information available.

The information corresponding to the direct measurements can be summarized in the form of derived statistics as in Table 3. Let us also assume that the symbols allocated to each quantity are as listed in Table 4.

The calibration table, by which a gage reading in millimeters can be converted to a volume in liters, was obtained from an unknown function of tank dimensions. No random error is created in the use of such a table, but an unknown systematic error is expected resulting from the approximate nature of the function. This was assumed to be level dependent, and the corresponding limit of uncertainty is estimated to be:

$$b(X_2) = 0.2\%\ X_2$$

Finally, the function (see Equation 25) used to correct the volume for temperature and expansion in the tank is:

$$\begin{aligned} X_4 &= F(X_2, X_3) \\ &= f(X_3)\, X_2\, [1 + 0.000022\,(X_3 - 15)] \end{aligned}$$

Table 5—Volume Measurement Statistics for Example

Value	Gage Reading, milliliters	Volume Measurement, liters
n	5	5
$\bar{y}$	6544.6	17016
$\sigma(\bar{y})$	2.07	5
$b_1(\bar{y})$	2.12	6

Where:

$f(X_3)$ = a factor (read from tables) corresponding to a temperature X_3.

Step 2—Estimating absolute volume.

The calibration table may be regarded as a means of converting a liquid depth measurement (gage reading) in millimeters to a liquid volume measurement in liters and may be represented by the function:

$$X_2 = PX_1$$

P is nearly constant in this example. The statistics that relate to volume results should, therefore, be read directly from the table. In this case, they are assumed to be those in Table 5.

The systematic error brought about by inaccuracies in the table should be considered at this point. In terms of results corrected for bias, the corresponding limit of uncertainty will be estimated as:

$$\begin{aligned} b_2(\bar{y}_2) &= 0.2\%\ \bar{y}_2 \\ &= 0.002 \times 17016 \\ &= 34 \text{ liters} \end{aligned}$$

The two limits for systematic errors that affect volume results are then combined by the root sum square method (Equation 18) to give:

$$\begin{aligned} b(y_2) &= \sqrt{b_1^2\,(y_2) + b_2^2\,(y_2)} \\ &= \sqrt{6^2 + 34^2} \\ &= 35 \text{ liters} \end{aligned}$$

Step 3—Estimating corrected volume.

According to Equation 26, the estimate of correct volume will be obtained by substituting estimates directly into the appropriate equation. If we assume that the temperature factor $f(x_3)$ is read from tables as:

$$\begin{aligned} f(\bar{y}_3) &= f(23.38) \\ &= 0.98 \text{ (given)} \end{aligned}$$

Then the true corrected volume is estimated to be:

$$\begin{aligned} \bar{y}_4 &= 0.98 \times 17016\,[1 + 0.000022(23.38 - 15)] \\ &= 16678.9 \text{ liters} \end{aligned}$$

Step 4—Estimating random uncertainty limit.

The random errors for volume and temperature measurements are combined according to Equation 33. In our case, the derivatives of the function are:

$$\frac{\partial F}{\partial X_2} = 0.98\,[1 + 0.000022\,(X_3 - 15)]$$

and

$$\frac{\alpha F}{\alpha X} = 0.98 \times X_2 \times 0.000022$$

Substituting the estimated values.

$$\bar{Y} = 23.38 \text{ (Table 3)}$$
$$\bar{Y}_2 = 17016 \text{ (Table 5)}$$

For X_1 and X_2, respectively, gives

$$\frac{\alpha F}{\alpha X_2} = 0.98018$$
$$\frac{\alpha F}{\alpha X_1} = 0.36638$$

The total limit of random uncertainty will then be given by.

$$a(y') = \sqrt{(0.98018 \times 5)^2 + (0.36686 \times 1.362)^2}$$
$$= 4.9 \text{ liters}$$

Step 5—Estimating systematic uncertainty limit.

Systematic uncertainty limits should be combined in a fashion similar to random uncertainty limits according to Equation 34. The total limit of systematic uncertainty will be:

$$b(\bar{y}_1) = \sqrt{(0.98018 \times 35)^2 + (0.36686 \times 0.5)^2}$$
$$= \sqrt{34.3036^2 + 0.18343^2}$$
$$= 34.3 \text{ liters}$$

Note that the systematic error in temperature measurements makes only a small contribution compared with that created by inaccuracies in the calibration table

Step 6—Stating the result.

Combining the random and systematic components of uncertainty by quadrature (Equation 19), the total uncertainty limit becomes:

$$e(\bar{y}_1) = \sqrt{a^2(\bar{y}_1) + b^2(\bar{y}_1)}$$
$$= \sqrt{4.9^2 + 34.3^2}$$
$$= 34.6 \text{ liters}$$

Rounding to the nearest unit of measurement, which from the calibration table was 1 liter, the final statement will be:

True corrected volume = 16,679 ± 35 liters (95 percent confidence level, 5 gage measurements, 9 temperature measurements).

NOTE One further gage reading is rejected as a faulty reading.

APPENDIX A
NORMAL (GAUSSIAN) DISTRIBUTION

Consider a set of n repeated measurements x_i, lying in the range a to b so that $a \leq x_i \leq b$. If the total range is split into p equal subranges of length $dx = (b - a)/p$, a frequency histogram can be drawn. The histogram (see Figure A-1) consists of a series of p contiguous rectangles, with base equal to the subrange dx and height proportional to the number of measurements falling in that range.

The height of each rectangle could just as easily represent the proportion of the total number falling in the subrange or the relative frequency. The total area of the histogram would then be 1, and the area in each rectangle would become the probability of a measurement falling in the subrange.

Now consider the number of measurements n becoming very large, and the length dx of each subrange becoming very small. A continuous line drawn through the midpoint of the tops of each rectangle, which represents the relative frequency of measurements, would give a bell-shaped curve similar to Figure A-2.

For the normal distribution, the curve is symmetrical about the mean and has the formula:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{(x-\mu)^2}{\sqrt{2\alpha}}\right)$$

Where

σ = standard deviation.

The area under the curve once again represents probability. Each of the shaded regions shown has an area of:

$$P = \int_{-\infty}^{\mu - c} f(x)\,dx = \int_{\mu + c}^{+\infty} f(x)\,dx$$

When $c = 1.96\sigma$, the probability P (one shaded area) will be 0.025, or 2½ percent of the total area under the curve.

Now if measurements x_i follow the normal distribution with mean μ and standard deviation σ, then values μ_i will follow a normal distribution with zero mean and unit standard deviation where:

$$\mu_i = \frac{(x_i - \mu)}{\sigma}$$

The value μ_i is termed the ***standard normal deviate***, and has been tabulated for different probabilities P. For a

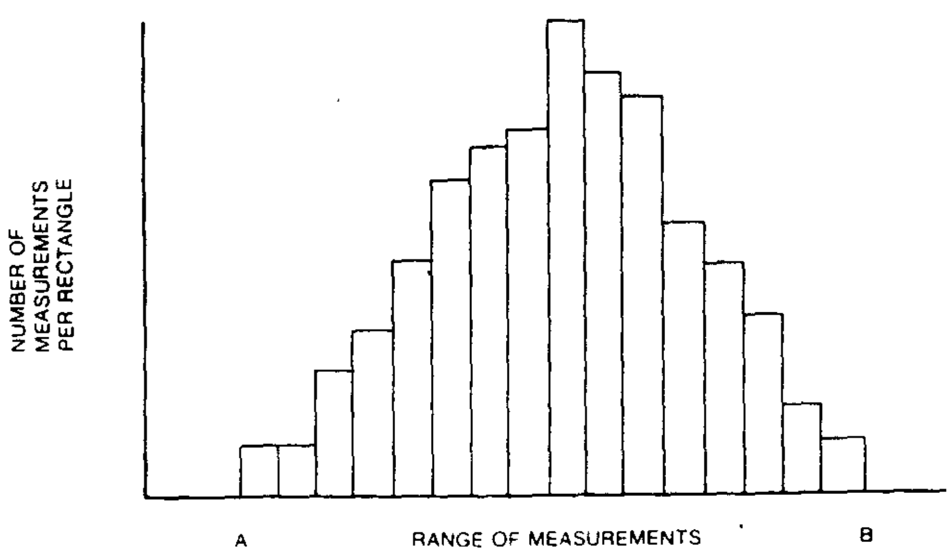


Figure A-1—Frequency Histogram

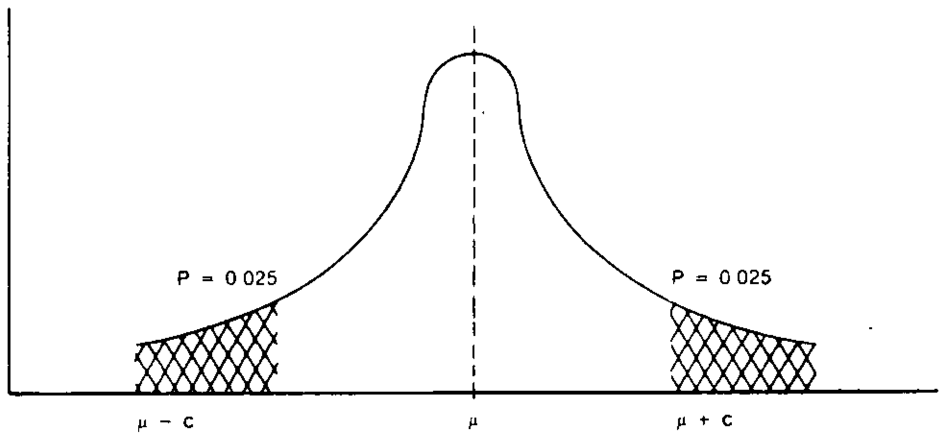


Figure A-2—Bell-Shaped Curve

probability $P = 0.05$, however, the standard normal deviate has a value 1.96. This probability is represented by both shaded areas in the distribution (Figure A-2) and includes all values of x which differ from the mean μ by more than 1.96σ.

APPENDIX B
DIXON'S TEST FOR OUTLIERS

The following steps should be followed (see Table B-1) to use Dixon's test for outliers.

1. Arrange the set of measurements x_i in ascending order of magnitude $x_1, x_2, \ldots x_n$.
2. Choose the appropriate test criterion, depending on the value of n and whether the measurement in question is low or high.
3. Calculate the Dixon R ratio. If this exceeds the critical ratio at the 5 percent probability level (P = 0.95), then the measurement in question is highly suspect and could possibly be rejected.

If the critical ratio at the 1 percent probability level (P = 0.99) is exceeded, then the measurement in question should be discarded.

When a measurement is rejected, the outlier test should be repeated.

NOTE: The two suffixes in the Dixon ratio refer to the differences in the numerator and denominator respectively

Table B-1—Dixon's Test for Outliers

Number of Values, n	Critical Values P = 0.95	Critical Values P = 0.99	Test Criterion Low Values		Test Criterion High Values
3	0.941	0.988			
4	0.765	0.889			
5	0.642	0.780	$R_{10} = \frac{x_2 - x_1}{x_n - x_1}$	or	$\frac{x_n - x_{n-1}}{x_n - x_1}$
6	0.560	0.698			
7	0.507	0.637			
8	0.554	0.683			
9	0.512	0.635	$R_{11} = \frac{x_2 - x_1}{x_{n-1} - x_1}$	or	$\frac{x_n - x_{n-1}}{x_n - x_2}$
10	0.477	0.597			
11	0.576	0.679			
12	0.546	0.642	$R_{21} = \frac{x_3 - x_1}{x_{n-1} - x_1}$	or	$\frac{x_n - x_{n-2}}{x_n - x_2}$
13	0.521	0.615			
14	0.546	0.641			
15	0.525	0.616			
16	0.507	0.595			
17	0.490	0.577			
18	0.475	0.561			
19	0.462	0.547			
20	0.450	0.535	$R_{22} = \frac{x_3 - x_1}{x_{n-2} - x_1}$	or	$\frac{x_n - x_{n-2}}{x_n - x_3}$
21	0.440	0.524			
22	0.430	0.514			
23	0.421	0.505			
24	0.413	0.497			
25	0.406	0.489			

SOURCE: *Biometrics*, Vol. 9, p. 89, 1953.

Chapter 3

Phase Behavior of Natural Gas

INTRODUCTION

Obviously, field processing of natural gas depends strongly on the behavior, characteristics, or properties of the well stream involved. It is important to know and predict the amount, composition, and density of any phases present in any process situation. Accordingly, hydrocarbon *phase behavior* is discussed, first for pure components and then for mixtures. The more commonly used *phase diagrams* are presented. Phase-equilibrium calculations are reviewed next, including both hand and computer methods. Phase equilibrium calculations require component K-values and densities. Two sources of these important data are reviewed: charts and equations of state.

Phase behavior in the presence of water is important also, since if water condenses a second liquid phase will be present. Water/hydrocarbon phase behavior is discussed in Chapter 4. At low temperatures, carbon-dioxide/hydrocarbon phase behavior is important, and this topic is summarized in Chapter 4 also.

PURE-SUBSTANCE PHASE DIAGRAMS

A simple or one-component system is defined as one that undergoes no changes in composition; in practice, this means either a *pure substance* or a homogeneous mixture. Frequently, air can be considered a pure substance even though it is a mixture of nitrogen, oxygen, carbon dioxide, and water vapor, plus minor amounts of other gases. In the compression or heat exchange of air, the air can be treated as homogeneous. Of course air must be considered a complex mixture when separated into oxygen and nitrogen, or when partially condensed into liquid and vapor phases having different compositions, or when one component (oxygen) reacts during combustion.

Everyday experience tells us the number of *independent thermodynamic variables* that can be assigned arbitrary values before the *state* or condition of a pure substance is known. For example, if we choose pure H_2O as the system and specify the temperature to be 20°C (68°F) and the pressure to be 1 atm (101.3 kPa, 14.696 psia), we know that the H_2O is liquid. In addition, all other properties (v, h, s, ρ, μ, etc.) are completely fixed also. Two variables have determined the state of the system.

We also know that, at one atmosphere, water boils at 212°F (100°C). Thermodynamics explains this experimental fact as follows: If the pressure is fixed at 1 atm, then the temperature must be 212°F for equilibrium to exist between liquid water and water vapor (steam). Again we have made two specifications: First, there are two phases (liquid and vapor) in equilibrium and, second, the pressure is 1 atm. Again two statements fix all the properties of the two phases (v_l, v_g, h_l, h_g, s_l, s_g, etc.). In fact, everything is known about both the liquid and the vapor phases except how much of each phase is present.

The above facts can be described from another viewpoint. We specify the liquid and vapor phases to be an equilibrium two-phase system Then only one additional thermodynamic property or variable can be chosen before the system is fixed

The number of choices required to specify or fix a system completely is called the *degrees of freedom* or *variance* (f). Gibbs' phase rule (Van Wylen and Sonntag, p. 534) is a convenient way of remembering the number of degrees of freedom:

$$f + \phi = C + 2 \qquad (3\text{-}1)$$

where f = number of degrees of freedom (the number of independent, intensive thermodynamic variables)

ϕ = number of equilibrium phases

C = number of components in system (by definition 1 for a pure substance).

Using the phase rule for a pure substance we find:

when ϕ = 1, there are 2 degrees of freedom
ϕ = 2, there is 1 degree of freedom
ϕ = 3, there are no degrees of freedom.

In addition, for a pure substance it is impossible to have four different phases coexisting in equilibrium.

The phase behavior of pure substances can be described using diagrams. One example is the pressure-temperature (P-T) diagram (Fig. 3–1) which shows vapor, liquid, and solid phases. In many cases, pure substances exhibit several different solid phases; e.g., there are at least six different phases for ice (Van Wylen and Sonntag, p. 42). Note Figure 3–1 also summarizes our previous "phase-rule" conclusions. Single-phase loci (ϕ = 1) are areas (f = 2). Two-phase loci (ϕ = 2) are lines (f = 1). The three-phase locus, or triple point, (ϕ = 3) is a point (f = 0).

Because a pure substance has, at most, two degrees of freedom, we can use any pair of independent thermodynamic properties for the axes of our phase diagram. Some of the more popular diagrams are the pressure-volume (P-v), temperature-entropy (T-s), pressure-enthalpy (P-h, or log [P-h]), and Mollier or enthalpy-entropy (h-s) diagrams. Figure 3–2 shows examples of these diagrams.

The liquid phase above (higher P) and left (lower T) of the vapor-pressure curve, such as point A in Figure 3–1, is called "sub-cooled" or "compressed" liquid. Vapor below (lower P and/or higher T) the vapor-pressure curve, e.g., B, is "superheated" vapor. The vapor pressure curve ends at the critical point, C. Above this critical temperature it is no longer possible for a change in phase to occur as the pressure is increased.

Consider a superheated vapor at state B in Figure 3–1. If the vapor is compressed at constant temperature (isothermally), as in a variable-volume cell in a constant-temperature bath, the path followed is the vertical dotted line shown. At first, the vapor is simply compressed until the vapor pressure curve is reached. Then further attempts at compression result in condensation. Note the *pressure* remains *constant* until *all* of the *vapor is condensed to liquid*. Only then does the pressure begin to rise again, and then very rapidly.

Let the process described above start at B, but now occur in three steps (B to D, D to E, and E to A) as shown by the dashed lines in Figure 3–1. Now a continuous path is followed with no visible phase change because we chose a temperature higher than the critical for the compression step. At such a temperature, we call the fluid a "gas" rather than a "vapor," the distinction being that a vapor is condensible and a gas is not.

To the right of and above the critical point (higher T and/or P) on the P-T diagram, the fluid is called a "supercritical fluid," or more simply, a "dense fluid."

Vapor-pressure curves (VP-T diagrams) can be plotted in various ways. One popular method is to plot log vapor pressure versus reciprocal absolute temperature because the resulting plot is very nearly a straight line. The abscissa is often plotted backwards and labeled as temperature rather than reciprocal absolute temperature, for convenience in use. The resulting temperature scale is highly nonlinear as shown in Figure 3–3. Another popular method is to plot log vapor pressure versus 1/(T°F + 382), which is

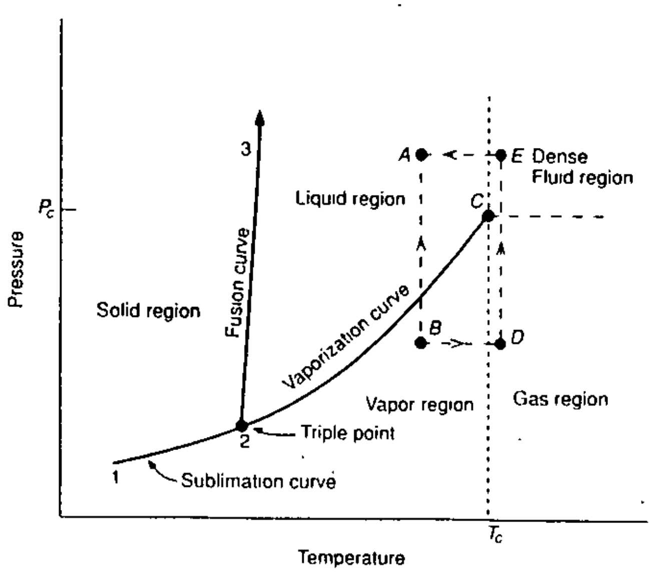


Figure 3–1. Pressure-temperature diagram.

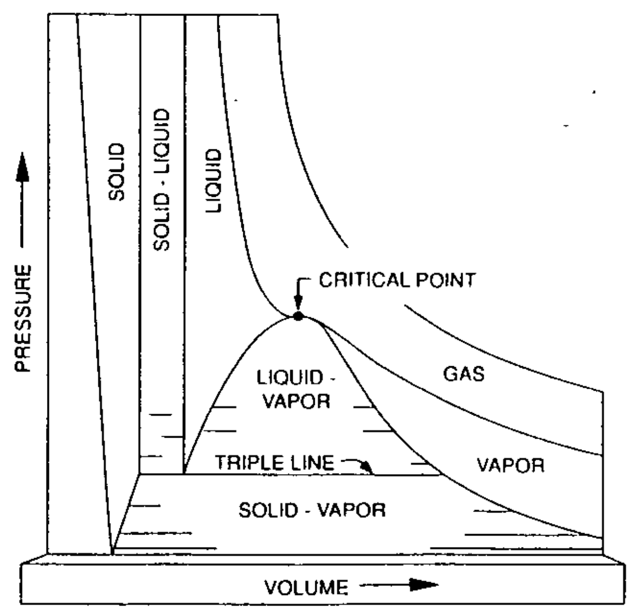


Figure 3–2a. P-V diagram for pure substances that contract on freezing (Lee and Sears, 1963, p. 40).

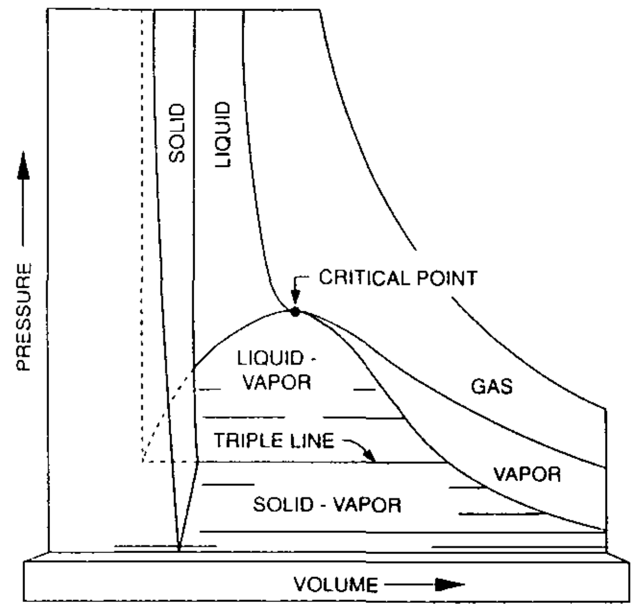


Figure 3–2b. P-V diagram for pure substances that expand on freezing (Lee and Sears, 1963, p. 40).

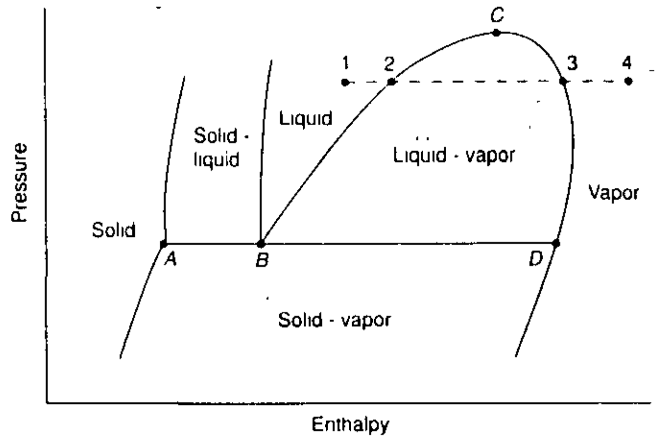


Figure 3–2d. Pressure-enthalpy (ln P-h) diagram for a single-component system (Smith and van Ness, 1973, p. 214)

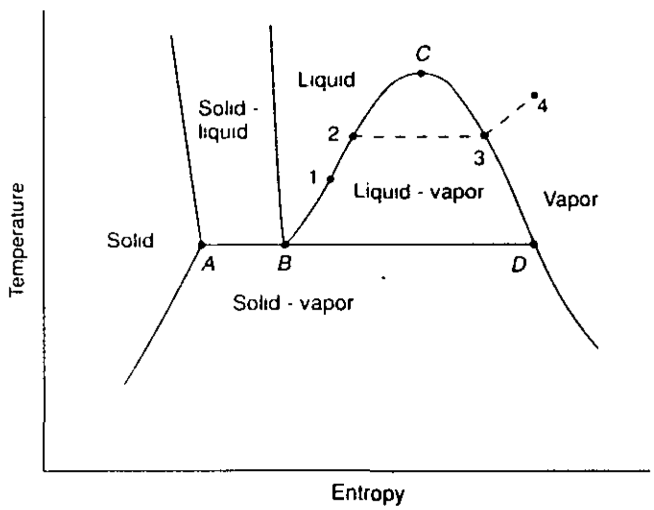


Figure 3–2c. Temperature-entropy (T-s) diagram for a single-component system (Smith and van Ness, 1975, p. 213)

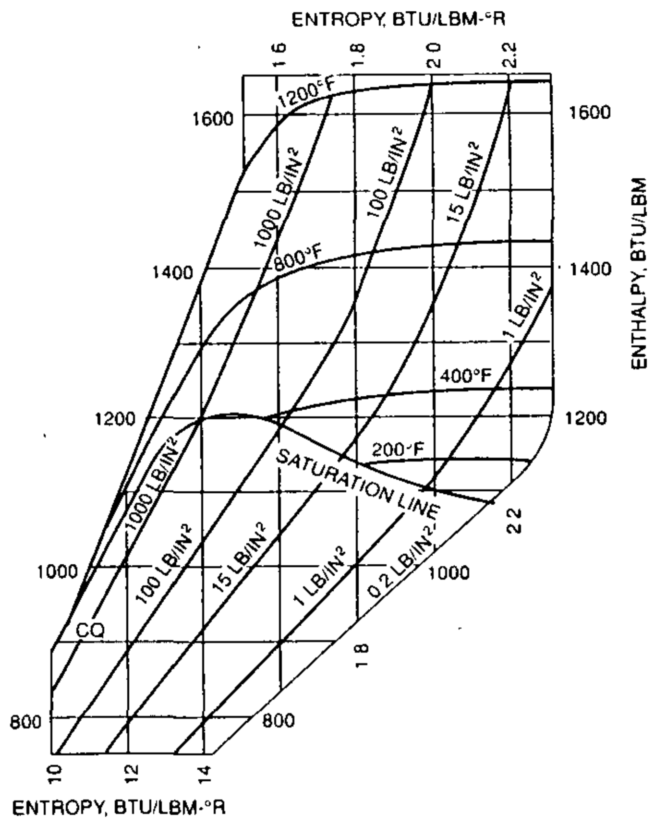


Figure 3–2e. The Mollier (h-s) diagram for water (Lee and Sears, 1963, p. 259).

Figure 3–2. Thermodynamic diagrams for pure substances.

Fig. 3-3

High-Temperature Vapor Pressures for Light Hydrocarbons

GPSA Engineering Data Book, p. 23-41

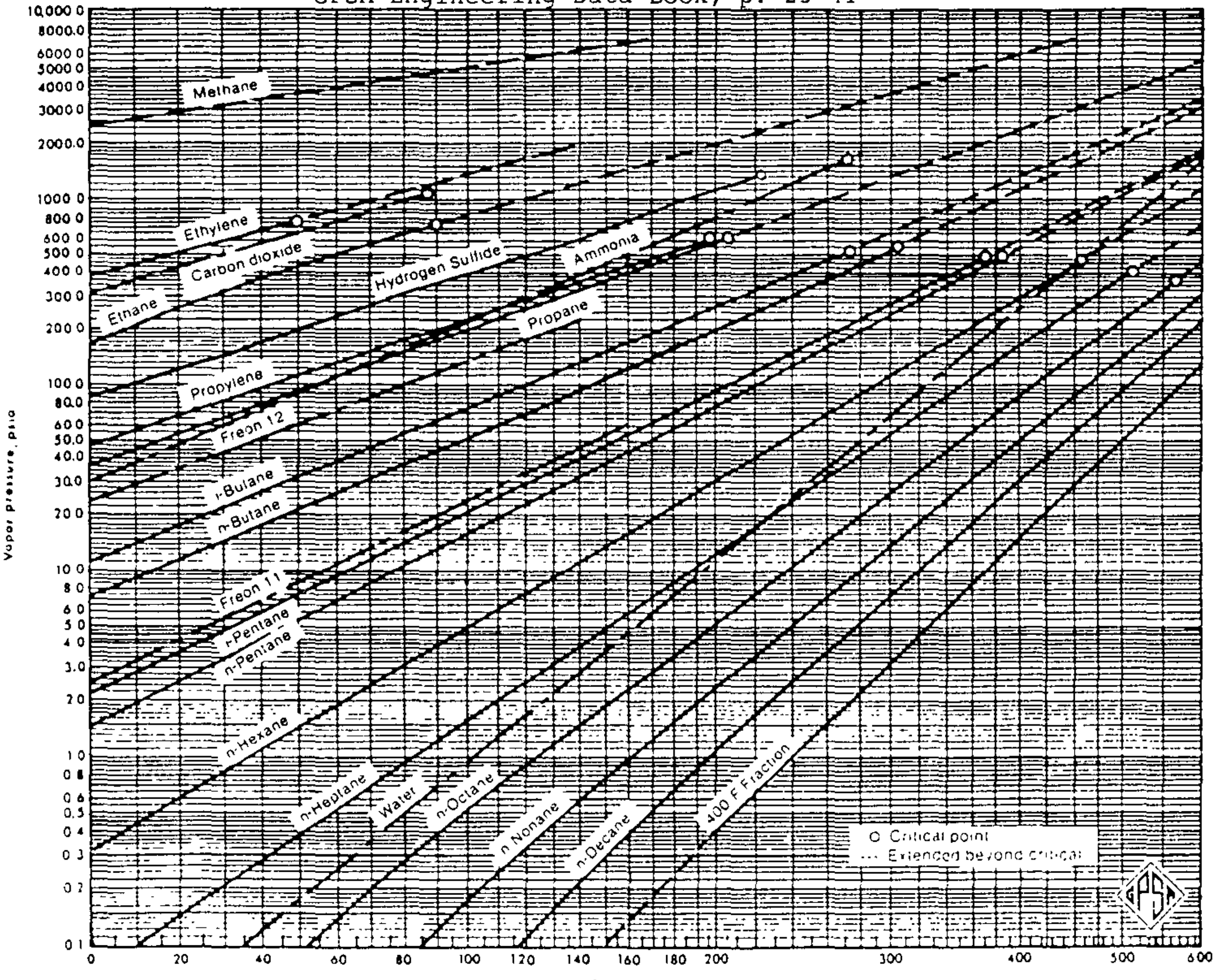


Figure 3–3. High-temperature vapor pressures for light hydrocarbons (GPSA, 1987, p. 23–41).

equivalent to the so-called Cox chart (Hougen *et al.*, 1962, p. 85).

TWO-COMPONENT SYSTEMS

Addition of a second pure component complicates the P-T diagram, although the P-v plot remains much the same. Figure 3–4 shows that the one-component, vapor-pressure *line* "becomes" an *envelope*. For a two-component, two-phase mixture the phase rule yields f = 2. Thus both P and T must be specified to define the state of the system; the two-phase locus is an area rather than a line, as Figure 3–4 also shows.

The location of this phase envelope depends on the vapor-pressure curves of the pure components and the composition of the mixture. Vapor pressure curves for the two pure components are shown also. The more volatile component, A, has its vapor-pressure line to the left (lower T) of the mixture phase envelope. The vapor-pressure curve for less-volatile pure B lies to the right (higher T) of the phase envelope. Notice that the critical pressure of the mixture, located at C, is much higher than the critical pressure of either pure component.

The *bubble-point line* is the locus at which vaporization begins. If the overall binary-mixture composition is given (one variable, since the second composition is found by difference), then f = 1 and the locus is a line, as shown. The *dew-point line* is the locus at which condensation begins for the given binary mixture. Again, this locus is a line.

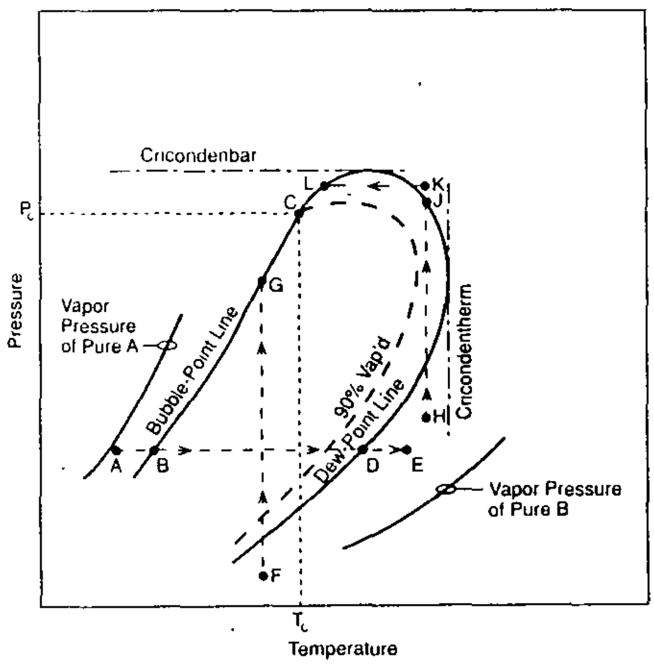


Figure 3–4. Phase envelope for a mixture of two components

The dew-point and bubble-point lines meet each other at the critical point, C. Any particular P-T diagram corresponds to a fixed composition for the overall mixture.

In addition to the bubble- and dew-point lines, Figure 3–4 shows a constant percent-vaporization line for 90 percent vaporized. This line converges to the critical point, as do all constant-percentage vaporization lines.

In Figure 3–4, A is a point in the subcooled liquid region. Suppose we heat this liquid at constant pressure. Point B is the bubble point of the mixture. As vaporization continues at constant pressure, the temperature rises. When the last drop of liquid vaporizes, the dew-point curve is reached (point D). In going at constant pressure from the bubble point to the dew point, the mixture undergoes a rise in temperature; it has a *boiling range, not a boiling point.* Further heating produces a superheated vapor, as at E.

Another new type of behavior arises with two-component mixtures. Line FG in Figure 3–4 shows a constant-temperature, or isothermal, compression at a temperature less than the critical. The dew point is first reached, then progressive condensation occurs until the mixture is all liquid at the bubble point (point G). This behavior is regarded as "normal."

Line HJ shows the new possibility. Start with vapor at a temperature higher than the critical (point H). If we compress isothermally, we reach the dew point and condensation results, as expected. Further increase in pressure at first results in more condensation, but a point is reached at which condensate begins to *decrease* in amount. With continued pressure increase, the dew point is again reached at point J. This phenomenon is known as *retrograde vaporization.*

Line KL depicts a second type of retrograde vaporization. In this case a decrease in temperature at constant pressure from point K at first yields liquid formation in increasing amount, but at some point the liquid begins to evaporate and the dew point is once again reached at point L. This is a bit confusing, because the fluid at point L is perhaps more liquid-like than vapor-like. Nevertheless, it is the fluid remaining above the liquid phase at dew-point L. One might term it a *dense phase.*

The highest pressure at which liquid and vapor can coexist in a mixture can be greater than the critical pressure. This pressure, shown in Figure 3–4, is referred to as the *cricondenbar*. Similarly, the highest temperature at which liquid and vapor can coexist for the mixture is called the *cricondentherm*.

MULTICOMPONENT SYSTEMS

The basic phase behavior of multicomponent systems is the same as for binary mixtures. This is because compositions for all but one component, or C–1 variables, must be specified to define the mixture. Only two degrees of freedom remain—exactly the same as for a binary mixture. The P-T diagram for a multicomponent mixture of given composition has a shape very similar to that of a binary mixture Phase envelopes for most naturally-occurring hydrocarbon mixtures are very broad because the components have a wide boiling range. Phase diagrams of typical full wellstreams are shown as examples.

Full Wellstreams

Figure 3–5 shows the general shape of the phase diagram for a *reservoir fluid* The type of reservoir and fluid produced from it depend upon the location of the reservoir temperature and pressure relative to the phase diagram.

Line A-A′ shows the situation for a low-GOR crude oil, one in which the amount of gas evolved from the oil is quite low. Point A represents the reservoir pressure and temperature. As the oil flows out of the reservoir, into the wellbore, and up the producing string to the wellhead, both the temperature and the pressure decrease.

The fluid temperature decreases for two reasons. First, the temperature of the surrounding rock decreases toward the surface, so that heat transfer occurs between the hot well fluid and the cooler rock. Second, vaporization may take place also, and the required energy is supplied by the fluid itself, causing a drop in temperature.

Similarly, the pressure decreases for two reasons. As fluid travels up the string, the depth decreases and the hydrostatic head thus decreases. In addition, there is frictional pressure drop in the tubing

The phenomena just described account for the general

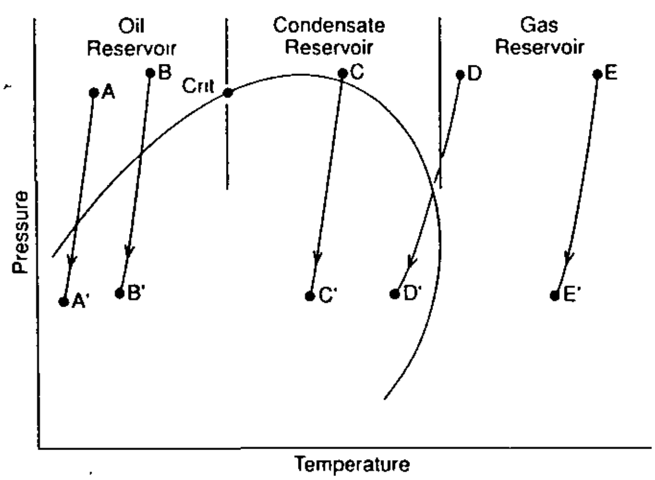


Figure 3–5. Typical phase diagram of a reservoir fluid (after McCain, 1990, and Sarssam, 1988).

shape of curve A-A′. The net effect is to bring the fluid below its bubble curve and into the two-phase region. A few crude oils do not reach the bubble-point curve and evolve no associated gas; such oils are referred to as "dead" oils.

Curve B-B′ corresponds to the situation of a high-GOR crude oil. More gas is evolved than for curve A-A′. If the reservoir fluid T and P lie in the region to the left (lower temperature) of the critical point, the produced fluid is termed a *crude oil*.

Reservoir pressure tends to decrease as the oil field is produced. Figure 3–5 shows that if point A falls below the bubble-point line, vaporization will occur in the reservoir itself. Valuable hydrocarbons may remain in the formation since the gas and liquid will not flow equally to the producing well. This explains why water injection is practiced in some fields almost from the beginning of production, to help maintain reservoir pressure.

Line C-C′ shows the behavior of a retrograde condensate fluid as it is produced, something between a natural gas and an oil. In this case, the relative amounts of both liquid and gas may be very high. If the reservoir temperature lies between the critical temperature and the cricondentherm, the reservoir is usually termed a *condensate reservoir* and the produced fluid is often called a *retrograde condensate gas*.

An important conclusion can be drawn from Figure 3–5. If the pressure in a *condensate reservoir* falls below the dew-point line during production, condensation will take place in the reservoir itself. Valuable heavier liquid components will likely remain in the reservoir and not be produced. Pressure maintenance by gas reinjection is sometimes practiced in such a reservoir. Reinjection and other producing strategies for gas condensate fields will be discussed in Chapter 5.

Suppose line B-B′ lies to the left and very close to the critical point and line C-C lies to the right and very close to the critical point. Now these two lines are very close to each other. Clearly, mere observation of the well-head separator GOR is not suffient evidence to decide the type of reservoir. Furthermore, the arbitrary nature of calling the reservoir a crude oil or a condensate reservoir becomes obvious.

Curve D-D′ depicts the situation for a "wet" natural gas. Reservoir conditions are in the gas or dense fluid region to the right of the cricondentherm. When produced, the fluid yields hydrocarbon condensate due to the temperature and pressure decrease. Point D′ is within the two-phase region, below the dew-point line. The arbitrary distinction between a condensate reservoir and a wet gas reservoir become clear.

Curve E-E′ represents the reservoir and producing conditions for a "dry" natural gas. No hydrocarbon condensate is formed in the surface separator.

Note well. While Figure 3–5 illustrates and clarifies the classification of well fluids, the figure is, however, misleading in the sense that points A', B', C', D', and E' actually represent approximately the same wellhead temperature, usually in the range of 100–140°F. Points A, B, C, D, and E will not be the same for the reason that the reservoir temperature and pressure are dependent on the depth of the producing formation. Nevertheless, these production lines will more or less coincide; it is the phase diagram of the reservoir fluid that will change its position relative to the line.

Another important point with respect to Figure 3–5 is that the shape of the phase diagram and the relative location of the critical point is highly dependent on the reservoir fluid composition. A dry natural gas has a fairly low range of components. Its phase diagram will be of relatively narrow width; the critical point will lie well down on the left side of the envelope. Conversely, a crude oil has a very wide range of components. An oil envelope will be very wide and the critical point near the top or somewhat to the right side of the envelope. Figures 3–6 and 3–7 show these features.

Source of Phase Diagrams

Phase diagrams are measured in the laboratory or predicted from equilibrium calculations as shown below. Very briefly, experimental measurements involve determining the locus of the dew and bubble points in a variable-volume cell. Determination may be visual, as in a windowed cell, or based on break points in the pressure-volume data. Jacoby and Yarborough (1967) and others describe apparatus and techniques.

Experimental *measurements* are extremely time-consuming and expensive. Such data are used to develop

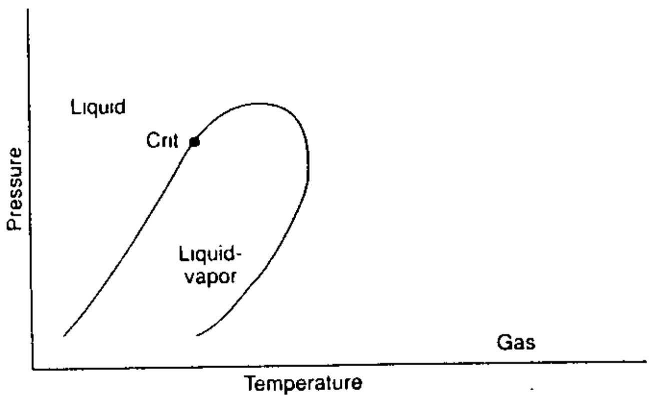


Figure 3–6. Typical phase diagram of a dry natural gas.

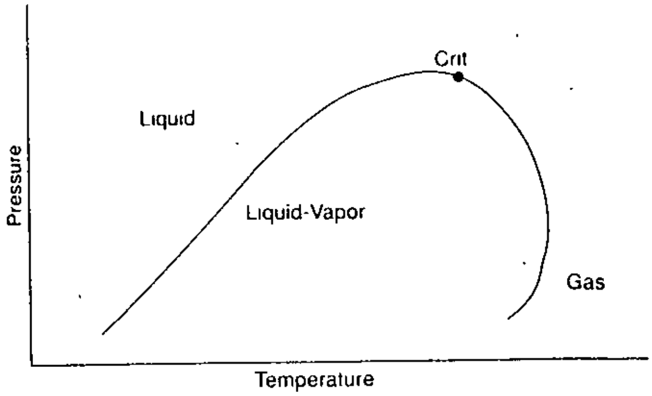


Figure 3–7. Typical phase diagram of a low-GOR crude oil

calculational methods for predicting phase behavior. Invariably, computer methods use equations of state and require very complex calculations. Hand calculation methods must be much simpler to be practical, and even then can be time-consuming.

Computer methods are generally quite satisfactory for phase calculations. However, the calculations are only as good as the analyses of the streams being considered. In general, sampling and analysis require great care, as discussed in Chapter 2.

A second source of error in computer-generated phase diagrams lies in the characterization of the heavy ends. In natural gases, the quantity of heavy ends may not be large, but the characterization of them influences the location of the dew-point line. Phase diagrams developed from computer calculations for two simulated natural gases and one simulated separator gas are shown in Figure 3–8. The two natural gases, A and B, differ only in the identity of the small fraction of C7+ material as nC7 or nC8. Yet the dew-point locus is shifted several degrees.

Accurate location of the dew-point locus is important in at least two cases. First is the simulation of phase behavior in a reservoir, in which the calculations must represent the actual reservoir fluid as well as possible. Second is the pipeline flow in which small amounts of hydrocarbon condense. Liquid formation greatly increases the pressure drop in the pipeline and hence gas-compression requirements. An undersized compressor can limit the production from a field.

The bubble-point locus in Figure 3–8 is close to the methane vapor-pressure curve for both simulated natural gases, as it is for all gases that contain more than about 80 mole percent of methane. A separator or associated gas, which contains a much higher amount of heavier components, has a broader phase diagram, as is shown in Figure 3–8.

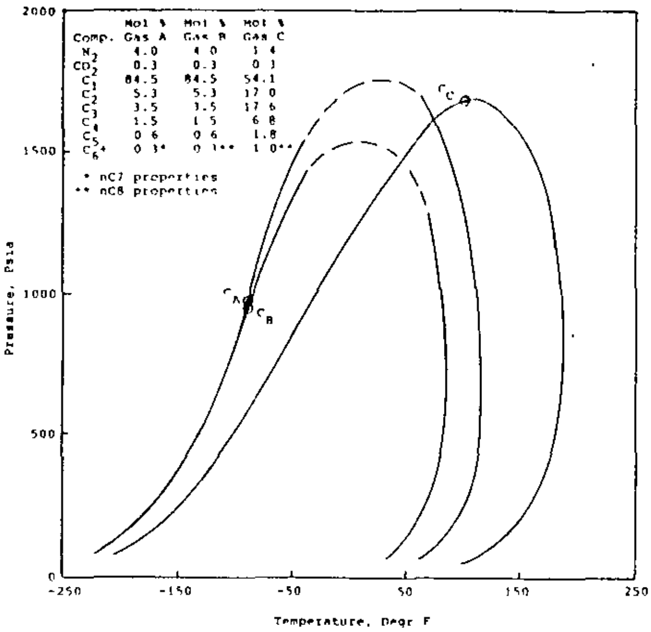


Figure 3–8. Phase diagrams for simulated natural gases.

Hand phase-equilibrium calculations can also be used but are not as accurate as computer calculations, as might be expected However, hand calculations are satisfactory for many purposes. These methods are discussed below.

Phase Behavior in Separators

Figure 3–9 shows computer-generated phase diagrams for a separator feed (F) and the liquid (F_L) and vapor (F_V)

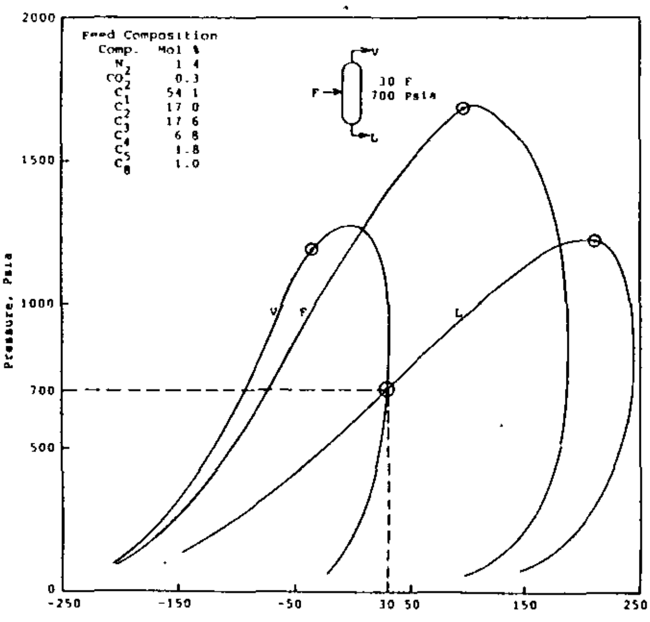


Figure 3–9. Phase diagrams for separator streams.

products. The separator products are assumed to leave in phase equilibrium with each other. The separator pressure and temperature are located at point A, where the products are saturated liquid and saturated vapor, respectively.

PHASE-EQUILIBRIUM CALCULATIONS

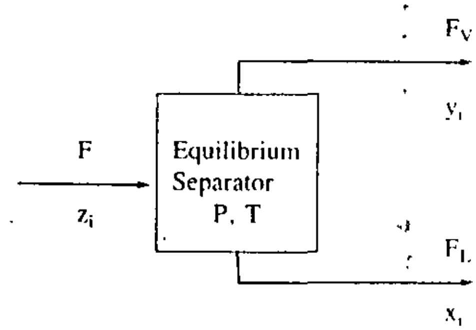
There are three basic phase-equilibrium calculations:

1. Bubble-point
2. Dew-point
3. Equilibrium-Flash

Types (1) and (2) determine phase envelopes and the temperature or pressure at which a given mixture will begin to vaporize or condense. Type (3) estimates the percentage vaporized and the equilibrium-phase compositions for mixtures that are partly vaporized or condensed

The nomenclature for phase-equilibrium calculations is shown below.

Flash-Vaporization Nomenclature



F = feed rate, mol/hr
F_L = liquid rate, mol/hr
F_V = vapor rate, mol/hr
z_i = mole fraction of component i in the feed
x_i = mole fraction of component i in the liquid
y_i = mole fraction of component i in the vapor
P = pressure of the flash vaporization
T = temperature of the flash vaporization

Phase-equilibrium calculations use a quantity, K_i, called the *vapor-liquid equilibrium ratio*, or more simply, the *K-value*.

$$K_i = y_i / x_i \qquad (3\text{-}2)$$

K_i's are functions of component identity, temperature, pressure, and composition. The vapor-liquid equilibrium ratio or K-value may be obtained from so-called K charts or calculated from equations of state using computer programs. The GPSA (1987) Section 25, Engineering Data Book presents three sets or types of K charts:

(i) K-values for specific binary systems: C1–C2, C1–C3, C1–nC4, C1–nC5, Cl-nC6, C1–nC7, N_2–C1, N_2–C2, and C1–CO_2. These charts are used for temperatures below −100°F.

(ii) K-values for various components based on different convergence pressures of hydrocarbon systems. These charts are described and used in the examples that follow.

(iii) K-values of high-boiling oil fractions. Poettman and Maylund (1949) developed K charts for heavier HC which are characterized by their normal boiling point (NBP) and characterization factor. Figure 2–5 shows a typical chart in which P is plotted against K at various temperatures. The GPSA (1987) presents charts for NBPs of 300, 400, 500, 600, 700, and 800°F.

The OPSIM computer program (Appendix 4) illustrates the calculation of K-values using the SRK equation of state.

Vapor-liquid equilibria will be discussed in more detail in Volume 2

For simplicity, the subscript i is now omitted from x, y, z, and K. Each component present is understood to have its own value for each of these variables, and the summation sign refers to the summation for all components present.

Bubble-Point Temperature

Consider a liquid mixture of composition z at pressure P. Mole fraction z is used because the given composition is regarded as the "feed." Actually, z plays the part of x, because the feed is liquid. The question is, at what temperature will the liquid feed begin to vaporize at the given pressure P? Calculations are based on the concept that the first tiny bubble of vapor formed is in equilibrium with the feed at essentially unchanged composition, z. The composition of the vapor bubble is, by the previous definition,

$$y = K\,z \qquad (3\text{–}3)$$

for each component. The sum of the mole fractions of any mixture must be identically one.

$$\Sigma\, y = \Sigma\, K\, z = 1.0 \qquad (3\text{–}4)$$

Thus, our task is to find T such that when the K's are obtained for that T and the given P, the sum of Kz's is indeed equal to one, within an acceptable tolerance. The procedure is trial-and-error.

Example 3–1. A mixture has the composition below at 400 psia. What is the bubble-point temperature?

Component	z
C1	0.75
C3	0 24
nC6	0.01

Solution: Look up the component K's in the GPSA Data Book. Use a convergence pressure of 800 psia (justified later). Three trials are shown below. The first temperature tried, −100°F, gives a sum greater than 1 0. Therefore the second temperature chosen is lower, −120°F. Note that the K-values for nC6 are so low that they are simply taken to be zero. The sum at −120°F is still slightly less than 1.0. The final trial is for −126°F. Within the ability to read the K-values, the sum is sufficiently close to one. At 400 psia, the feed bubble-point is −126°F.

Comp.	z	$K^{-100°F}_{400\ psia}$	Kz	$K^{-120°F}_{400\ psia}$	Kz	$K^{-126°F}_{400\ psia}$	Kz
C1	0.75	2.0	1.500	1.45	1.087	1.33	0.998
C3	0 24	0.030	0 007	0.019	0 005	0.016	0.004
nC6	0.01		0.000		0.000		0 000
		~0		~0		~0	
Sum			1.507		1.092		1.002

Convergence Pressure

The above K-values are based on a convergence pressure of 800 psia. This choice must be justified. First, the concept of convergence pressure is reviewed.

Convergence pressure of a multicomponent mixture is somewhat analogous to critical pressure of a binary mixture. However, in the GPSA Data Book method, it is used as a correlating parameter for estimating the effect of composition on K-values. There are 7 different sets of K-charts for 14 hydrocarbons (C1 through C10) and N_2, and H_2S in Section 25 of the Data Book, each set for a different convergence pressure. Figure 25–2 GPSA (1987) lists the components and convergence pressures, which vary from 800 to 10000 psia.

To find the convergence pressure, the multicomponent mixture is treated as a pseudobinary. By convention, the light component of the pseudobinary is the lightest hydrocarbon component present to at least 0.1 mol percent in the liquid phase. The heavy component is represented by the weight-average critical temperature and pressure of the remaining heavier (less volatile) components.

The technique for finding convergence pressures, which is described in GPSA (1987) on p. 25–4, is now illustrated using the above bubble-point calculation. A convergence pressure of 800 psia is used. Refer to steps 1–8, p. 25–4, GPSA (1987).

Example 3–2. Calculate the convergence pressure for Example 3–1.

Step 1. Estimate the liquid-phase composition. Here, the liquid composition is the given feed composition.

Step 2. Select the light component as the lightest hydrocarbon present with $x > 0.001$. Here methane is the light component ($x = 0.75$, which is $>>0.001$)

Step 3. Calculate the weight-average critical temperature and pressure of the remaining heavier components.

Comp.	x	MW	g	w	Tc	Pc
C3	0.24	44.1	10.58	0.925	206.1	616.0
nC6	0.01	86.2	0.86	0.075	453.6	436.9
			$\Sigma g = 11.44$	1.000		

$$g = x\ MW$$

$$w = g / \Sigma g$$

$$T_{cm} = \Sigma\ w_i T_{ci} = 225°F \quad (3\text{–}5)$$

$$P_{cm} = \Sigma\ w_i P_{ci} = 603 \text{ psia} \quad (3\text{–}6)$$

Step 4. Locate T_{cm}, P_{cm} on Figure 3–10 (GPSA, Fig. 25–11). Now, sketch in the locus of the pseudobinary critical envelope, as shown. This is done by comparison with the critical locus curves for actual binary mixtures shown in Figure 3–10.

Step 5. Read the convergence pressure from the envelope at the temperature of the calculation. For the bubble-point T of −126°F, go vertically to the critical envelope just sketched. Read to the left to estimate the convergence pressure. For the present example, the envelope lies to the right of the operating temperature. In such a case, the convergence pressure is chosen as the critical pressure of the light component, methane in this case. The convergence pressure is about 670 psia, but the lowest chart convergence pressure is 800 psia, thus verifying the choice of 800 psia. Steps 6, 7, and 8 need not be repeated, since the calculated and assumed convergence pressures are the same. If the assumed and calculated convergence pressures were not the same, these steps would be done, as follows.

Step 6. Look up the K's for $P = 400$ psia, $T = -126°F$, $P_k = 800$ psia, as done in the example.

Step 7. Carry out the bubble-point calculation.

Step 8. Repeat steps 2–7 as necessary for convergence.

Bubble-Point Pressure

If temperature is given instead of pressure, the bubble-point pressure is calculated similarly.

Example 3–3. The mixture of Example 3–1 is at −100°F. What is the bubble-point pressure?

Solution: Trial-and-error is required, as before. A pressure is guessed and the K-values (at the given T and assumed P) read from the charts. The sum of the Kz's is determined and compared to one. The convergence pressure can be determined directly, since the temperature is known, not guessed. The convergence pressure is 800 psia, as in Example 3–1. Only the final trial is shown.

Comp.	z	$K^{-100°F}_{620\ psia}$	Kz	
C1	0.75	1.31	0.983	
C3	0.24	0.062	0.015	
nC6	0.01	~0	0.000	
Sum			0.998	Accept

Dew-Point Calculations

For dew-point calculations, the vapor feed composition is given. We wish to know at what temperature will this gas, or vapor, begin to condense at the given pressure. When the first tiny drop of liquid is condensed, the feed composition is essentially unchanged and the liquid is in

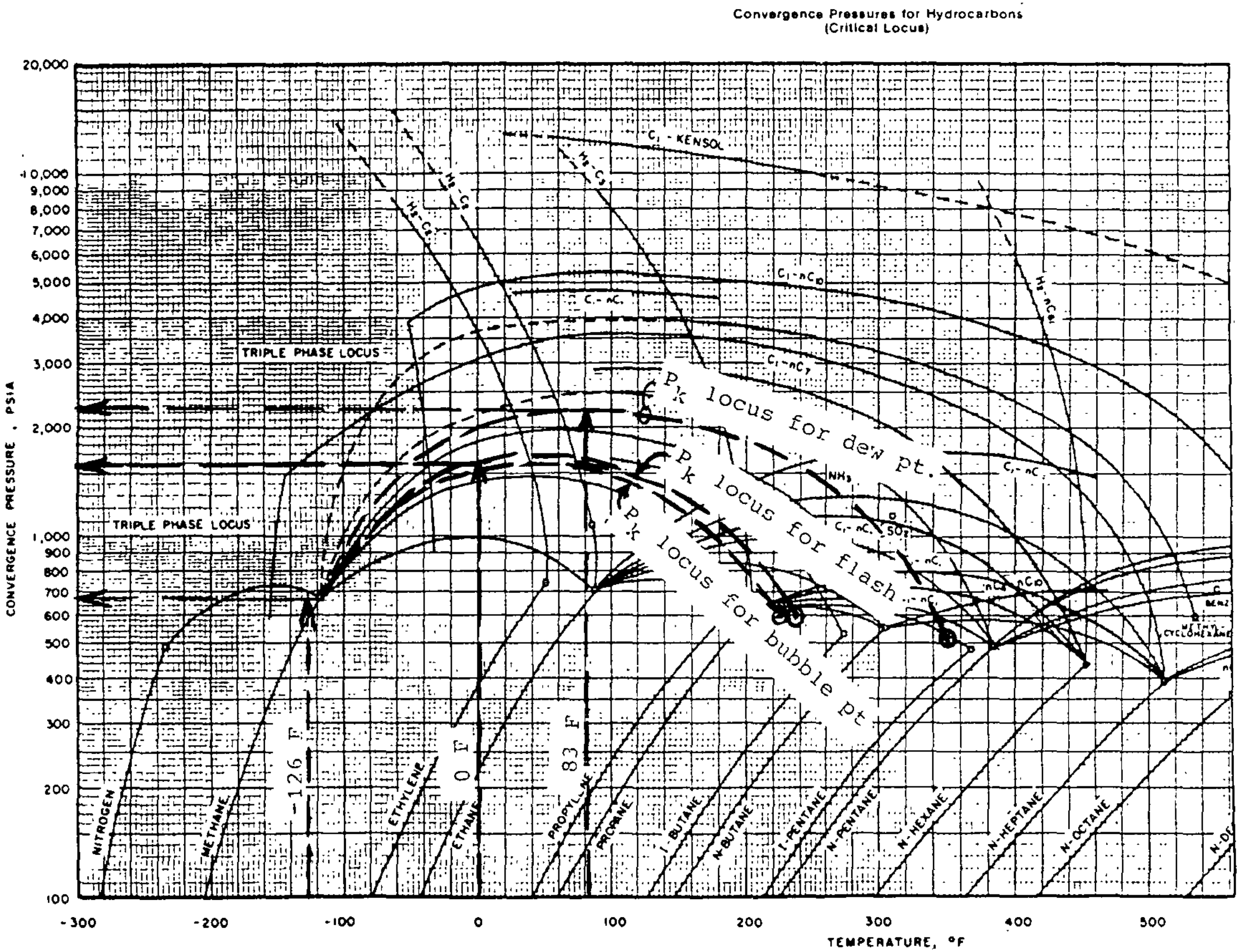


Figure 3–10. Determination of convergence pressure for example calculations (GPSA, 1987, p. 25–11).

equilibrium with the vapor. The liquid mol fraction of each component is:

$$x = z / K \quad (3\text{–}7)$$

As before, the sum of the x's must be one

$$\Sigma x = \Sigma z / K = 1.0 \quad (3\text{–}8)$$

Trial-and-error is required; a temperature is guessed and the K's found from the charts. The summation of x's is computed and compared to one. The temperature is adjusted as necessary to satisfy the dew-point requirement.

Example 3–4. The mixture previously given in Example 3–1 is at 400 psia. What is its dew-point temperature? Assume a convergence pressure of 2000 psia.

Solution: Only the final trial at 83°F is shown below.

Comp.	z	$K^{83°F}_{400\ psia}$	x = z/K	Normalized x
C1	0.75	6.6	0.114	0.113
C3	0.24	0.49	0.490	0.488
nC6	0.01	0.025	0.400	0.399
Sum			1.004	1.000

Now check the assumed convergence pressure. The light component is methane. The weight-average critical temperature and pressure of the remaining liquid-phase C3 and nC6 are 358°F and 506 psia, respectively. Figure 3–10 indicates a convergence pressure of about 2200 psia, which, for the present conditions, represents a close-enough check of the assumed value.

A dew-point pressure can be calculated similarly, if the temperature is specified instead of the pressure.

Example 3–5. The mixture given in Example 3–4 is at 60°F. What is the lower dew-point pressure? The convergence pressure is 2000 psia, as in Example 3–4.

Solution: Only the last trial is shown.

Comp.	z	$K^{60°F}_{205\ psia}$	z/K	
C1	0 75	11.7	0.064	
C3	0 24	0 60	0.400	
nC6	0.01	0.0188	0.532	
Sum			0 996	Accept

Equilibrium Flash Vaporization (EFV) Calculations

Flash calculations combine the total stream material balance, the component material balance, and the equilibrium relation.

Total stream balance $F = F_L + F_V \quad (3\text{–}9)$

Component balance $Fz = F_L x + F_V y \quad (3\text{–}10)$

Equilibrium relation $y = Kx \quad (3\text{–}11)$

Eliminate y between the last two equations and solve for x

$$x = \frac{Fz}{F_L + F_V K} \quad (3\text{–}12)$$

Let F be 1 mole. Then

$$x = \frac{z}{F_L + F_V K} \quad (3\text{–}13)$$

where

$$F_V = 1.0 - F_L \quad (3\text{–}14)$$

Finally,

$$\Sigma x = 1.0 \quad (3\text{–}15)$$

The usual calculation is the so-called isothermal flash, which does not mean the feed is flashed isothermally from its initial condition, but that the temperature and pressure of the flash are specified. In this case, one can look up the K's. The z's are known. The unknown is F_L. We guess F_L, compute F_V by the next-to-last equation above, then calculate the x's for each component. The sum of the x's should be one within a specified tolerance; if it is not, F_L is adjusted and the calculation repeated.

In flash calculations, be sure the feed is indeed flashed at the specified P and T. Check to be sure that the mixture is above its bubble-point and below its dew-point temperature. Use the following relations.

$\Sigma Kz > 1.0$ guarantees vapor is present (3–16)

$\Sigma z/K > 1.0$ guarantees liquid is present (3–17)

If both sums are greater than one, proceed with the flash; otherwise only a single phase is present.

Example 3–6. The mixture of Example 3–5 is at 400 psia, 0°F. Find the percent vaporized and the compositions of the vapor and liquid phases. Assume a convergence pressure of 1500 psia and check as usual.

Solution: Look up the K-values at 0°F and 400 psia and obtain the check sums.

Comp.	z	$K^{0°F}_{400\ psia}$	z K	z/K
C1	0.75	4.4	3.300	0.170
C3	0.24	0.173	0.042	1.387
nC6	0.01	0.0048	0.000	2.083
Sum			3.342	3.640

Both Σ Kz and Σ z/K are greater than one; therefore, the feed is a flashed vapor-liquid mixture. Flash calculations are performed.

Comp	z	$K^{0°F}_{400\ psia}$	$F_L = 0.15$, $F_V = 0.85$, $x = \frac{z}{F_L + KF_V}$	$F_L = 0.18$, $F_V = 0.82$, $x = \frac{z}{F_L + KF_V}$	$F_L = 0.179$, $F_V = 0.821$, $x = \frac{z}{F_L + KF_V}$
C2	0.75	4.4	0.193	0.198	0.1978
C3	0.24	0.173	0.808	0.746	0.7476
nC6	0.01	0.0048	0.065	0.054	0.0547
Sum			1.066	0.998	1.0001

Note the check sum must be very close to 1.0000 in order that the solution be precise. The x's are normalized by dividing each by 1.0001. Then y = Kx is calculated. If the sum of the y's is not quite 1.0, the y's also must be normalized.

	60°F	
Comp.	x	y = Kx
C1	0.1978	0.8704
C3	0.7475	0.1293
nC6	0.0547	0.0003
Sum	1.0000	1.0000

The weight-average critical temperature and pressure of the pseudo heavy-liquid component are 237°F and 593 psia, respectively. Figure 3–10 confirms the convergence pressure of 1500 psia very closely.

K-Value Behavior

The K charts in the GPSA Data Book are plotted as log K versus log pressure, for lines of constant temperature. Ideal gas behavior and ideal liquid solutions may be assumed for paraffin hydrocarbon mixtures at low pressure. Now Raoult's Law gives the K-values.

$$K = VP / P \tag{3–18}$$

where VP = vapor pressure of the component
P = total pressure

Taking logarithms, we obtain

$$\log K = \log VP - \log P \tag{3–19}$$

At constant temperature, the vapor pressure is constant so that the latter equation has the form of a straight line, if plotted as log K versus log P. The intercept is log VP and the slope is −1. GPSA (1987) K-charts show this behavior at low pressures; the isotherms indeed asymptotically approach a straight line with slope −1 at low pressure. At higher pressures, the K-values deviate from this ideal behavior and approach a value of 1.0 at the convergence pressure. This behavior is typical of a true binary mixture, as is shown in Figure 3–11, for example.

Applicability of the Equilibrium Model

The liquid and vapor products from a separator are assumed to be in phase equilibrium. Similar assumptions are made about vapor and liquid streams in other process applications. For example, products from reboilers are assumed to be in equilibrium; vapors and liquids from distillation tower reflux accumulators are also assumed to be in equilibrium.

How good are these equilibrium assumptions? In general, the vapor and liquid from a separator approach equilibrium with each other. Entrainment of liquid droplets may cause small deviations. As long as sufficient contact time is provided and entrainment is not excessive, separator products are essentially in equilibrium (Plane, 1966). This model is used routinely in process calculations and yields reasonable results. The liquid leaving a reboiler is slightly superheated compared to the vapor, but the model is still applicable as long as the flow pattern matches that of the model, i.e., thorough mixing followed by efficient

MANEJO DE GAS.
PARTE II.

TEMARIO.

CAPÍTULO 1

Estática de fluidos

FLUIDOS

Todos los gases y líquidos reciben el nombre de fluidos, con lo cual se indica que no tienen forma definida como los sólidos, sino que fluyen, es decir, escurren bajo la acción de fuerzas.

En los líquidos las moléculas están más cercanas entre sí debido a las fuerzas de atracción, y toman la forma del recipiente que los contiene, conservando su volumen prácticamente constante. La superficie libre de un líquido en reposo es siempre horizontal.

Los gases están formados por moléculas que se mueven en todas direcciones, por lo que ocupan todo el volumen del recipiente que los contiene, aunque sean colocados en equipos de diferentes formas.

Propiedades de los fluidos

Densidad Absoluta

La densidad absoluta de una sustancia expresa la cantidad de masa contenida en la unidad de volumen.

$$\rho = \frac{M}{V}$$

donde:

ρ ≐ densidad $(=)ML^{-3}$
M = masa $(=)M$
V = volumen $(=)L^{-3}$

En el Sistema Internacional (SI) la densidad se mide en kg/m^3, aunque es frecuente obtener los datos de densidad en otras unidades tales como lb/gal, g/cm^3, lb/ft^3, etc. (Apéndice III).

Densidad relativa

Se llama densidad relativa a la relación que existe entre la densidad de un material y la de una sustancia de referencia. En el caso de los líquidos, esta sustancia es el agua; tratándose de los gases, generalmente se adopta el aire. La ρ del agua entre 0 y 100°C puede considerarse cercana a 1000 kg/m^3 (ver Apéndice II).

$$\rho r = \frac{\rho \text{ sustancia}}{\rho \text{ sust. referencia}} \ ; \ \rho r = \text{densidad relativa adimensional}$$

Debido a que la densidad varía con la temperatura, la densidad relativa se da mostrando la temperatura a la cual se hizo la medición y la temperatura a la cual se obtuvo la densidad de la sustancia de referencia:

$$\rho r \ \frac{20°C}{4°C}$$

(Ver apéndices IV y V.)

Peso específico

Es el peso de la unidad de volumen de un material determinado.

$$Pe = \frac{\text{Peso}}{V} \qquad Pe = \text{Peso específico} = ML^{-2}\theta^{-2}$$

$$\text{Peso} = ML\theta^{-2}$$

$$V = \text{Volumen} = L^3$$

$$Pe = \rho g \qquad g = 9.81 \text{ m/seg}^2$$

Las unidades en el SI son N/m^3, o sea $kg \cdot m/seg^2 \cdot m^3$.

Principio de Arquímedes

Cuando un sólido se sumerge en un líquido sufre una aparente pérdida de peso igual al peso del líquido desalojado. Al establecerse un equilibrio entre el peso y la fuerza debida al peso del líquido desalojado, el cuerpo flota; por ello resulta que mientras menos denso sea el líquido en el que flota un cuerpo más se sumergirá, puesto que la menor densidad del líquido tiene que compensarse con un mayor volumen desaloja-

Densidad de una mezcla de líquidos ideales

La densidad de una mezcla de líquidos ideales (aquellos que al mezclarse no reducen su volumen) puede calcularse a partir de:

$$\frac{1}{\rho \text{mezcla}} = \frac{X_1}{\rho_1} + \frac{X_2}{\rho_2} + \ldots + \frac{X_n}{\rho_n}$$

X_n = fracción masa del líquido n.
ρ_n = densidad del líquido puro n.

Densidad en los gases

La manera común de obtener la densidad de un gas es a través de una ecuación de estado que relaciona su presión, temperatura y volumen. Los gases ideales obedecen la ecuación:

$$PV = nRT = \frac{M}{PM} RT$$

$$\rho \text{gas} = \frac{M}{V}$$

$$\rho \text{gas} = \frac{P \cdot PM}{RT}$$

P = presión(=)$ML^{-1} \theta^{-2}$
V = volumen(=)L^3
T = temperatura(=)T
R = constante de los gases (tabla II, apéndice)
n = número de moles
M = masa (=) M
PM = peso molecular(=)$M mol^{-1}$

Los gases siguen esta ley a temperaturas reducidas mayores de 2 y a presiones reducidas menores de 1, es decir, a presiones menores de 10 atm y temperaturas mayores a 0°C.

$$Pr = \frac{P}{Pc} \qquad Tr = \frac{T}{Tc}$$

Pr = presión reducida (=) adimensional
Pc = presión crítica (=) $ML^{-1} \theta^{-2}$ (=) FL^{-2}
Tr = temperatura reducida (=) adimensional
Tc = temperatura crítica (=) T

2 CÁLCULOS

2.1 Densidad

$$°API = \frac{141.5}{\rho r} - 131.5$$

2.2 Masa

$$\rho r = \rho_{H_2O}\, \rho \text{ sustancia}$$

$$\rho \text{ sustancia} = \frac{\text{Masa}}{\text{Volumen}}$$

3 CÁLCULOS

3.1 Densidad

$$\rho r = \frac{141.5}{131.5 + 26} = 0.8984$$

$$\rho sus = 0.8984\ (1000\ \frac{kg}{m^3}) = 898.4\ kg/m^3$$

3.2 Masa

$$M = 898.4\ \frac{kg}{m^3} \times 8\ m^3 = 7187.2\ kg = 7.18\ ton$$

4 RESULTADO

El trailer transporta 7.18 ton.

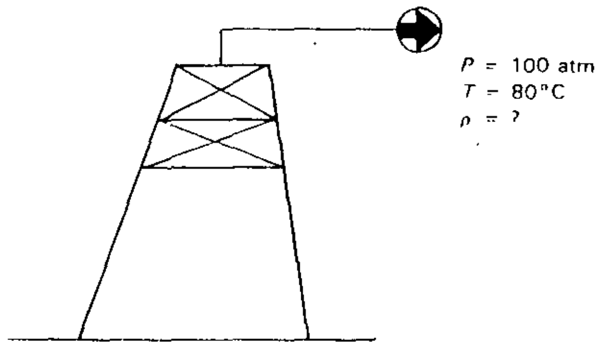
Problema 1.6

El gas natural saliente de un pozo petrolero está a 100 atm de presión y 80°C y tiene la siguiente composición:

metano	40%	en mol
etano	2%	en mol
nitrógeno	58%	en mol

Calcule el volumen ocupado por 1000 kg de ese gas. ¿Cuál será su densidad absoluta?

1. TRADUCCIÓN



2 PLANTEAMIENTO

2.1 Discusión

Este problema se puede tratar como una mezcla real, usando la ley de los estados correspondientes.

2.2 Condiciones seudocríticas

$$P'c = Pc^{N_2}\,\tilde{y}^{N_2} + Pc^{CH_4}\,\tilde{y}^{CH_4} + Pc^{C_2H_6}\,\tilde{y}^{C_2H_6}$$

$$T'c = Tc^{N_2}\,\tilde{y}^{N_2} + Tc^{CH_4}\,\tilde{y}^{CH_4} + Pc^{C_2H_6}\,\tilde{y}^{C_2H_6}$$

$$P'r = \frac{P}{Pc'} \qquad Tr' = \frac{T}{T'c}$$

2.3 Volumen

$$\mathbf{G} = Z\tilde{G}RT/P$$

2.4 Densidad

$$\rho = m/v$$

3 CÁLCULOS

3.1 Datos de los gases (apéndice VIII)

	PM	*Tc* °C	*Pc* atm	$\bar{y}$
Metano	16	-82.5	45.8	0.4
Etano	30	32.1	48.8	0.02
Nitrógeno	28	-147.1	33.5	0.58

3.2 Condiciones seudocríticas

$PM = 0.4(16) + 0.02(30) + 0.58(28) = 23.24$ g/gmol
$P'c = 0.4(45.8) + 0.02(48.8) + 0.58(33.5) = 38.726$ atm.
$T'c = 0.4(190.5) + 0.02(305.1) + 0.58(125.9) = 155.28$ °K

3.3 Valor del factor de compresibilidad

$$P'r = \frac{100 \text{ atm}}{38.726 \text{ atm}} = 2.582$$

$$T'r = \frac{80 + 273}{155.28} = 2.27$$

Del diagrama $Z = 0.96$

3.4 Volumen

$$\text{Moles de gas} = \frac{1000 \text{ kg}}{23.24 \text{ kg/kgmol}} = 43.02 \text{ kgmol}$$

$$G = 0.96\,(43.02)\,(0.082)\,(273 + 80) = 11.954 \text{ m}^3$$

3.5 Densidad

$$\rho = \frac{1000 \text{ kg}}{11.954 \text{ m}^3} = 83.65 \text{ kg/m}^3$$

4 RESULTADOS

El volumen es de 11.954 m^3 y la densidad de 83.65 kg/m^3.

Apéndice VIII. Valores críticos.

		T_c °C	P_c atm
Ácido acético	$C_2H_4O_2$	321.6	57.2
Ácido bromhídrico	HBr	90	84
Ácido clorhídrico	HCl	51.4	81.6
Ácido sulfhídrico	H_2S	100.4	88.4
Acetona	C_3H_6O	235	47
Acetonitrilo	C_2H_3N	274.7	47.7
Aire	—	—140.7	37.2
Agua	H_2O	374.15	218.4
Alcohol metílico	CH_3OH	240	78.7
Amoniaco	NH_3	132.4	111.5
Benceno	C_6H_6	288.5	47.7
Bromo	Br_2	311	102
n-butano	C_4H_{10}	153	36
i-butano	C_4H_{10}	134	37
Ciclohexano	C_6H_{12}	281	40.4
Cloro	Cl_2	144	76.1
Cloruro de metilo	CH_3Cl	143.1	65.8
Dióxido de carbono	CO_2	31.1	73
Etano	C_2H_6	32.1	48.8
Etileno	C_2H_4	9.7	50.5
Flúor	F	—155	25
Helio	He	—267.9	2.26
Heptano	C_7H_{16}	266.8	26.8
Hexano	C_6H_{14}	234.8	29.5
Hidrógeno	H_2	239.9	12.8
Metano	CH_4	— 82.5	45.8
Monóxido de carbono	CO	—139	35
Nitrógeno	N_2	—174.1	33.5
Mercurio	Hg	1550	200
Octano	C_8H_{18}	296	24.6
Oxígeno	O_2	—118.8	49.7
n-pentano	C_5H_{12}	197.2	33
i-pentano	C_5H_{12}	187.8	32.8
Propano	C_3H_8	96.8	42
Propileno	C_3H_6	92.3	45
Tetracloruro de carbono	CCl_4	283.1	45
Tolueno	$C_6H_5CH_3$	320.6	41.6
Vapor de agua	H_2O	374	217.7

Apéndice VII. Valores de la constante de los gases (*R*).

1.9872 cal/gmol°K

8.3144 joules (abs)/gmol°K

82.057 cm^3 at/mol°K

0.082 lt atm/gmol°K

0.082 m^3 atm/kgmol°K

62.361 lt mmHg/gmol°K

1.314 ft^3 atm/lbmol°R

1.9872 BTU/lbmol°R

0.7302 ft^3 atm/lbmol°R

21.85 ft^3 inHg/lbmol°R

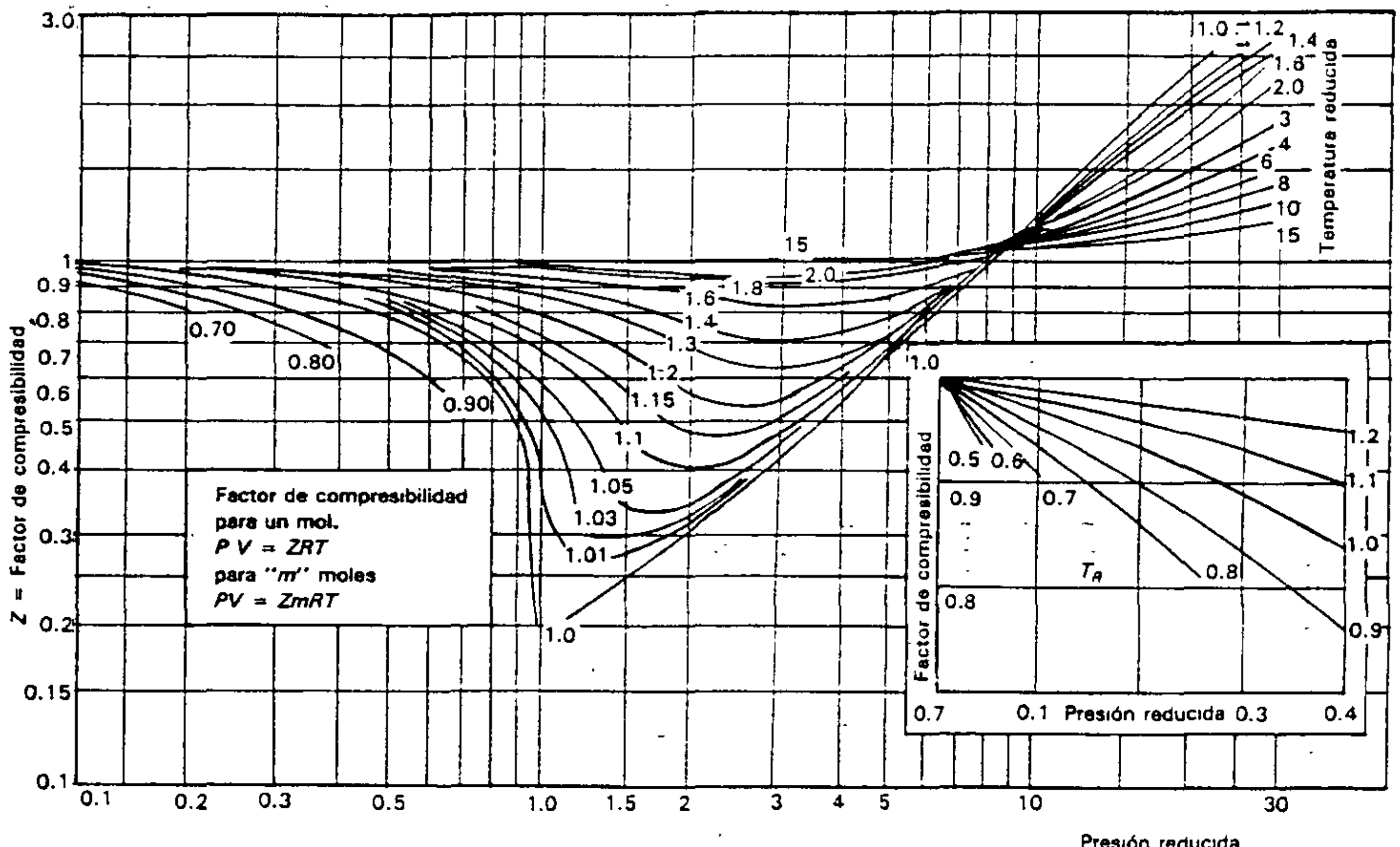
555.0 ft^3 mmHg/lbmol°R

1545.0 ft^3 (lb/ft^2)/lbmol°R

10.73 ft^3 (lb/in^2)/lbmol°R

847.3 m^3 ($\overline{kg}$/m^2)/kg mol°R

Apéndice IX. Factores de compresibilidad.



Fuente: O. A. Hougen y K. M. Watson. *Chemical Process Principles Charts.* John Wiley. Nueva York, 1946

CAPÍTULO 2

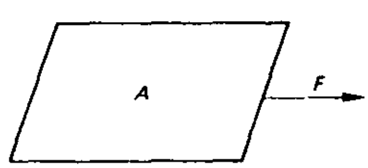
Dinámica de fluidos

Un fluido es una sustancia que sufre deformación continua cuando se sujeta a un esfuerzo cortante.

El esfuerzo cortante, también llamado fuerza de cizallamiento, es aquella fuerza que se aplica tangencialmente a un área y que provoca deformaciones en los cuerpos. Se distingue de la presión en que esta última es la fuerza aplicada perpendicularmente a un área, provocando compresión.

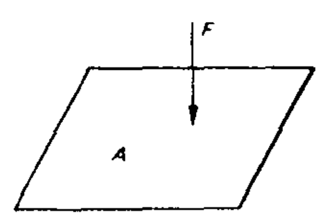
ESFUERZO CORTANTE

$$\tau = \frac{F}{A}$$



PRESIÓN

$$P = \frac{F}{A}$$



τ = esfuerzo cortante (=) $ML^{-1}\theta^{-2}$ (=) FL^{-2}
P = presión (=) $ML^{-1}\theta^{-2}$ (=) FL^{-2}
F = fuerza (=) $ML\theta^{-2}$ (=) F
A = área (=) L^2

Cuando se aplica un esfuerzo cortante sobre un fluido éste se deforma y fluye. La resistencia a la deformación ofrecida por los fluidos recibe el nombre de viscosidad, la cual se define mediante la ley de Newton:

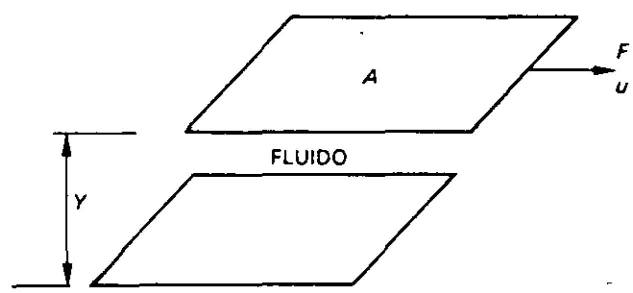
$$\tau = -\mu \frac{du}{dy}$$

μ = viscosidad del fluido (=) $FL^{-2}\theta$ (=) $ML^{-1}\theta^{-1}$

$\frac{du}{dy}$ = gradiente de velocidad (=) θ^{-1}

u = velocidad (=) $L\theta^{-1}$

y = distancia



La unidad de viscosidad en el Sistema Internacional es el kg/(m.seg), pero es más frecuente su medición en centipoise. Un poise equivale a 1 g/cm.s, y 1 centipoise = 1cp = 0.01 poise.

La viscosidad indica la facilidad con que un fluido fluye cuando actúan fuerzas externas sobre él. También se le considera como una conductividad de momento, análoga, a la conductividad de calor o al coeficiente de difusión. En flujo de fluidos recibe el nombre de momento (en latín *momentum*) el producto de la masa por la velocidad.

$$\text{Momentum} = M.u \ (=) \ ML\theta^{-1}$$

Considerando lo anterior, el esfuerzo cortante puede tomarse como el momento que pasa por unidad de área y por unidad de tiempo:

$$\tau \ (=) \ FL^{-2} \ (=) \ ML^{-1}\theta^{-2} \ (=) \ \frac{ML\theta^{-1}}{L^2\theta} = \frac{M}{L\theta^{-2}}$$

Viscosidad cinemática

Con frecuencia se suele usar la llamada viscosidad cinemática, que se define por:

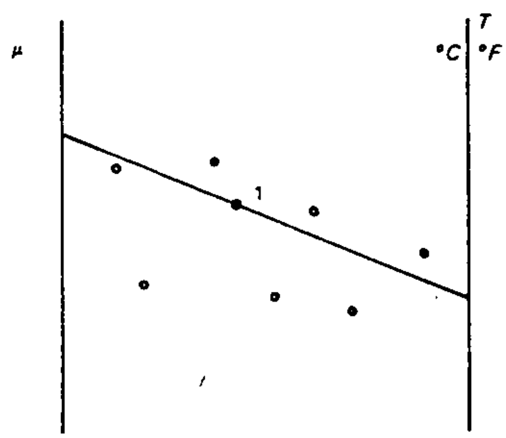
$$\nu = \frac{\mu}{\rho}$$

ν = viscosidad cinemática (=) $L^2\theta^{-1}$
ρ = densidad (=) ML^{-3}

La unidad en el sistema cgs para la viscosidad cinemática es el stoke, que es igual a 1 cm^2/s.

Viscosidad en los gases

Los valores para la viscosidad en los gases suelen obtenerse mediante nomogramas del siguiente tipo, los cuales se pueden encontrar en el apéndice XIX, o mediante tablas o gráficas de viscosidad contra temperatura.



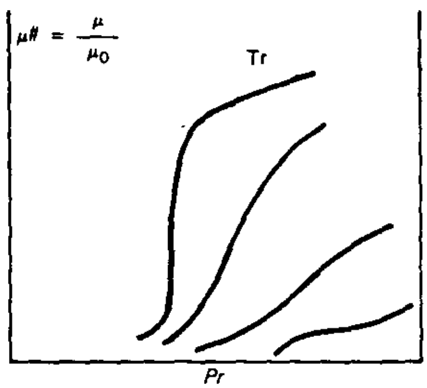
En caso de que faltaran datos experimentales, la viscosidad de los gases se puede obtener mediante la ecuación de Enskog:

$$\mu = 2.6693 \cdot 10^{-21} \frac{\sqrt{PM \cdot T}}{\sigma^2 \Omega}$$

μ = g/cms
σ = diámetro de colisión (=) L = cm
Ω = integral de colisión
T = temperatura absoluta (=) T = °K
$\frac{\epsilon}{K}$ = parámetro del potencial (=) T = °K
PM = peso molecular

Los valores del diámetro de colisión, integral de colisión y parámetro del potencial pueden encontrarse en los apéndices XI y XII.

Si se está trabajando con presiones altas (mayores de 10 atm), los valores de viscosidad deben corregirse mediante gráficas del siguiente tipo (apéndice XV):



$\mu_0 = \mu$ a 1 atm.
$\mu\# = \mu$ corregida

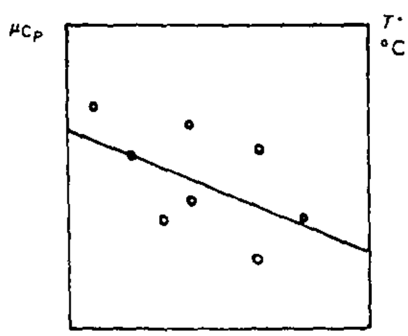
Al tener una mezcla de gases, la viscosidad se calcula con la siguiente expresión:

$$\frac{\text{PM mezcla}}{\mu\text{mezcla}} = \frac{\bar{y}_1 PM_1}{\mu_1} + \frac{\bar{y}_2 PM_2}{\mu_2} + \frac{\bar{y}_3 PM_3}{\mu_3} + \;....\; + \frac{\bar{y}_n PM_n}{\mu_n}$$

PM_n = peso molecular del gas n
$\bar{y}_n$ = fracción mol del gas n
μ_n = viscosidad del gas puro n

Viscosidad en los líquidos. Obtención

Los valores de la viscosidad en los líquidos se pueden obtener mediante nomogramas como los del apéndice XX.



Si faltan datos experimentales, la viscosidad de muchos líquidos orgánicos se pueden calcular por la fórmula de Souders:

$$\log\left((\log \mu)\ 10\right) = m\rho L - 2.9$$

$m = \dfrac{I}{PM}$ I = constante que depende de la estructura (apéndice XIII).

I = $\Sigma An + \Sigma P$

μ = viscosidad en cp

ρL = densidad del líquido a 20°C en g/cm^3

Para mezclas de líquidos ideales la viscosidad se obtiene a partir de:

$$\log\mu mez = \bar{x}_1\log\mu_1 + \bar{x}_2\log\mu_2 + ... + \bar{x}_n\log\mu_n$$

μ_n = viscosidad del líquido puro n

$\bar{x}_n$ = fracción mol de los líquidos

La viscosidad en suspensiones diluidas se puede obtener mediante la siguiente ecuación para concentraciones de fase sólida menor del 10% en volumen:

$$\mu Sus = \mu_L(1 + 2.5.\varphi)$$

μ Sus = viscosidad de la suspensión

μ_L = viscosidad del líquido puro

φ = volumen del sólido en suspensión = volumen fase sólida/volumen total.

Para concentraciones de fase sólida hasta 30% en volumen:

$$\mu_S = \mu_L\left[\frac{0.59}{(0.77-\varphi)^2}\right]$$

La viscosidad de los líquidos varía con la temperatura. La siguiente fórmula representa la variación de la viscosidad con respecto a la temperatura:

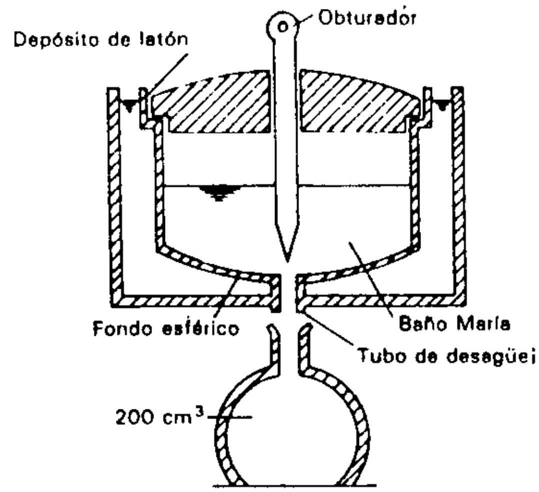
$$\log\mu = a + \frac{b}{T} \text{ Fórmula de Andrade (apéndice XVIII)}$$

a y b = constantes de los líquidos.

La viscosidad se mide con la ayuda de viscosímetros, de los cuales existen varios tipos, como son los de Ostwald, Engler, Saybolt, etc.

En estos aparatos la viscosidad se mide en segundos, los que se deben cambiar a viscosidad cinemática mediante fórmulas adecuadas.

Viscosímetro de Engler



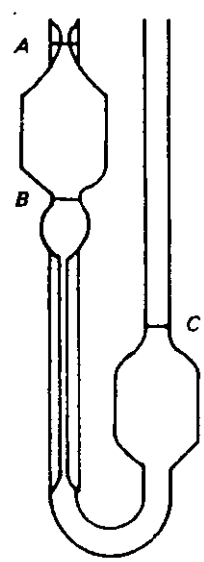
$\nu = 0.00147t - (3.74/t)$

En donde t son los segundos que tarda en llenarse el depósito del viscosímetro *Engler*.

Viscosímetro de Ostwald

$$\frac{\mu 1}{\mu 2} = \frac{\rho_1 \theta_1}{\rho_2 \theta_2}$$

El subíndice 1 indica al líquido que se quiere conocer la viscosidad, y el subíndice 2 indica al líquido de referencia del cual se conoce la viscosidad.



El esfuerzo cortante o flujo de momento está relacionado con la viscosidad mediante:

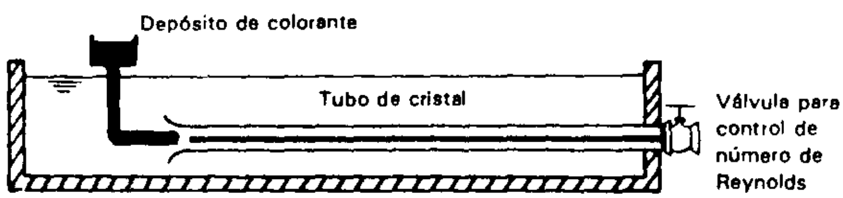
$$\tau \Omega = -\mu \Omega \text{ y } \Omega = 2 \cdot \pi \text{RPM}$$

Perfiles de velocidad

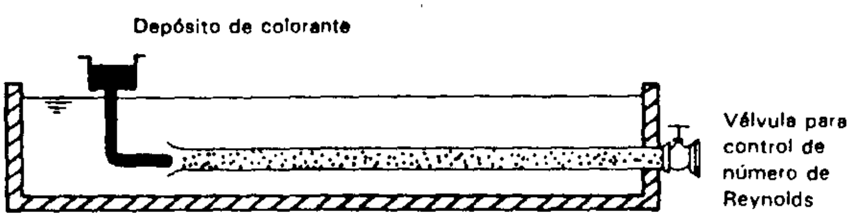
El movimiento de los fluidos a través de tuberías o de equipos de proceso tales como torres de destilación, cambiadores de calor, torres de absorción, etc., se encuentran constantemente en la práctica de la ingeniería.

Dependiendo de las condiciones, un fluido se puede mover en dos tipos de patrones de flujo, llamados laminar o turbulento. La distinción entre estos patrones de flujo fue indicada por primera vez por Osborne Reynolds.

A velocidades bajas el fluido tiende a fluir sin mezclado lateral, resbalando las capas adyacentes unas sobre otras como los naipes de una baraja. En este caso no hay corrientes cruzadas perpendicularmente a la dirección de flujo ni tampoco remolinos. A este régimen o tipo de flujo se le llama flujo laminar.



A velocidades más altas se forman remolinos, lo que provoca un mezclado lateral; éste recibe el nombre de flujo turbulento. La velocidad a la cual ocurre el cambio de laminar a turbulento recibe el nombre de velocidad crítica.



El trabajo de Osborne Reynolds mostró que el tipo de flujo en una tubería depende del diámetro de la misma, así como de la velocidad, densidad y viscosidad del fluido. El valor numérico de la combinación de estas cuatro variables se conoce como número de Reynolds, y se considera que es la relación de las fuerzas dinámicas del flujo al esfuerzo cortante debido a la viscosidad. El número de Reynolds es:

$$NoRe = \frac{D.u.\rho}{\mu} = \frac{D.u}{\nu}$$

Para los propósitos ingenieriles se considera que el flujo en tuberías es laminar si el Reynolds es menor de 2100 y turbulento si es mayor de 10 000. Entre estos dos valores se encuentra la zona de transición en donde existe el proceso de cambio de flujo laminar a turbulento.

En un fluido en movimiento se consideran líneas de corriente a las líneas orientadas según la velocidad del líquido y que gozan de la propiedad de no ser atravesadas por partículas del fluido.

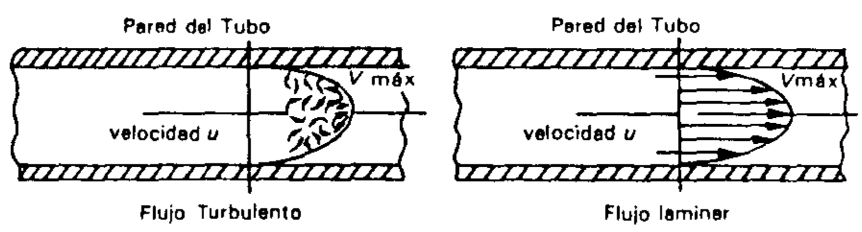
Cuando un líquido fluye se efectúa un movimiento relativo entre sus partículas, resultando una fricción o rozamiento entre las mismas. Existen dos tipos de fricción:

- *Fricción interna.* También llamada viscosidad. Es la resistencia a la deformación, que presentan todos los fluidos.
- *Fricción externa.* Es la resistencia al deslizamiento de los fluidos a lo largo de superficies sólidas.

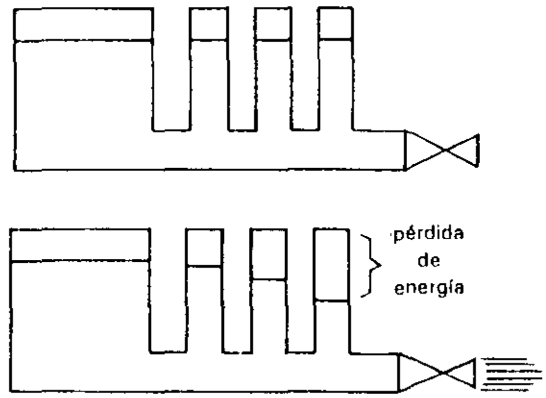
Cuando un líquido escurre a lo largo de una superficie sólida, existe siempre una capa adherida a esta superficie que no se pone en movimiento.

Se debe entender que la fricción externa es una consecuencia de la acción de freno ejercida por esa capa estacionaria sobre las demás partículas en movimiento.

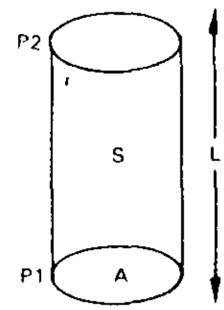
Un ejemplo importante es lo que ocurre con el flujo de un líquido en un tubo: junto a las paredes existe una película del líquido que no participa del movimiento, siendo la velocidad igual a cero. En la parte central se encuentra la velocidad máxima.



A consecuencia de la fricción interna y externa el flujo de un líquido en una tubería se verifica solamente con la pérdida de energía.



De acuerdo con la ecuación de Newton, para un tubo por el que fluye un líquido .



Igualando las fuerzas $\Delta PA = \tau S$

$$\tau = -\mu \frac{du}{dy}$$

$$\Delta P \pi r^2 = \tau 2 \pi r L$$

$$\frac{(P1 - P2) \cdot r}{2 \cdot L} = -\mu \frac{d\hat{u}}{dy}$$

$$d\hat{u} = -\frac{(P1 - P2) \cdot r}{2 \cdot L} \cdot \frac{dy}{\mu} = \frac{(P1 - P2) \cdot r}{2 \cdot L} \cdot \frac{dr}{\mu}$$

Integrando

$$\int_0^u d\hat{u} = -\frac{(P1 - P2)}{2 \cdot L\mu} \int_r^R r\,dr$$

$$\hat{u} = \frac{(P1 - P2)}{4 \cdot L \cdot \mu} \cdot (R^2 - r^2)$$

$\hat{u}$ = velocidad puntual en el punto r
L = Longitud de la tubería

Para obtener la velocidad promedio en un tubo teniendo régimen laminar se aplica la ecuación de Pouseuille:

$$u = \frac{Ca}{\pi \cdot R^2} = \frac{(P1 - P2) \cdot R^2}{8 \cdot L \cdot \mu}$$

Ca = caudal (=) $L^3\theta^{-1}$
u = velocidad promedio

$$\frac{\hat{u}}{u} = 2\left[1 - \frac{r^2}{R^2}\right]$$

Para flujo laminar en tuberías circulares el perfil de velocidades es parabólico, con una velocidad máxima en el centro (apéndice XXIII).

Para tubos lisos en flujo turbulento se presentan tres zonas de flujo:

- Una zona pegada a la pared, en donde el flujo es laminar y está dado por:

$$u^+ = y^+ \text{ para } y^+ < 5$$

- Una zona de transición.

$$u^+ = -3.05 + 5.\, ln y^+ \quad \text{para } 5 < y^+ < 30$$

- Una zona turbulenta.

$$u^+ = 5.5 + 2.5\, ln y^+ \quad \text{para } y^+ > 30$$

- Para tubos rugosos.

$$u^+ = 8.5 + 2.5\, ln \frac{y^+}{e} \quad \text{para } y^+ > 30$$

en donde

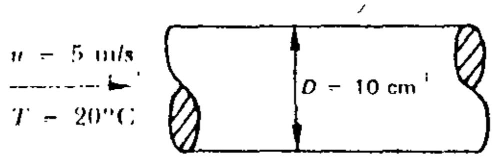
$\hat{u}$ = velocidad local a una distancia desde la pared del tubo
u^+ = (u / u^*)
u^+ = $(\tau w.gc/\rho)$
τw = esfuerzo cortante en la pared
gc = factor de conversión = 9.81 kg m/kg seg^2
ρ = densidad del fluido (=) ML^{-3}
y^+ = $(y.u^* \cdot \rho/\mu)$
y = distancia desde la pared de la tubería
e = altura de la rugosidad (=) L

A continuación se ilustran diferentes perfiles de velocidades para flujo turbulento.

Problema 2.9

Por una tubería de 10 cm de diámetro interno fluye agua a una velocidad de 5 m/s a 20°C. Determine si el flujo es laminar o turbulento.

1 TRADUCCIÓN



2 PLANTEAMIENTO

2.1 Discusión

Para saber si el flujo es laminar o turbulento se debe obtener el número de Reynolds:

$$N^{\circ}Re = \frac{Du\rho}{\mu}$$

3 CÁLCULOS

3.1 Número de Reynolds

μ_{H_2O} a 20°C = 1.005 cps (apéndice XIV); ρ_{H_2O} a 20°C = 998.2 kg/m³ (apéndice II)

$$Re = \frac{0.1 \text{ m} \times 5 \text{ m/s} \times 998.2 \text{ kg/m}^3}{1.005 \times 10^{-3} \text{ kg/ms}}$$

$$Re = 496\,616.92$$

4 RESULTADO

El flujo es turbulento, pues el Re es 496616.92.

4. RESULTADOS

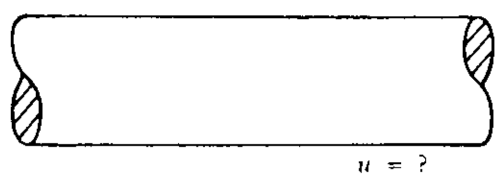
La caída de presión es de 14 605 $\vec{kg}/m^2$ por 100 m de tubo. La velocidad en el centro del tubo es de 0.0848 m/s. El esfuerzo cortante es de 9.128 $\times 10^{-4}$ $\vec{kg}/m^2$.

Problema 2.12

Por una tubería con 0.68 m de diámetro interno fluye un aceite con μ = 15 cps y ρ = 800 kg/m^3 y un caudal de 40 m^3/h.
Determine el perfil de velocidades y la caída de presión por metro de tubería.

1 TRADUCCIÓN

$Ca = 40\ m^3/h$
$\rho = 800\ kg/m^3$
$\mu = 15$ cps



2 PLANTEAMIENTO

2.1 Discusión

Si el fluido se mueve en régimen laminar se puede aplicar la ecuación de Poiseuille.

2.2. Perfil de velocidades

Para régimen laminar:

$$u = 2\bar{u}\left(1 - \frac{r^2}{R^2}\right)$$

2.3 Caída de presión

Para régimen laminar:

$$\Delta P = \frac{32\mu\bar{u}L}{D^2 gc}$$

3 CÁLCULOS

3.1 Velocidad

$$\hat{u} = \frac{Ca}{A} = \frac{40\ m^3\ h}{h\ (3600\ s)\ \frac{\Pi}{4}(0.68)^2} = 0.0306\ m/s$$

3.2 Número de Reynolds

$$Re = \frac{D\hat{u}\rho}{\mu} = \frac{0.68\ m\ (0.0306)\ m/s\ (800)\ kg/m^3}{15 \times 10^{-3}\ kg/ms}$$

$$Re = 1110$$

3.3 Perfil de velocidades

$$u = 2\ (0.0306)\left(1 - \frac{r^2}{(0.34)^2}\right) = 0.0612\left(1 - \frac{r^2}{0.116}\right)$$

Mediante la ecuación de Poiseuille se obtienen los datos de *r* y *u*.

r m	*u m/s*
0	0 0612
± 0 085	0.0574
± 0.17	0 0459
± 0 255	0.0268
± 0 340	0

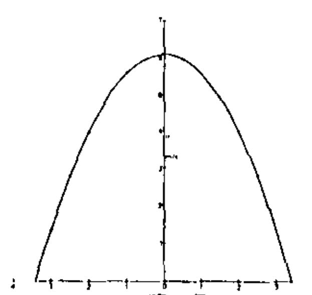
r	*u*
0	0 0612
± 0 05	0.059881
± 0.10	0 05592
± 0.15	0 04932
± 0 20	0.040096
± 0 25	0 02822
± 0.30	0.013717
± 0.34	0

3.4 Caída de presión

$$\Delta P = \frac{32 \times 15 \times 10^{-3}\ kg/ms \times 1m \times 0.0306\ m/s}{(0.68)^2 m^2 \times 9.81\ \frac{Ns^2}{\vec{kg}m}} = 0.0032379 \frac{\vec{kg}}{m^2}$$

4 RESULTADOS

El perfil de velocidades es:



CAPÍTULO 3

Balance de masa y energía en flujo de fluidos

CAUDAL

Se denomina caudal al volumen del líquido o gas que atraviesa una sección en la unidad de tiempo. En México suele recibir también el nombre de gasto volumétrico.

$$Ca = uA$$

Ca = caudal (=) $L^3\ \theta^{-1}$
u = Velocidad promedio del fluido (=) $L\ \theta^{-1}$
A = Sección transversal de flujo (=) L^2

Gasto másico

Con mucha frecuencia se utiliza el término de gasto o flujo másico o gasto o flujo molar, el cual indica la cantidad de masa o moles que pasan por un punto dado.

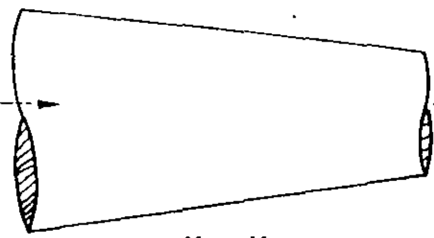
$$M = uA\rho = Ca.\rho$$

$$\tilde{M} = \frac{M}{PM}$$

M = Gasto másico del fluido (=) $M\ \theta^{-1}$
ρ = Densidad del fluido (=) ML^{-3}
$\tilde{M}$ = Gasto molar del fluido (=) moles θ^{-1}
PM = Peso molecular del fluido

ECUACIÓN DE CONTINUIDAD

Aplicando el balance de materia a un ducto por el cual fluye un fluido a régimen permanente se tiene:



$$u_1 A_1 \rho_1 = u_2 A_2 \rho_2$$
$$Ca_1 \rho_1 = Ca_2 \rho_2$$

Para el caso de que el fluido sea gas:

$$\rho = \frac{P.PM}{R.T}$$

Sustituyendo

$$u_1 A_1 \frac{P_1 PM_1}{R.T_1} = \frac{u_2 A_2 \, P_2 PM_2}{R.T_2}$$

Si no hay reacción química: $PM_1 = PM_2$
por lo que:

$$\frac{u_1 A_1 P_1}{T_1} = \frac{u_2 A_2 P_2}{T_2}$$

$$u_2 = u_1 \frac{P_1}{P_2} \cdot \frac{T_2}{T_1} \cdot \frac{A_1}{T_2} = \frac{u_1 \, P_1 \, T_2}{u_2 \, P_2 \, T_1} \left(\frac{D_1}{D_2}\right)^2$$

Si es fluido incompresible:

$$\rho_1 = \rho_2$$

$$u_1 A_1 = u_2 A_2$$

$$u_2 = u_1 \frac{A_1}{A_2} = u_1 \left(\frac{D_1}{D_2}\right)^2$$

Balance de materia

$$M1 = M2$$

Balance de energía

$$Ep_1 + Ec_1 + EPe_1 + U_1 + Q = Ep_2 + Ec_2 + EPe_2 + U_2 + \mathscr{T}$$

$$(Ep_2 - Ep_1) + (Ec_2 - Ec_1) + (EPe_2 - EPe_1) + (U_2 - U_1) = Q - \mathscr{T}$$

Sabiendo que $H = U + PV$ y $PV = EPe$

$$(Ep_2 - Ep_1) + (Ec_2 - Ec_1) + (H_2 - H_1) = Q - \mathscr{T}$$

$$\Delta Ep + \Delta Ec + \Delta H = Q - \mathscr{T}$$

en donde

- variación de energía potencial

$$\Delta Ep = (Z_2 - Z_1) \cdot g\, M$$

- variación de energía cinética

$$\Delta Ec = \frac{1}{2}(u_2^2 - u_1^2)\, M$$

- cambio de entalpia

$$\Delta H = (H_2 - H_1)\, M$$

Un tipo de balance de energía más útil para flujo de fluidos es el que considera la energía mecánica. Los términos de calor y energía interna no permiten una conversión simple en trabajo, tal como lo indica la segunda ley de la termodinámica, dependiendo la eficiencia de la conversión de la temperatura. Al hacer un balance de energía mecánica la parte de la energía mecánica que se convierte en calor se considera como pérdida de fricción. De acuerdo con la primera ley de la termodinámica:

$$\Delta U = Q - \tau \quad \ldots \quad (1)$$

$$\mathrm{T} = \int_{V_1}^{V_2} P \cdot dV_a - \Sigma F$$

$\mathcal{T}$ = trabajo que realiza el fluido (=) FL
Q = calor (=) FL
V = volumen (=) L^3
ΣF = pérdidas por fricción (=) FL.

Sustituyendo en la ecuación 1:

$$\Delta U = Q - \int_{V_1}^{V_2} P \cdot dV_0 + \Sigma F \ldots (2)$$

pero $H = U + PV_0 \ldots (3)$

Sustituyendo 2 en 3:

$$\Delta H = Q - \int_{V_1}^{V_2} P \cdot dV_0 + \Sigma F + \int_{V_1}^{V_2} PdV_0 + \int_{P_1}^{P_2} V_0 \cdot dP$$

$$\Delta H = Q + \int_{P_1}^{P_2} V_0 \cdot dP + \Sigma F$$

Sustituyendo en la ecuación de balance de energía:

$$M(Z_2 - Z_1)g + \frac{1}{2} M(u_2^2 - u_1^2) + Q + M\int_{P_1}^{P_2} V_0 dP + \Sigma F = Q - \mathcal{T}$$

$$(Z_2 - Z_1)g + \frac{1}{2}(u_2^2 - u_1^2) + \int_{P_1}^{P_2} V \cdot dP = \frac{-\Sigma F - \mathcal{T}}{M}$$

La ecuación anterior se conoce con el nombre de ecuación de Bernoulli.

El valor de la integral depende de la ecuación de estado del fluido y de la trayectoria del proceso. Si el fluido es incompresible el volumen será constante, por lo que la ecuación quedaría:

$$(Z_2 - Z_1)g + \frac{1}{2}(u_2^2 - u_1^2) + (P_2 - P_1) \cdot \frac{1}{\rho} = \frac{-\mathcal{T} - \Sigma F}{M}$$

La ecuación anterior se aplica al flujo isotérmico de un fluido incompresible que fluye por un ducto, con pérdidas de fricción pero sin adición de calor.

En las ecuaciones anteriores las unidades están en $L^2\,\theta^{-2}$. Si se hacen conversiones con el factor gc las unidades quedarían FL/M

$$gc = 9.81\ \overrightarrow{\text{kg}}\ \text{m/ kg seg}^2$$

De manera que la ecuación anterior quedaría:

$$(Z_2 - Z_1) \cdot \frac{g}{gc} + (u_2^2 - u_1^2) \cdot \frac{1}{2 \cdot gc} + \frac{1}{\rho}(P_2 - P_1)$$

$$= \frac{-\mathcal{W} - \Sigma F}{M}$$

Si se utiliza el sistema MKS absoluto en la ecuación anterior todos los miembros estarían dados en $\frac{\vec{\text{kg}}.\text{m}}{\text{kg}}$

en donde:

Z en m

$g = 9.81$ m/seg^2

u en m/seg

P en $\vec{\text{kg}}$/m^2

ρ en kg/m^3

$\frac{\mathcal{W}}{M}$ en $\vec{\text{kg}}$ m/kg

$\frac{\Sigma F}{M}$ en $\bar{\text{kg}}$.m/kg

Es importante notar que cada uno de los términos de energía pueden ser expresados en metros para el sistema MKS, o en pies para el sistema inglés, constituyendo lo que se conoce como carga, altura o cabeza.

En este capítulo se resolverán problemas aplicando la ecuación de Bernoulli a sistema de transporte fluido, dándose o ignorándose las pérdidas por fricción. Asimismo, se indicará posteriormente cómo obtener estas pérdidas.

El teorema de Bernoulli puede ser enunciado de la siguiente manera: "A lo largo de cualquier línea de corriente la suma de las alturas cinéticas, de presión o piezométricas y potencial es constante".

El teorema de Bernoulli no es más que el principio de la conservación de la energía, ya que cada término de la ecuación representa una forma de energía. Esta ecuación puede simplificarse seleccionando los límites del sistema apropiados.

PROBLEMAS RESUELTOS

Problemas 3.1

Calcule despreciando las pérdidas por fricción la potencia que desarrolla la turbina hidráulica de la figura siguiente:

$$\Delta Epe = 2.27 \frac{\text{kcal}}{\text{kg}}$$

$$\therefore Q = 10 + 2.27 + 18 = 30.27 \text{ kcal/kg}$$

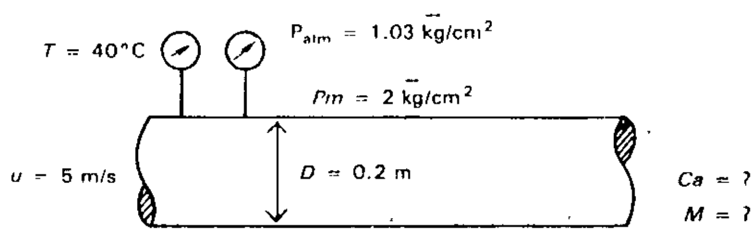
1 RESULTADO

El calor será de 30.27 kcal/kg

Problema 3.6

A través de una tubería de 20 cm de diámetro interno circula un gas con una presión manométrica de 2 $\overrightarrow{kg}/cm^2$ y una temperatura de 40°C. Si la presión barométrica es de 1.03 $\overrightarrow{kg}/cm^2$ y la velocidad a que circula el gas es de 5.0 m/s, ¿cuál es el gasto másico y el caudal? El peso molecular del gas es de 29.

1 TRADUCCIÓN



2 PLANTEAMIENTO

2.1 Ecuación de la continuidad

$$M_1 = M_2 \quad ; u_1 \rho_1 A_1 = u_2 \rho_2 A_2$$

$$Ca = M_1/\rho_1$$

2.2 Densidad

$$\rho = \frac{M}{V} = \frac{PPM}{RT}$$

3 CÁLCULOS

3.1 Densidad del gas

$$\rho = \frac{(2 + 1.03)\ \overline{kg}/cm^2 \times 29\ kg/kgmol}{1.033\ \frac{\overline{kg}/cm^2}{atm} \times \frac{0.082\ m^3\ atm}{kgmol\ °K} \times (273 + 40)\ °K} = 3.314$$

3.2 Gasto másico

$$M = \frac{5m}{s} \times 3.314\ \frac{kg}{m^3} \times \frac{\pi}{4}(0.2)^2 = 0.52029\ kg/s$$

3.3 Caudal

$$Ca = 0.52029\ kg/s \times \frac{m^3}{3.314\ kg} = 0.1569\ m^3/s$$

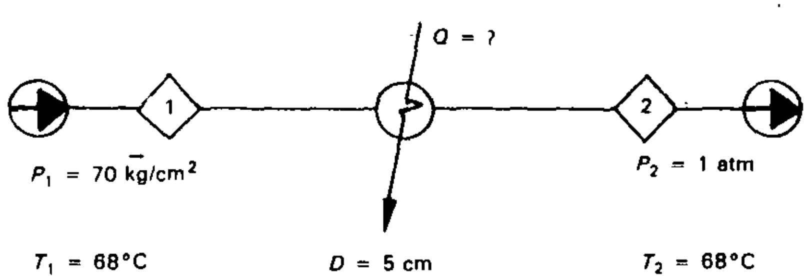
4 RESULTADOS

El gasto másico es de 0.52029 kg/s y el caudal es de 0.1569 m^3/s.

Problema 3.7

A través de una tubería horizontal de 5 cm de diámetro interno circula metano a razón de 1400 kg/h. El gas entra a la tubería a la presión absoluta de 70 $\overline{kg}/cm^2$ y a 68°C y sale a la presión atmosférica. ¿Qué cantidad de calor habría que suministrar para que el gas saliera de la tubería a la misma temperatura de entrada?

1. TRADUCCIÓN



2 PLANTEAMIENTO

2.1 Discusión

Considérese al metano como si fuera un gas ideal.

2.2 Balance de energía

$$M\left[\Delta H + \Delta EP + \Delta Ec\right] = Q - \mathscr{W}$$

En este caso $\mathscr{W} = 0$

$Z_2 - Z_1 = 0 \qquad \therefore \Delta EP = 0$

$T_2 = T_1 = 0 \qquad \therefore \Delta H = Cp\,\Delta T = 0$

$$\therefore M\,\Delta Ec = Q$$

2.3 Velocidades

$$M_1 = A_1\,u_1\,\rho_1 = A_2\,u_2\,\rho_2$$

$$A_1 = A_2$$

$$u_2 = u_1\,\rho_1/\rho_2$$

$$\rho = \frac{m}{v} = \frac{PPM}{RT} \quad ; T_1 = T_2$$

$$u_2 = u_1\,\frac{P_1\,PM_1\,R_2\,T_2}{R_1\,T_1\,P_2\,PM_2} = u_1\,\frac{P_1}{P_2}$$

$$\Delta Ec = \frac{u_2^2 - u_1^2}{2gc} = \frac{\left(u_1\,\frac{P_1}{P_2}\right)^2 - u_1^2}{2gc}$$

$$u_1 = \frac{Ca}{A} = \frac{M}{\rho A}$$

3 CÁLCULOS

3.1 Velocidad inicial

$$\rho_1 = \frac{70\ \vec{\text{kg}}/\text{cm}^2 \times 1\text{atm}/1.033\ \vec{\text{kg}}/\text{cm}^2 \times 16\ \text{kg/kgmol}}{0.082\ \dfrac{\text{m}^3\ \text{atm}}{\text{kg mol}^\circ\text{K}} \times 341^\circ\text{K}}$$

$$\rho_1 = 38.77\ \text{kg/m}^3$$

$$u_1 = \frac{1400\ \text{kg/h} \times 1\text{h}/3600\ \text{s}}{38.77\ \text{kg/m}^3 \times \dfrac{\pi}{4}\,(0.05)^2} = 5.108\ \text{m/s}$$

3.2 Balance de energía

$$1400\ \frac{\text{kg}}{\text{h}}\left(\frac{1\text{h}}{3600\text{s}}\right)\left[\frac{\left[5.108\left(\dfrac{70}{1.033}\right)\right]^2 - (5.108)^2}{2 \times 9.81\ \dfrac{\vec{\text{kg}}\text{m}}{\text{s}\ \vec{\text{kg}}}}\right]\frac{\text{m}^2}{\text{s}^2} = Q$$

$$Q = 2374.2\ \frac{\vec{\text{kg}}\text{m}}{\text{s}}$$

$$Q = 2374.2\ \frac{\vec{\text{kg}}\text{m}}{\text{s}} \times \frac{9.81\ \text{J}}{\vec{\text{kg}}} \times \frac{1\ \text{cal}}{4.2\ \text{J}} \times \frac{1\ \text{kcal}}{1000\ \text{cal}} = 5.545\ \frac{\text{kcal}}{\text{s}}$$

4 RESULTADO

Se deberán suministrar 5.545 kcal/s al gas para que salga a una temperatura de 68°C.

Problema 3.8

Si en el problema 3.7 la conducción se recubre con una capa de material aislante de forma que la circulación pueda considerarse adiabática, ¿cuál sería la temperatura de salida del metano? Dato: Cp = 9.28 kcal/kg mol °C.

CAPÍTULO 4

Pérdidas por fricción en flujo de fluidos

Para la aplicación industrial de la ecuación de Bernoulli es necesario conocer el término de pérdida por fricción por unidad de masa de fluido.

Si se aplica la ecuación de Bernoulli al siguiente sistema, donde el área es constante, la presión de salida es menor a la de entrada y el fluido en movimiento es incompresible.

$P_2 < P_1$

$A_2 = A_1$

$$(Z2 - Z1)\frac{g}{gc} + (u_2^2 - u_1^2)\frac{1}{2 \cdot gc} + (P2 - P1)\frac{1}{\rho} = -\frac{\mathcal{W} - \Sigma F}{M}$$

$$u_2 = u_1$$
$$Z_2 = Z_1$$
$$\mathcal{W} = 0$$

por lo que:

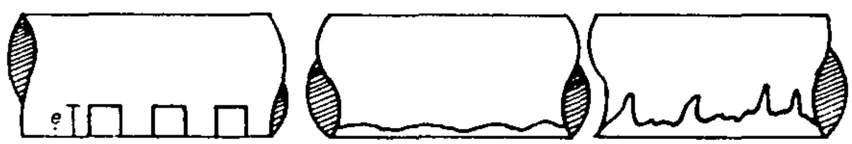
$$\frac{\Delta P}{\rho} = -\Sigma F/M$$

lo que significa que las pérdidas de presión son debidas a la fricción.

Para obtener la forma en que influye la fricción en la caída de presión se deben examinar las variables que influyen en el flujo de fluidos. Entre ellas figuran:

- Caída de presión ΔP
- Velocidad media u
- Diámetro del tubo D
- Longitud del tubo L
- Rugosidad del tubo ϵ
- Viscosidad del fluido μ
- Densidad del fluido ρ

Todas las variables son ya familiares, con excepción de la rugosidad del tubo; ésta se debe a que en general el tubo no es liso, existiendo una longitud transversal desde la pared del tubo.

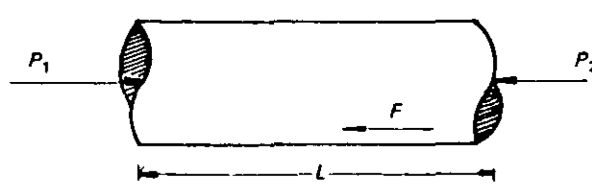


Si se define la fricción en las paredes de la tubería en términos de la cantidad de momento transferido, puede deducirse que:

$$\frac{\Sigma F}{M} = f_F(\rho u^2/2 \cdot gc)$$

ΣF = fuerza de fricción
A = área sobre la cual actúa la fuerza de fricción πDL
ρ = densidad del fluido
u = velocidad del fluido
f_F = coeficiente llamado factor de fricción de Fanning

Efectuando un balance de energía sobre una longitud de tubería horizontal y recta y de diámetro D.



La fuerza requerida para sobreponerse a la fricción debe suministrarse por la presión.

$$\frac{\Sigma F \pi D L}{M} = \Delta P \cdot \text{área de flujo} = \Delta P \cdot \frac{\pi D^2}{4}$$

La fuerza de fricción es:

$$\frac{\Sigma F}{M} \cdot \pi D \cdot L = f_F\ (\rho u^2/2gc)\ \pi D \cdot L$$

por lo tanto:

$$\Delta P \cdot \frac{\pi D^2}{4} = f_F\ (\rho u^2/2gc)\ \pi D \cdot L$$

$$\Delta P = 4\ \frac{L}{D}\ (\rho u^2/2gc)\ f_F$$

$$\Delta P = (P_1 - P_2) = \frac{4 \cdot f_f \cdot \rho\ u^2}{2 \cdot gc} \cdot \frac{L}{D}$$

La ecuación anterior es muy importante y se conoce como ecuación de Fanning, y se utiliza para calcular la caída de presión que se produce cuando un fluido circula por el interior de una tubería.

El coeficiente f_F se conoce como factor de Fanning y depende del número de Reynolds y de la rugosidad de la tubería. No ha sido posible encontrar una sola ecuación que prediga los valores de f_F para todos los patrones de flujo, encontrándose las siguientes relaciones a partir de datos experimentales:

a) Para flujo laminar

$$f_F = \frac{16}{NoRe}$$

b) Para flujo turbulento. $NoRe > 10000$
En tubos lisos

$$f_F = 0.316\ (NoRe)^{-0.25}$$

En tubos rugosos

$$\sqrt{\frac{1}{f_F}} = 4.06\ \log(D/\epsilon) + 2.16$$

c) Para flujo transicional. $2100 < NoRe < 10000$

$$\frac{1}{\sqrt{f_F}} = 4\log(D/\epsilon) + 2.28 - 4\log\left(4.67\,\frac{D/\epsilon}{NoRe\sqrt{f_f}} + 1\right)$$

Otro factor usado con frecuencia es el factor Darcy

$$f_D = 4f_f$$

Para ser procesado por medio de computadoras el factor f_D puede calcularse mediante*

$$f_D' = 8 \times \left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A + B)^{3/2}}\right]^{1/12}$$

en donde:

$$A = \left[2.457 \ln \frac{1}{\left(\frac{7}{Re}\right)^{0.9} + \frac{0.27\,\epsilon}{D}}\right]^{16}$$

$$B = \left(\frac{37530}{Re}\right)^{16};$$

Moody presentó una gráfica basada en las correlaciones anteriores, la que permite obtener rápidamente el valor del factor de fricción f de Darcy en función del número de Reynolds y de ϵ/D.

La gráfica de Moody aparece en el apéndice XXIV. El valor de ϵ/D se puede obtener fácilmente a partir de la gráfica del apéndice XXV. La combinación de estas dos gráficas permite calcular las pérdidas por fricción en tubos de longitud L y diámetro D cuando la velocidad promedio es u y las propiedades del fluido son ρ y μ.

PÉRDIDAS DE ENERGÍA POR CAMBIOS DE DIRECCIÓN Y POR ACCESORIOS

Cuando la dirección del flujo se altera o distorsiona, como ocurre en serpentines, codos o a través de reducciones y válvulas, se producen pérdidas

* Stuart W. Churchill-Chem. Eng. Nov. 7, 1977

de fricción que no se recuperan. Esta energía se disipa en remolinos y turbulencias adicionales y se pierde finalmente en forma de calor.

Las pérdidas en los accesorios son proporcionales a la velocidad. Con frecuencia estas pérdidas se encuentran en forma de tablas basadas en datos experimentales, aunque en ciertos casos pueden calcularse.

Una forma de obtener estas pérdidas por fricción es mediante la siguiente relación:

$$\frac{\Delta P}{\rho} = \frac{\Sigma F}{M} = K \frac{u^2}{2gc}$$

donde K es un coeficiente que depende del accesorio y se obtiene por tablas (apéndice XXVII).

Otra manera de calcular estas pérdidas es por la longitud equivalente, de manera que:

$$\frac{\Delta P}{\rho} = \frac{\Sigma F}{M} = f_D \frac{u^2}{2gc} \frac{Leq}{D}$$

donde Leq es la longitud equivalente, siendo la longitud del tubo recto que provocaría una caída de presión semejante a la causada por el accesorio estudiado. La longitud equivalente se obtiene por medio de gráficas o tablas (apéndice XXVI).

Las pérdidas de fricción total en un sistema de bombeo estarán dadas por:

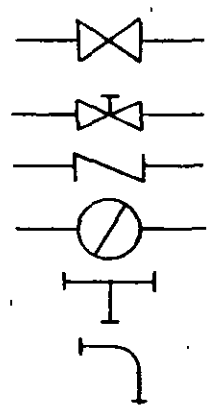
$$\frac{\Delta P}{\rho} = \frac{\Sigma F}{M} = \frac{f_D \cdot u^2(L + Leq)}{2gc \cdot D}$$

L = longitud del tubo recto (=) L

ΣF = ΣF tubo recto + ΣF de accesorios

Entre los accesorios más comunes se encuentran los siguientes:

- Válvula de globo (asiento)
- Válvula de compuerta (atajadera)
- Válvula de retención (check)
- Válvula de mariposa
- "Te"
- Codo 90°

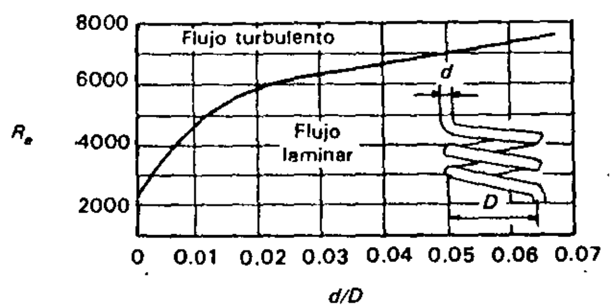


- Codo 45°


- Ensanchamiento brusco


- Contracción brusca


Para los fluidos que pasan por tubos enroscados (serpentines) el valor crítico del número de Reynolds es mayor que en los tubos rectos y depende de la relación *d/D*, donde *d* es el diámetro del tubo y *D* el diámetro de las espiras del serpentín. Esta relación se observa en la siguiente figura:



La pérdida de presión por rozamiento en un tubo enroscado (serpentín) es mayor que en un tubo recto.

$$\Delta P_{ser} = \Delta P_{recto}\,\psi$$
$$\psi = 1 + 3.54(d/D)$$

Para los ductos de sección transversal no circular se introduce en el número de Reynolds el diámetro equivalente, que es igual a cuatro veces el radio hidráulico r_H. El radio hidráulico es la relación entre el área de la sección transversal del flujo *A* y el perímetro mojado.

$$r_H = (\text{área de flujo/perímetro mojado})$$
$$Deq = 4 \cdot r_H$$

Cuando existe una contracción o expansión súbita se da una pérdida de energía por fricción.

Para la expansión:

$$\frac{\Sigma F}{M} = Kex\,\frac{u_1^{\,2}}{2 \cdot gc}$$

u_1 = velocidad en el área más pequeña
Kex = coeficiente de expansión (apéndice XXIX)

Para la contracción:

$$\frac{\Sigma F}{M} = Kc\,\frac{u_2^2}{2 \cdot gc}$$

u_2 = velocidad en el área más pequeña corriente abajo
Kc = coeficiente de contracción (apéndice XXIX)

EFECTOS DE LA TRANSFERENCIA DE CALOR EN EL FACTOR DE FRICCIÓN

El factor de fricción se emplea para flujo isotérmico, y en el caso de que se tenga flujo no isotérmico se puede utilizar el método de Sieder y Tate para predecir el factor de fricción en líquidos y gases.

En un líquido el cambio de temperatura afecta las propiedades físicas de dicho fluido, en especial lo que se refiere a viscosidad.

La secuencia del método de Sieder y Tate para el cálculo del factor de fricción es como sigue:

1. Calcular la temperatura total media Tm como el promedio de las temperaturas de entrada y salida.
2. Calcular el número de Reynolds con la densidad y viscosidad a la temperatura total media para que se pueda obtener el factor de fricción f.
3. Determinar la viscosidad a la temperatura de la pared Tw.
4. Calcular ψ según sea el caso:

   $\psi = (\mu m/\mu w)^{0.17}$ calentamiento $NoRe > 2100$
   $\psi = (\mu m/\mu w)^{0.11}$ enfriamiento $NoRe > 2100$
   $\psi = (\mu m/\mu w)^{0.38}$ calentamiento $NoRe < 2100$
   $\psi = (\mu m/\mu w)^{0.23}$ enfriamiento $NoRe < 2100$

   donde:

   μm = μ a la T media del fluido
   μw = μ a la T de la pared

5. Dividir el factor de fricción obtenido en el punto 2 entre el valor de ψ, obteniendo así el valor del factor de fricción final.

Las tuberías utilizadas para flujo de fluidos se dividen en dos grandes rubros: las tuberías basadas en el número de cédula NPT(nominal pipe tube) empleadas para el transporte de fluidos y las tuberías basádas en calibres *AWG*(American wire gauge) y *BWG*(Birmingham wire gauge), empleadas en la construcción de cambiadores de calor y calderas.

El número de cédula está relacionado con la presión por:

No. cédula = $1000(P/S)$

P = presión interna en lb/in^2

S = tensión a la ruptura lb/in^2

Estas denominaciones se utilizan para tuberías de acero, acero inoxidable, acero galvanizado y hierro colado. Los datos más importantes sobre estas tuberías aparecen en la tabla del apéndice XXXI.

En las tuberías para cambiadores de calor el diámetro externo coincide con el nominal, y a mayor calibre menor es el grueso de la tubería.

En general se tiene diagrama para flujo de fluidos a través de tubos de intercambiadores de calor para obtener el factor de fricción contra el número de Reynolds (ver gráfica del apéndice XXXII).

Materiales empleados en las tuberías

Los materiales usuales son: acero, acero inoxidable, aluminio, plomo, asbesto, cemento, cobre, concreto, hierro forjado, hierro fundido, hierro negro, latón, cerámica vitrificada, plásticos y aun vidrio.

Velocidades en las líneas

Para evitar deposiciones en las tuberías la velocidad mínima generalmente es fijada entre 0.25 y 0.4 m/seg. Si lo que se transporta tiene materiales en suspensión la velocidad no deberá ser inferior a 0.6 m/seg.

Velocidades recomendadas

Las velocidades más comúnmente aplicadas en el diseño de redes de tuberías se indican en la siguiente tabla:

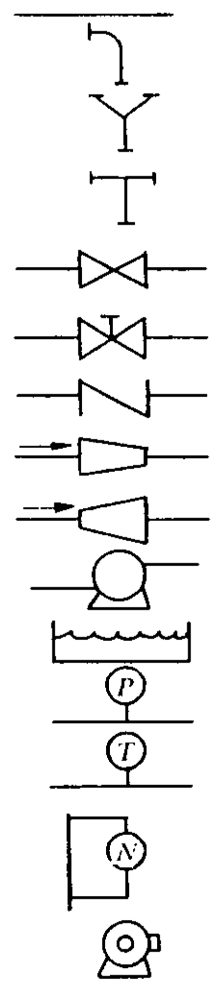
Flujo	*Velocidad m/seg*
Gases a tiro natural	2-4
Gases a presión atmosférica o cercana a ésta en conductos de gas y tuberías de ventilación	5-20

Líquidos al desplazarse por acción de gravedad	0.1-0.5
Líquidos en tuberías de presión	0.5-2.5
Vapor de agua a presión absoluta mayor o igual a 0.5 atm	15-40
De 0.2 a 0.5 atm	40-60

En este capítulo se verán solamente problemas relacionados con fluidos incompresibles.

Símbolos utilizados en esta obra

- Tubería
- Codo
- "Ye"
- "Te"
- Válvula de globo
- Válvula de compuerta
- Válvula de retención
- Contracción
- Expansión
- Bomba
- Tanque abierto
- Manómetro
- Termómetro
- Nivel
- Ventilador



$A = 7.951 \times 10^{20}$

$$f_D = 8 \times \left[\left(\frac{8}{632311} \right)^{12} + \frac{1}{(7.951 \times 10^{20} + 2.3722 \times 10^{20})^{3/2}} \right]^{1/12}$$

$f_D = 0.0195$

4 RESULTADO

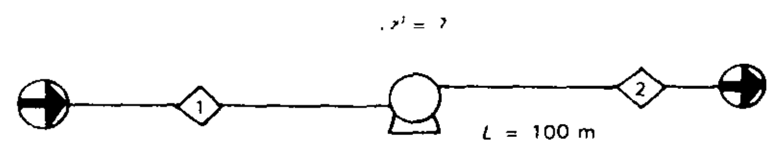
Las pérdidas por fricción serán de 2.18 $\overrightarrow{\text{kgm}}$/kg

Problema 4.3

Calcule la potencia que se requiere para bombear aceite de densidad relativa 0.85 y viscosidad 3 cps a razón de 4 l/s, a través de una tubería de acero de 2 pulgadas Cd 40 y 100 m de longitud. La tubería es horizontal y la presión de descarga es la misma que la presión de entrada.

Si como consecuencia de la corrosión y de la formación de costras la rugosidad se incrementa 10 veces, ¿en qué porcentaje se aumentará la potencia de bombeo requerida?

1 TRADUCCIÓN



2 PLANTEAMIENTO

2.1 Ecuación de Bernoulli

$$\Delta Z \frac{g}{gc} + \frac{\Delta u^2}{2gc} + \frac{\Delta P}{\rho} = -\frac{\mathcal{P}}{M} - \frac{\Sigma F}{M}$$

En este caso $Z_1 = Z_2$; $P_1 = P_2$ y para un fluido incompresible

$$u_1 A_1 \rho_1 = u_2 A_2 \rho_2; \qquad \rho_1 = \rho_2; \; A_1 = A_2$$

$$\therefore u_1 = u_2$$

La ecuación resultante es

$$\frac{\mathscr{P}}{M} = -\frac{\Sigma F}{M}$$

3 CÁLCULOS

3.1 Pérdidas por fricción

$DI = 2.067$ pulgadas $= 0.0525$ m

$$u = \frac{0.004\ m^3\ (4)}{S\ \pi\ (0.0525)^2} = 1.847\ \frac{m}{s}$$

$$Re = \frac{0.0525\ m\ (850\ kg/m^3)\ (1.847\ m/s)}{3 \times 10^{-3}\ kg/m/s} = 27474$$

Del apéndice XXV $\frac{\epsilon}{D} = 0.0009$

Del apéndice XXIV $f_D = 0.027$

$$\frac{\Sigma F}{M} = \frac{0.027\ (1.847)^2\ (100)}{2\ (9.81)\ (0.0525)} = 8.94\ \overrightarrow{kg}m/kg$$

Si $\frac{\epsilon}{D}$ diez veces mayor $\cong 0.009$, $f_D = 0.039$

$$\frac{\Sigma F}{M} = 8.94\ \frac{(0.039)}{(0.027)} = 12.916\ \overrightarrow{kg}m/kg$$

3.2 Potencia

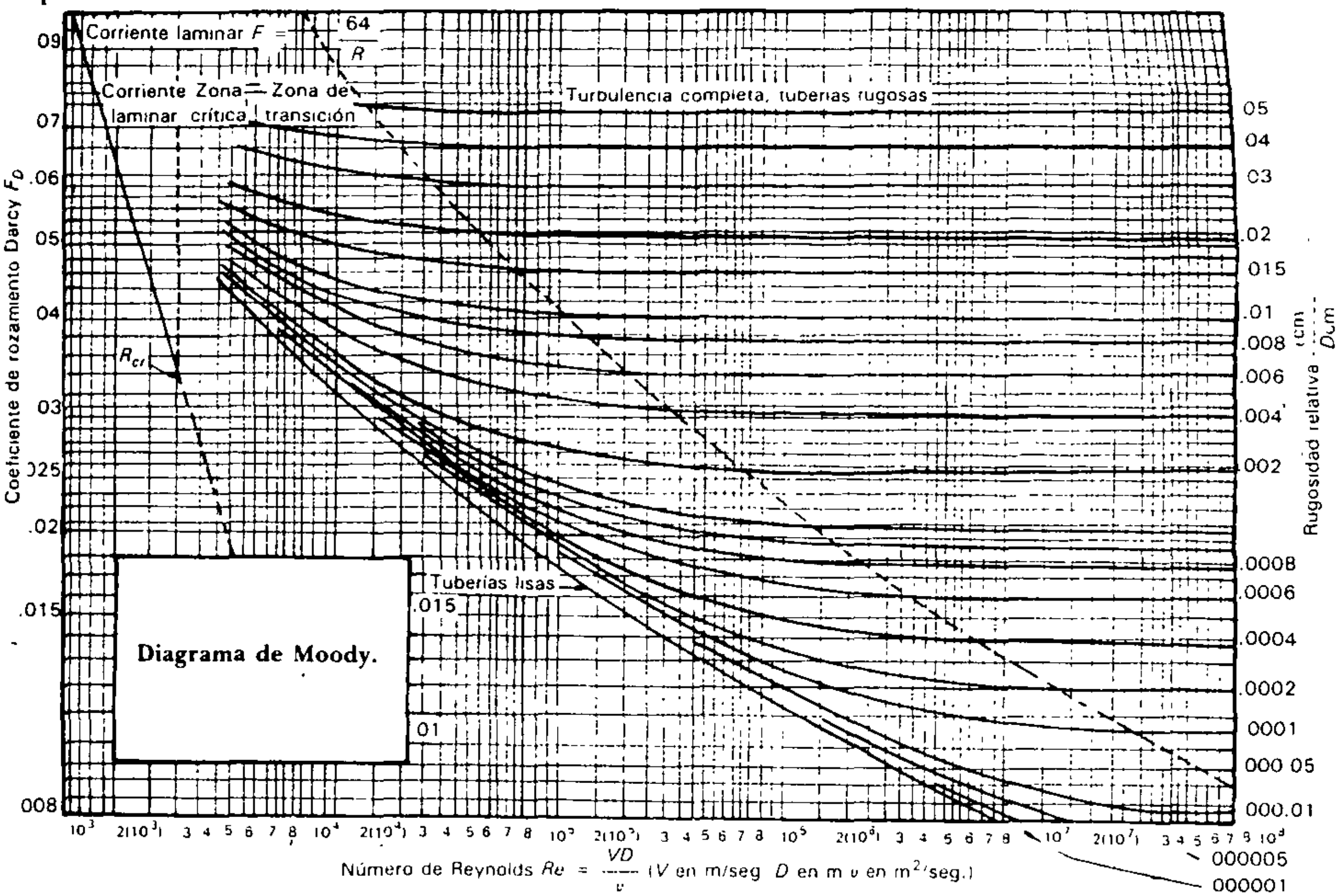
$M = 4\ l/s\ (0.85\ kg/l) = 3.4\ kg/s$

$$\mathscr{P}_1 = 8.94\ \frac{\overrightarrow{kg}m}{kg}\ (3.4\ \frac{kg}{s}) = 30.396\ \overrightarrow{kg}m/kg$$

$$\mathscr{P}_2 = 12.916\ (3.4\ kg/s) = 43.914\ \overline{kg}m/kg$$

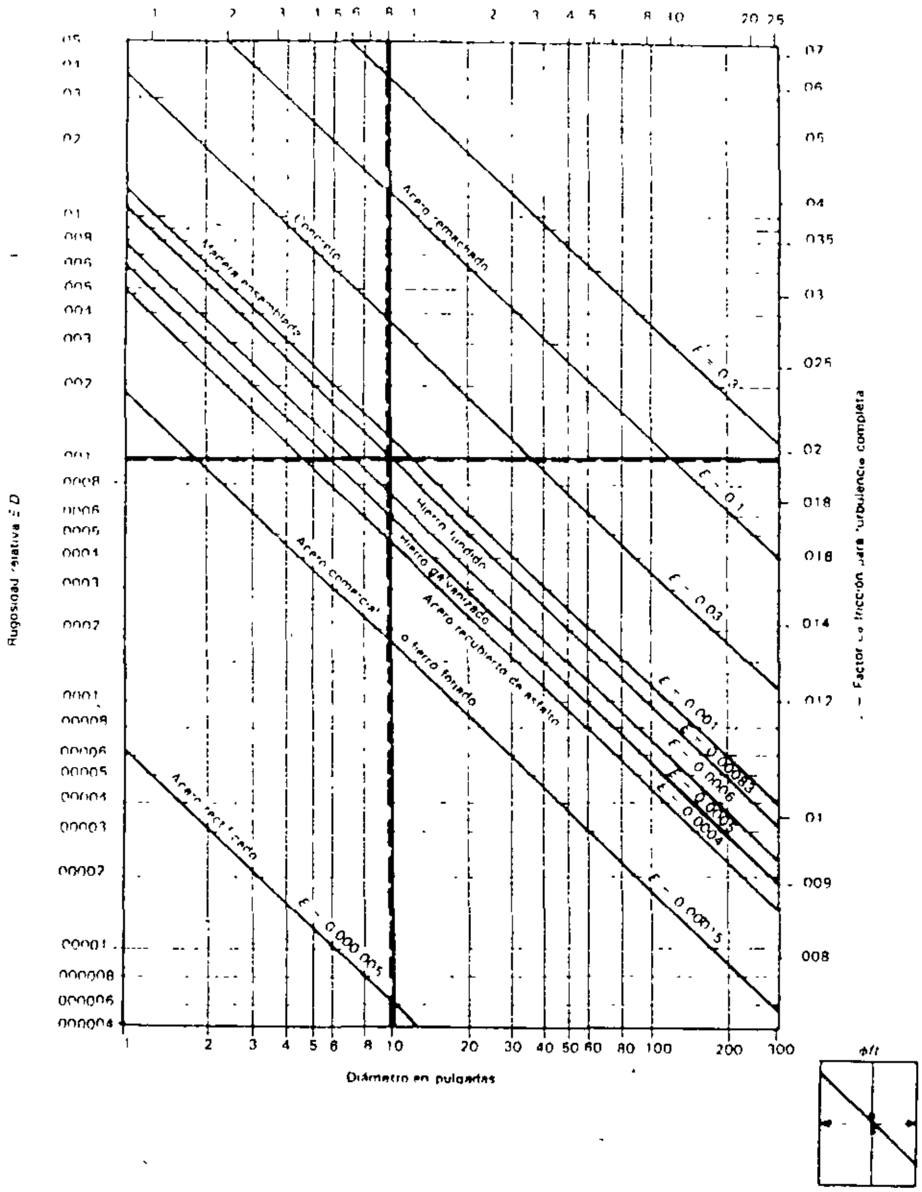
$$\frac{\mathscr{P}_2}{\mathscr{P}_1} = \frac{43.914 - 30.396}{30.396} \times 100 = 14.44\%$$

Apéndice XXIV.



Fuente: G. Mataix. *Mecánica de fluidos*. Harla, México. 1970

Apéndice XXV. Rugosidad relativa para tubería de diferentes materiales y factor de fricción para turbulencia completa.



Fuente: Crane, *Flow of fluids* Technical Paper No 10, 1979

Apéndice XXVI. Longitudes equivalentes (expresadas en metros de tubería rectilínea)*

Diámetro D mm	Diámetro D pulg	Codo 90° Radio largo	Codo 90° Radio medio	Codo 90° Radio corto	Codo 45°	Curva 90° R/D = 1 1/2	Curva 90° R/D = 1	Curva 45°	Entrada normal	Entrada de borda	Válvula de compuerta abierta	Válvula tipo globo abierta*	Válvula de ángulo abierta	Te paso directo	Te salida lateral	Te salida bilateral	Válvula de pie	Salida de tubería	Válvula de retención tipo ligero	Válvula de retención tipo pesado
13	1/2	0.3	0.4	0.5	0.2	0.2	0.3	0.2	0.2	0.4	0.1	4.9	2.6	0.3	1.0	1.0	3.6	0.4	1.1	1.6
19	3/4	0.4	0.6	0.7	0.3	0.3	0.4	0.2	0.2	0.5	0.1	6.7	3.6	0.4	1.4	1.4	5.6	0.5	1.6	2.4
25	1	0.5	0.7	0.8	0.4	0.3	0.5	0.2	0.3	0.7	0.2	8.2	4.6	0.5	1.7	1.7	7.3	0.7	2.1	3.2
32	1 1/4	0.7	0.9	1.1	0.5	0.4	0.6	0.3	0.4	0.9	0.2	11.3	5.6	0.7	2.3	2.3	10.0	0.9	2.7	4.0
38	1 1/2	0.9	1.1	1.3	0.6	0.5	0.7	0.3	0.5	1.0	0.3	13.4	6.7	0.9	2.8	2.8	11.6	1.0	3.2	4.8
50	2	1.1	1.4	1.7	0.8	0.6	0.9	0.4	0.7	1.5	0.4	17.4	8.5	1.1	3.5	3.5	14.0	1.5	4.2	6.4
63	2 1/2	1.3	1.7	2.0	0.9	0.8	1.0	0.5	0.9	1.9	0.4	21.0	10.0	1.3	4.3	4.3	17.0	1.9	5.2	8.1
75	3	1.6	2.1	2.5	1.2	1.0	1.3	0.6	1.1	2.2	0.5	26.0	13.0	1.6	5.2	5.2	20.0	2.2	6.3	9.7
100	4	2.1	2.8	3.4	1.5	1.3	1.6	0.7	1.6	3.2	0.7	34.0	17.0	2.1	6.7	6.7	23.0	3.2	6.4	12.9
125	5	2.7	3.7	4.2	1.9	1.6	2.1	0.9	2.0	4.0	0.9	43.0	21.0	2.7	8.4	8.4	30.0	4.0	10.4	16.1
150	6	3.4	4.3	4.9	2.3	1.9	2.5	1.1	2.5	5.0	1.1	51.0	26.0	3.4	10.0	10.0	39.0	5.0	12.5	19.3
200	8	4.3	5.5	6.4	3.0	2.4	3.3	1.5	3.5	6.0	1.4	67.0	34.0	4.3	13.0	13.0	52.0	6.0	16.0	25.0
250	10	5.5	6.7	7.9	3.8	3.0	4.1	1.8	4.5	7.5	1.7	85.0	43.0	5.5	16.0	16.0	65.0	7.5	20.0	32.0
300	12	6.1	7.9	9.5	4.6	3.6	4.8	2.2	5.5	9.0	2.1	102.0	51.0	6.1	19.0	19.0	78.0	9.0	24.0	38.0
350	14	7.3	9.5	10.5	5.3	4.4	5.4	2.5	6.2	11.0	2.4	120.0	60.0	7.3	22.0	22.0	90.0	11.0	28.0	45.0

* Los valores indicados para válvulas tipo globo se aplican también a llaves para regaderas y válvulas o llaves de descarga

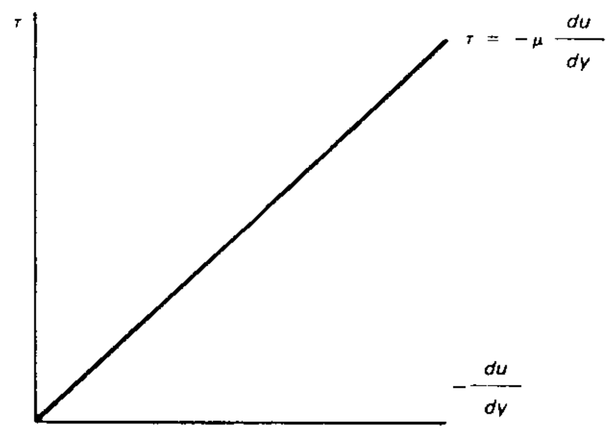
Fuente: Azevedo, Álvarez. *Manual de hidráulica*, Harla. México, 1975

CAPÍTULO 10

Fluidos no newtonianos

FLUIDO NEWTONIANO

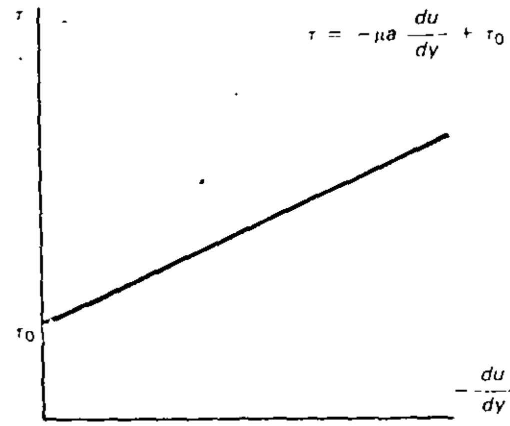
Cuando un fluido presenta una viscosidad constante aun con el cambio de velocidad de corte, se trata de un fluido newtoniano.



Los fluidos que presentan cambios al variar la velocidad de corte reciben el nombre de fluidos no newtonianos, entre los que se encuentran:

a) Fluidos Bingham

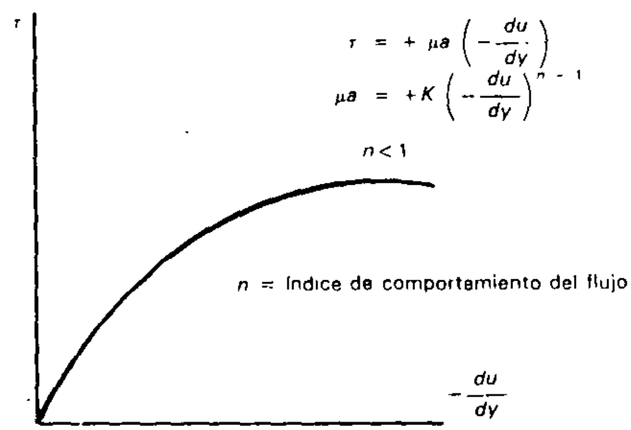
Son aquellos que necesitan de un cierto esfuerzo para comenzar a fluir. Como ejemplo podemos citar las suspensiones de rocas y arcilla.



b) Fluidos seudoplásticos

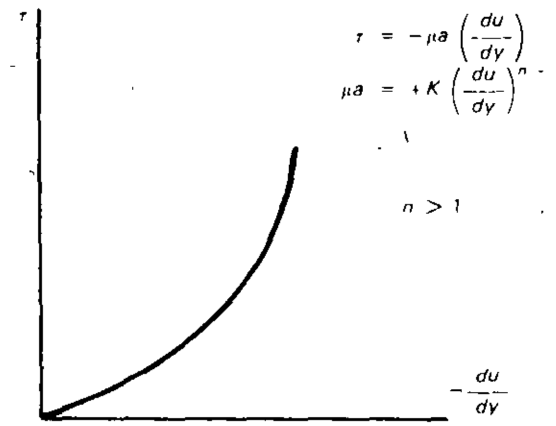
Su viscosidad decrece al aumentar el gradiente de la velocidad. Como ejemplos podemos mencionar las soluciones poliméricas de peso molecular elevado, la pulpa de papel y la mayonesa.

Existen varias ecuaciones que predicen el comportamiento de estos fluidos; la más común es el modelo empírico de Ostwald-de Waele-Nutting



c) Fluidos dilatantes

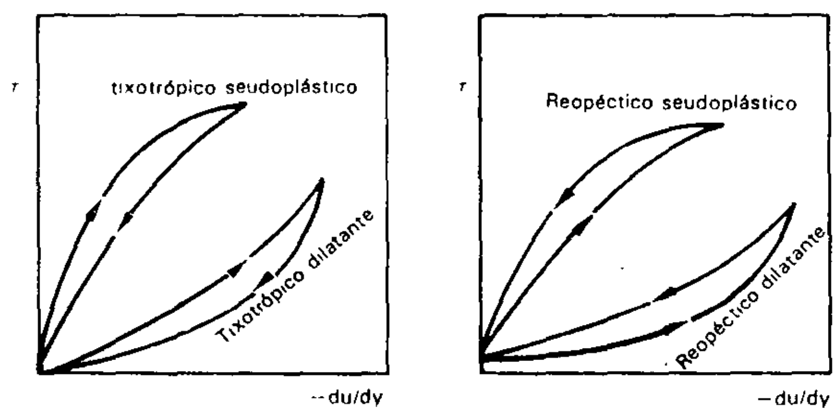
En ellos la viscosidad aumenta al aumentar el gradiente de velocidad. Las suspensiones de almidón, de silicato de potasio y de goma arábiga son ejemplos de fluidos dilatantes.



d) Fluidos tixotrópicos y reopécticos

Si se somete un fluido a tensiones y velocidades de deformación, primero crecientes y luego decrecientes, y presenta un ciclo de histéresis, o sea que las curvas de esfuerzo cortante contra la velocidad de deformación o reogramas no coinciden, se dice que este fluido es tixotrópico o reopéctico.

Se denominará al fluido tixotrópico si su viscosidad aparente disminuye con el tiempo y reopéctico si aumenta. Como ejemplos de fluidos tixotrópicos están los aceites vegetales y minerales, las gelatinas, la miel, la crema de afeitar, las pinturas y la mayonesa. Como ejemplo de fluidos reopécticos están las suspensiones de yeso en agua y las de bentonita y pentóxido de vanadio.



Desplazamiento laminar de los fluidos no newtonianos.

MANEJO DE GAS.
PARTE III.

TEMARIO.

MEDICION CON PLACA ORIFICIO.

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

Part 1—General Equations and Uncertainty Guidelines

THIRD EDITION, SEPTEMBER 1990

AGA	American Gas Association	Report No. 3, Part 1
GPA	Gas Processors Association	GPA 8185-90, Part 1

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005

This new revision of the API *Manual of Petroleum Measurement Standards,* Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters" (A.G.A. Report No. 3; GPA 8185-90), consists of four parts:

Part 1—"General Equations and Uncertainty Guidelines"
Part 2—"Specifications and Installation Requirements"
Part 3—"Natural Gas Applications"
Part 4—"Background, Development, Implementation Procedure, and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation"

Each of the four parts is published separately to facilitate future changes, allow immediate use, and reduce the size of the applicable part needed by most users. Although for many applications each part can be used independently, users with natural gas applications should obtain Parts 3 and 4 before implementing Part 1.

Note: At the time of initial publication of MPMS Chapter 14, Section 3, Part 1, approval by the American National Standards Institute was pending.

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Chapter 14—Natural Gas Fluids Measurement

SECTION 3—CONCENTRIC, SQUARE-EDGED ORIFICE METERS

PART 1—GENERAL EQUATIONS AND UNCERTAINTY GUIDELINES

1.1 Introduction

1.1.1 SCOPE

This standard provides a single reference for engineering equations, uncertainty estimations, construction and installation requirements, and standardized implementation recommendations for the calculation of flow rate through concentric, square-edged, flange-tapped orifice meters. Both U.S. customary (IP) and International System of Units (SI) units are included.

1.1.2 ORGANIZATION OF STANDARD

The standard is organized into four parts. Parts 1, 2, and 4 apply to the measurement of any Newtonian fluid in the petroleum and chemical industries. Part 3 focuses on the application of Parts 1, 2, and 4 to the measurement of natural gas.

1.1.2.1 Part 1—General Equations and Uncertainty Guidelines

The mass flow rate and base (or standard) volumetric flow rate equations are discussed, along with the terms required for solution of the flow equation.

The empirical equations for the coefficient of discharge and expansion factor are presented. However, the bases for the empirical equations are contained in other sections of this standard or the appropriate reference document.

For the proper use of this standard, a discussion is presented on the prediction (or determination) of the fluid's properties at flowing conditions. The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state.

Uncertainty guidelines are presented for determining the possible error associated with the use of this standard for any fluid application. User-defined uncertainties for the fluid's physical properties and auxiliary (secondary) devices are required to solve the practical working formula for the estimated uncertainty.

1.1.2.2 Part 2—Specifications and Installation Requirements

Specifications are presented for orifice meters, in particular, orifice plates, orifice plate holders, sensing taps, meter tubes, and flow conditioners.

Installation requirements for orifice plates, meter tubes, thermometer wells, flow conditioners, and upstream/downstream meter tube lengths are presented.

1.1.2.3 Part 3—Natural Gas Applications

The application of this standard to natural gas is presented, along with practical guidelines. Mass flow rate and base (or standard) volumetric flow rate methods are presented in conformance with North American industry practices.

1.1.2.4 Part 4—Background, Development, and Implementation Procedure and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation

The coefficient of discharge data base for flange-tapped orifice meters and its background, development, and limitations are presented.

Implementation procedures for flange-tapped orifice meters are presented, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the implementation procedures.

1.1.3 REFERENCED PUBLICATIONS

Several documents served as references for the revision of this standard. In particular, previous editions of Chapter 14.3 (ANSI[1]/API 2530; A.G.A.[2] Report No. 3) provided a wealth of information. The laboratory reports for the experimental data bases also provided valuable information concerning the control of independent variables, both qualitatively and quantitatively. Other publications, symposium proceedings, trade journals, textbooks, and society papers were consulted for the revision of this standard.

A complete bibliography is available upon request from the American Petroleum Institute. A reduced list, referencing the major experimental research, is contained in Appendix 1-A.

1.2 Field of Application

1.2.1 APPLICABLE FLUIDS

This standard applies to steady-state mass flow conditions for fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous, and Newtonian and have pipe Reynolds numbers of 4000 or greater. All gases, most liquids, and most dense phase fluids associated with the petroleum, petrochemical, and natural gas industries are usually considered Newtonian fluids.

1.2.2 TYPES OF METERS

This standard provides design, construction, and installation specifications for flange-tapped, concentric, square-edged orifice meters of nominal 2-inch Schedule 160 and larger pipe diameters.

An orifice meter is a fluid flow measuring device that produces a differential pressure to infer flow rate. The meter consists of the following elements (see Figure 1-1):

a. A thin, concentric, square-edged orifice plate.
b. An orifice plate holder consisting of a set of orifice flanges (or an orifice fitting) equipped with the appropriate differential pressure sensing taps.
c. A meter tube consisting of the adjacent piping sections (with or without flow conditioners).

The auxiliary (secondary) devices necessary for the precise determination of flow rate are not included in the scope of this standard. These devices are usually instruments that sense the differential and static pressure, fluid temperature, and fluid density and/or relative density (specific gravity), and either mechanical recording devices or electronic calculators. Publications of the A.G.A., API, GPA,[3] and others should be used to specify and install these auxiliary (secondary) devices.

[1]American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.
[2]American Gas Association, 1515 Wilson Boulevard, Arlington, Virginia 22209.
[3]Gas Processors Association, 6526 East 60th Street, Tulsa, Oklahoma 74145.

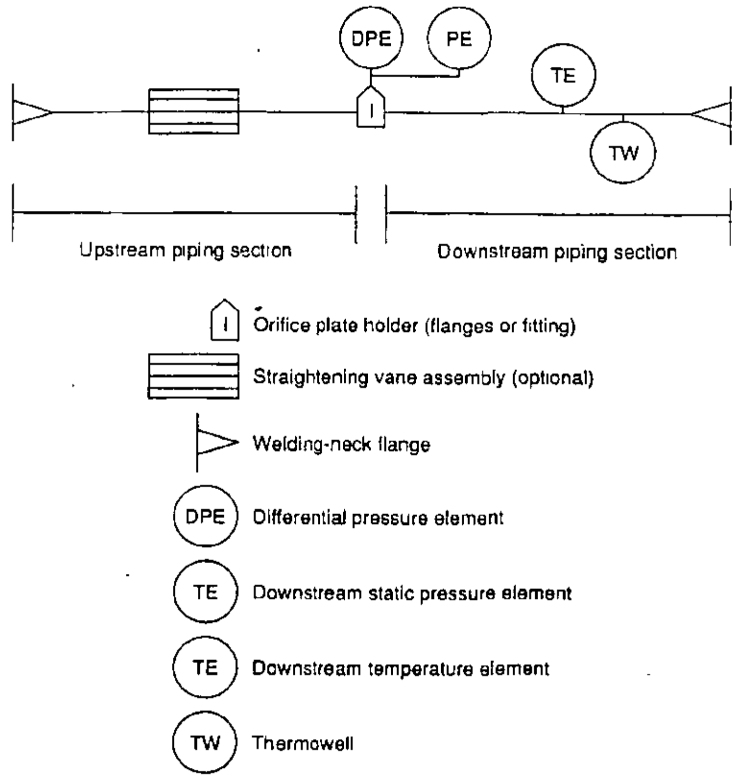


Figure 1-1—Orifice Meter

1.2.3 UNCERTAINTY OF MEASUREMENT

Many factors influence the overall measurement uncertainty associated with a metering application. Major contributors include construction tolerances in the meter components, tolerances of empirical coefficient of discharge data bases or in-situ flow calibrations, predictability of and variations in the fluid's physical properties, and uncertainties associated with the auxiliary (secondary) devices.

Using the guidelines contained in this standard in combination with the associated uncertainty tolerances for the fluid's physical properties, in-situ calibrations, or coefficient of discharge data bases, and the appropriate auxiliary (secondary) devices, the user can estimate the overall measurement uncertainty associated with a properly designed, installed, and maintained thin plate, concentric, square-edged orifice metering application.

1.3 Method of Calculation

This standard provides recommended standardized calculation implementation methods for the quantification of fluid flow under defined conditions, regardless of the point of origin or destination or the units of measure required by governmental customs or statute. The recommended implementation procedures provided in Chapter 14.3, Part 4, allow different entities using various computer languages on different computing hardware to arrive at nearly identical results using the same standardized input data.

The following two recommended implementation procedures have been prepared to illustrate the standardized set of mathematical expressions and sequencing, including iteration/rounding techniques:

Date of Issue: July 1991
Affected Publication: *Manual of Petroleum Measurement Standards*, Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 1, "General Equations and Uncertainty Guidelines," Third Edition, September 1990

ERRATA

On page 2, Footnote 1 should read as follows:

[1]American National Standards Institute, 11 West 42nd Street, New York, New York 10036

On page 3, Figure 1-1 should appear as follows (that is, the letters PE *should be used to represent the downstream static pressure element):*

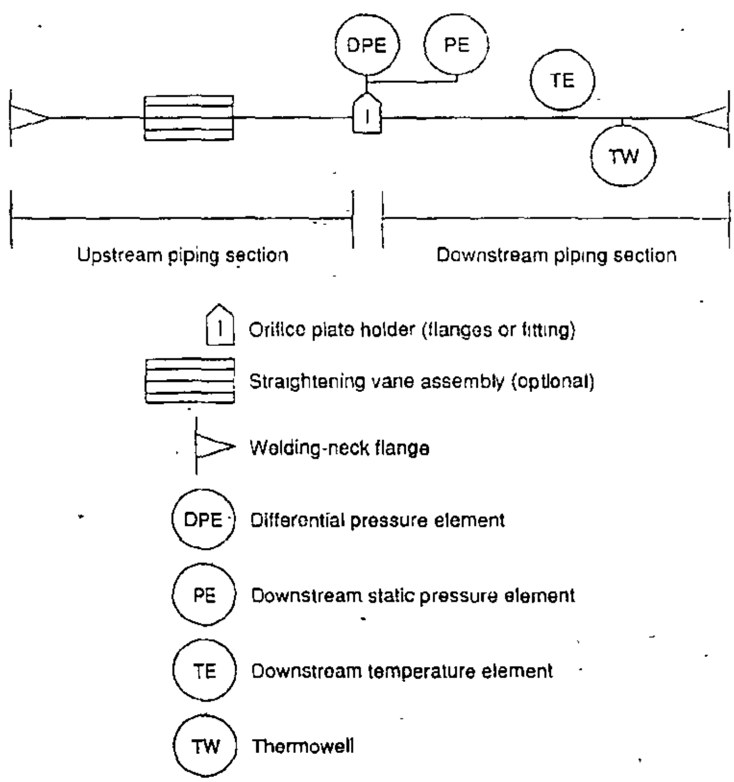


Figure 1-1—Orifice Meter

On page 13, the first paragraph should read as follows (that is, the word Ohio *should replace the word* Oklahoma*):*

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Ohio State University Data Base (303 flange-tapped points), the 1983 NBS Boulder Experiments, the Foxboro Columbus–Daniel 1000-Point Data Base, and the Japanese Water Data Base.

a. Mass flow rate.
b. Standard volumetric flow rate.

The procedures presented address only the solution of the flow rate equation and require specific inputs (fixed and variable). Typical fixed inputs include meter tube internal diameter, orifice plate bore diameter, and linear coefficient of expansion for steels (pipe and orifice plate) Typical variable inputs may include differential and static pressure, temperature, fluid density, isentropic exponent for compressible fluids, and fluid viscosity.

The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state. If multiple parties are involved in the measurement, the appropriate technical method selected for determining the fluid's physical properties shall be mutually agreed upon.

1.4 Symbols

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

Symbol	Represented Quantity
C_d	Orifice plate coefficient of discharge.
C_d(FT)	Coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
C_i	Coefficient of discharge at infinite pipe Reynolds number.
C_i(CT)	Coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
C_i(FT)	Coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
c_p	Specific heat at constant pressure.
c_v	Specific heat at constant volume.
d	Orifice plate bore diameter calculated at flowing temperature, T_f.
d_m	Orifice plate bore diameter measured at T_m.
d_r	Orifice plate bore diameter at reference temperature, T_r.
D	Meter tube internal diameter calculated at flowing temperature, T_f.
D_m	Meter tube internal diameter measured at T_m.
D_r	Meter tube internal diameter at reference temperature, T_r.
ΔP	Orifice differential pressure.
°C	Temperature, in degrees Celsius.
°F	Temperature, in degrees Fahrenheit.
K	Temperature, in kelvins.
°R	Temperature, in degrees Rankine.
E_v	Velocity of approach factor.
g_c	Dimensional conversion constant.
G_i	Ideal gas relative density (specific gravity).
k	Isentropic exponent.
k_i	Ideal gas isentropic exponent.
k_p	Perfect gas isentropic exponent.
k_r	Real gas isentropic exponent.
MF	In-situ calibration meter factor.
Mr_{air}	Molar mass of air.
Mr_{gas}	Molar mass of gas.
N_1	Unit conversion factor (orifice flow).
N_2	Unit conversion factor (Reynolds number).
N_3	Unit conversion factor (expansion factor).
N_4	Unit conversion factor (discharge coefficient).
P_b	Base (reference or standard) pressure.

P_f	Static pressure of fluid at the pressure tap.
P_{f_1}	Absolute static pressure at the orifice upstream differential pressure tap.
P_{f_2}	Absolute static pressure at the orifice downstream differential pressure tap.
q_m	Mass flow rate.
q_{m_i}	Mass flow rate indicated by the orifice meter being calibrated.
q_{m_p}	Mass flow rate determined by the primary mass flow system (or master meter).
q_v	Volume flow rate at flowing (actual) conditions.
q_{v_i}	Volume flow rate indicated by the orifice meter being calibrated.
Q_v	Volume flow rate at base (standard) conditions.
R	Universal gas constant.
R_a	Roughness average value from continuously averaging meter readings.
Re_D	Pipe Reynolds number.
T	Temperature.
T_b	Base (reference or standard) temperature.
T_f	Temperature of fluid at flowing conditions.
T_m	Temperature of the orifice plate or meter tube at time of diameter measurements.
T_r	Reference temperature of orifice plate bore diameter and/or meter tube inside diameter.
x	Ratio of differential pressure to absolute static pressure.
x_1	Ratio of differential pressure to absolute static pressure at the upstream pressure tap.
S( )	Sensitivity coefficient (influence coefficient).
Y	Expansion factor.
Y_1	Expansion factor based on upstream absolute static pressure.
Y_2	Expansion factor based on downstream absolute static pressure.
Z	Fluid compressibility.
Z_f	Fluid compressibility at flowing conditions.
Z_{f_1}	Compressibility of the fluid flowing at the upstream pressure tap location.
Z_{f_2}	Compressibility of the fluid flowing at the downstream pressure tap location.
α	Linear coefficient of thermal expansion.
α_1	Linear coefficient of thermal expansion of the orifice plate material.
α_2	Linear coefficient of thermal expansion of the meter tube material.
β	Ratio of orifice diameter to meter tube diameter calculated at flowing conditions.
μ	Absolute viscosity of fluid flowing.
π	Universal constant.
ρ	Density of the fluid.
ρ_b	Density of the fluid at base conditions $(P_{b'}, T_b)$.
$\rho_{f,p}$	Density of the fluid at flowing conditions (P_f, T_f).

1.5 Definitions

This standard reflects orifice meter application to fluid flow measurement. The definitions are given to emphasize the particular meaning of the terms as used in this standard.

1.5.1 PRIMARY ELEMENT

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, and the meter tube.

1.5.1.1 Orifice Plate

The orifice plate is defined as a thin plate in which a circular concentric aperture (bore) has been machined. The orifice plate is described as a thin plate with sharp, square edge because the thickness of the plate material is small, compared with the internal diameter of the measuring aperture (bore), and because the upstream edge of the measuring aperture is sharp and square.

1.5.1.2 Orifice Plate Bore Diameter (d, d_m, d_r)

The calculated orifice plate bore diameter (d) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature (T_f), as specified in 1.6.2. The calculated orifice plate bore diameter (d) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter (d_m) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate (T_m) at the time of bore diameter measurements, determined as specified in Chapter 14.3, Part 2.

The reference orifice plate bore diameter (d_r) is the internal diameter of the orifice plate measuring aperture at reference temperature (T_r), calculated as specified in Chapter 14.3, Part 2. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

1.5.1.3 Orifice Plate Holder

The orifice plate holder is defined as a pressure-containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

1.5.1.4 Meter Tube

The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in Chapter 14.3, Part 2.

1.5.1.5 Meter Tube Internal Diameter (D, D_m, D_r)

The calculated meter tube internal diameter (D) is the inside diameter of the upstream section of the meter tube computed at flowing temperature (T_f), as specified in 1.6.3. The calculated meter tube internal diameter (D) is used in the diameter ratio and Reynolds number equations.

The measured meter tube internal diameter (D_m) is the inside diameter of the upstream section of the meter tube at the temperature of the meter tube (T_m) at the time of internal diameter measurements, determined as specified in Chapter 14.3, Part 2.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube at the reference temperature (T_r), calculated as specified in Chapter 14.3, Part 2. The reference meter tube internal diameter is the certified or stamped meter tube internal diameter.

1.5.1.6 Diameter Ratio (β)

The diameter ratio (β) is defined as the calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

1.5.2 PRESSURE MEASUREMENT

1.5.2.1 Tap Hole

A tap hole is a hole drilled radially in the wall of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

1.5.2.2 Flange Taps

Flange taps are a pair of tap holes positioned as follows (see Figure 1-2):

a. The upstream tap center is located 1 inch (25.4 millimeters) upstream of the nearest plate face.
b. The downstream tap center is located 1 inch (25.4 millimeters) downstream of the nearest plate face.

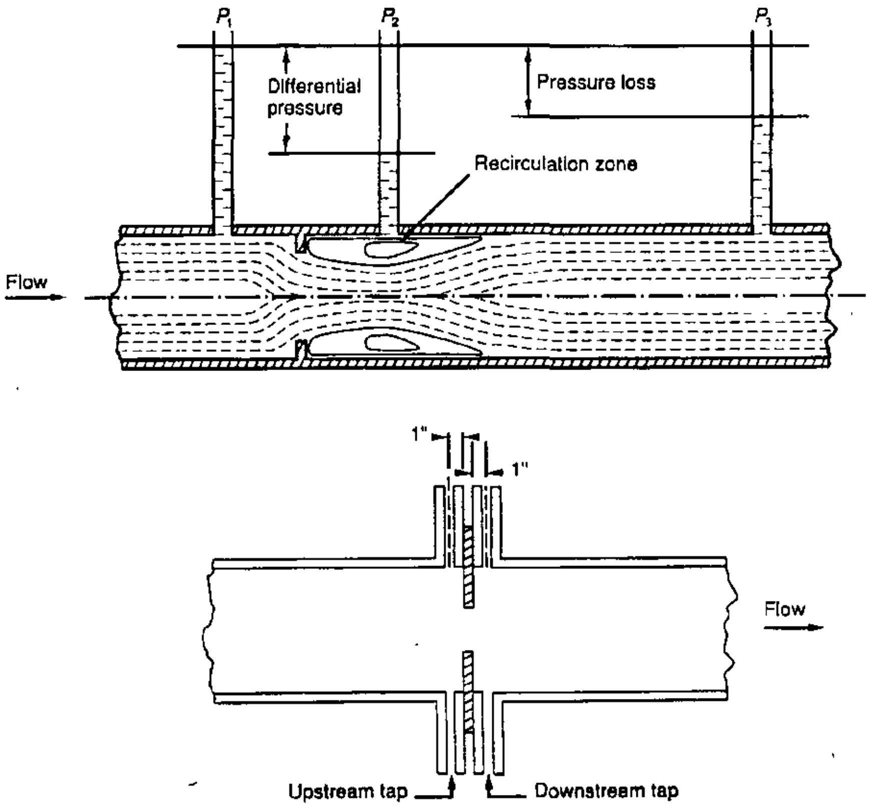
1.5.2.3 Differential Pressure (ΔP)

The differential pressure (ΔP) is the static pressure difference measured between the upstream and downstream flange taps.

1.5.2.4 Static Pressure (P_f)

The static pressure (P_f) is the absolute flowing fluid pressure measured at one of the flange tap holes. The absolute pressure may be measured directly or can be obtained by adding local barometric pressure to measured gauge pressure:

Absolute static pressure = Gauge static pressure + Local barometric pressure



FLANGE-TAPPED ORIFICE METER

Figure 1-2—Orifice Tapping Location

1.5.3 TEMPERATURE MEASUREMENT (T_f)

The temperature is the flowing fluid temperature (T_f) measured at the designated upstream or downstream location, as specified in Chapter 14.3, Part 2.

In flow measurement applications where the fluid velocity is well below sonic, it is common practice to insert a temperature sensing device in the middle of the flowing stream to obtain the flowing temperature. For practical applications, the sensed temperature is assumed to be the static temperature of the flowing fluid.

The use of flowing temperature in this part of the standard requires the temperature to be measured in degrees Fahrenheit or degrees Celsius. However, if the flowing temperature is used in an equation of state to determine the density of the flowing fluid, it may require that the Fahrenheit or Celsius values be converted to absolute temperature values of degrees Rankine or kelvins through the following relationships:

$$°R = °F + 459.67$$

$$K = °C + 273.15$$

1.5.4 FLOW RATE DETERMINATION

1.5.4.1 Orifice Flow Rate (q_m, q_v, Q_v)

The orifice flow rate is the mass or volume flow through an orifice meter per unit of time.

1.5.4.2 Orifice Plate Coefficient of Discharge (C_d)

The orifice plate coefficient of discharge (C_d) is the ratio of the true flow to the theoretical flow and is applied to the theoretical flow equation to obtain the actual (true) flow.

1.5.4.3 Velocity of Approach (E_v)

The velocity of approach factor (E_v) is a mathematical expression that relates the velocity of the flowing fluid in the orifice meter approach section (upstream meter tube) to the fluid velocity in the orifice plate bore.

1.5.4.4 Expansion Factor (Y)

The expansion factor (Y) is an empirical expression used to correct the flow rate for the reduction in fluid density that a compressible fluid experiences when it passes through the orifice plate bore.

1.5.4.5 Pipe Reynolds Number (Re_D)

The pipe Reynolds number is a dimensionless ratio of forces used to correlate the variations in the orifice plate coefficient of discharge (C_d) with changes in the fluid's properties, flow rate, and orifice meter geometry.

1.5.5 FLUID PHYSICAL PROPERTIES

1.5.5.1 Density ($\rho_{t,p}$, ρ_b)

The flowing fluid density ($\rho_{t,p}$) is the mass per unit volume of the fluid being measured at flowing conditions (T_f, P_f).

The base fluid density (ρ_b) is the mass per unit volume of the fluid being measured at base conditions (T_b, P_b).

1.5.5.2 Absolute Viscosity (μ)

The absolute viscosity (μ) is the measure of a fluid's intermolecular cohesive force's resistance to shear per unit of time.

1.5.5.3 Compressibility (Z)

The compressibility (Z) is an adjustment factor used to account for the deviation from the ideal gas law.

1.5.5.4 Isentropic Exponent (k)

The isentropic exponent (k) is a thermodynamic state property that establishes the relationship between an expanding fluid's pressure and density as the fluid flows through the orifice plate bore.

1.5.6 BASE CONDITIONS (P_b, T_b)

Historically, the flow measurement of some fluids, such as custody transfer and process control, have been stated in volume units at base (reference or standard) conditions of pressure and temperature.

The base conditions for the flow measurement of fluids, such as crude petroleum and its liquid products, whose vapor pressure is equal to or less than atmospheric at base temperature are defined in the United States as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 60.0°F (15.56°C). According to the International Standards Organization, base conditions are defined as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 59.00°F (15.00°C)

For fluids, such as liquid hydrocarbons, whose vapor pressure is greater than atmospheric pressure at base temperature, the base pressure is customarily designated as the equilibrium vapor pressure at base temperature.

The base conditions for the flow measurement of natural gases are defined in the United States as a pressure of 14.73 pounds per square inch absolute (101.560 kilopascals) at a temperature of 60.0°F (15.56°C). According to the International Standards Organization, base conditions are defined as a pressure of 14.696 pounds per square inch absolute (101.325 kilopascals) at a temperature of 59.00°F (15.00°C).

For both liquid and gas applications, these base conditions can change from one country to the next, one state to the next, or one industry to the next. Therefore, it is necessary that the base conditions be identified for standard volumetric flow measurement.

1.5.7 SENSITIVITY COEFFICIENT (S)

In estimating the uncertainty associated with the metering facility, a number of variables must be combined. The mathematical relationships among the variables establish the sensitivity of the metered quantities to each of these variables. As such, each variable that may influence the flow equation has a specific sensitivity coefficient. The derivation of this coefficient is based on a mathematical relationship or estimated from calculations, tables, or curves.

1.5.8 METER FACTOR (MF)

The meter factor (MF) is a number obtained by dividing the quantity of fluid measured by the primary mass flow system by the quantity indicated by the orifice meter during calibration.

1.6 Orifice Flow Equation

The accepted one-dimensional equation for mass flow through a concentric, square-edged orifice meter is stated in Equation 1-1 or 1-2. The derivation is based on conservation of mass and energy, one-dimensional fluid dynamics, and empirical functions such as equations of state and thermodynamic process statements. Any derivation is accurate when all the assumptions used to develop it are valid. As a result, an empirical orifice plate coefficient of discharge is applied to the theoretical equation to adjust for multidimensional viscous fluid dynamic effects. In addition, an empirical expansion factor is applied to the theoretical equation to adjust for the reduction in fluid density that a compressible fluid experiences when it passes through an orifice plate.

The fundamental orifice meter mass flow equation is as follows:

$$q_m = C_d E_v Y(\pi/4)d^2 \sqrt{2g_c \rho_{t,p} \Delta P} \quad (1\text{-}1)$$

Where:

C_d = orifice plate coefficient of discharge.
d = orifice plate bore diameter calculated at flowing temperature (T_f).
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
g_c = dimensional conversion constant.
π = universal constant
= 3.14159.
q_m = mass flow rate.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
Y = expansion factor.

The practical orifice meter flow equation used in this standard is a simplified form that combines the numerical constants and unit conversion constants in a unit conversion factor (N_1):

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \quad (1\text{-}2)$$

Where:

C_d = orifice plate coefficient of discharge.
d = orifice plate bore diameter calculated at flowing temperature (T_f).
ΔP = orifice differential pressure.
E_v = velocity of approach factor.
N_1 = unit conversion factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
Y = expansion factor.

The expansion factor, Y, is included in Equations 1-1 and 1-2 because it is applicable to all single-phase, homogeneous Newtonian fluids. For incompressible fluids, such as water at 60°F (15.56°C) and atmospheric pressure, the empirical expansion factor is defined as 1.0000.

The orifice plate coefficient of discharge, C_d, and the expansion factor, Y, are empirical functions derived from experimental data.

The orifice meter is a mass meter from which a differential pressure signal is developed as a function of the velocity of the fluid as it passes through the orifice plate bore. Manipulation of the density variable in the equation permits calculation of flow rate in either mass or volume units. The volumetric flow rate at flowing (actual) conditions can be calculated using the following equation:

$$q_v = q_m / \rho_{t,p} \quad (1\text{-}3)$$

The volumetric flow rate at base (standard) conditions can be calculated using the following equation:

$$Q_v = q_m / \rho_b \quad (1\text{-}4)$$

The mass flow rate (q_m) can be converted to a volumetric flow rate at base (standard) conditions (Q_v) if the fluid density at the base conditions (ρ_b) can be determined or is specified.

The unit conversion factor, N_1, is defined and presented in 1.11.

1.6.1 VELOCITY OF APPROACH FACTOR (E_v)

The velocity of approach factor, E_v, is calculated as follows:

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \quad (1\text{-}5)$$

And,

$$\beta = d/D \quad (1\text{-}6)$$

Where:

d = orifice plate bore diameter calculated at flowing temperature (T_f).
D = meter tube internal diameter calculated at flowing temperature (T_f).

1.6.2 ORIFICE PLATE BORE DIAMETER (d)

The orifice plate bore diameter, d, is defined as the diameter at flowing conditions and can be calculated using the following equation:

$$d = d_r[1 + \alpha_1(T_f - T_r)] \quad (1\text{-}7)$$

Where:

α_1 = linear coefficient of thermal expansion for the orifice plate material (see Table 1-1).
d = orifice plate bore diameter calculated at flowing temperature (T_f).
d_r = reference orifice plate bore diameter at T_r.
T_f = temperature of the fluid at flowing conditions.
T_r = reference temperature of the orifice plate bore diameter.

Note: α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F (20°C)

The orifice plate bore diameter, d_r, calculated at T_r is the diameter determined in accordance with the requirements contained in Chapter 14.3, Part 2.

1.6.3 METER TUBE INTERNAL DIAMETER (D)

The meter tube internal diameter, D, is defined as the diameter at flowing conditions and can be calculated using the following equation:

$$D = D_r[1 + \alpha_2(T_f - T_r)] \quad (1\text{-}8)$$

Where:

α_2 = linear coefficient of thermal expansion for the meter tube material (see Table 1-1).
D = meter tube internal diameter calculated at flowing temperature (T_f).

Table 1-1—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion (α) U.S. Units (in/in-°F)	Metric Units (mm/mm-°C)
Type 304 and 316 stainless steel[a]	0.00000925	0.0000167
Monel[a]	0.00000795	0.0000143
Carbon steel[b]	0.00000620	0.0000112

Note. For flowing temperature conditions outside those stated above and for other materials, refer to the American Society for Metals *Metals Handbook*.
[a]For flowing conditions between −100°F and +300°F, refer to ASME PTC 19.5.
[b]For flowing conditions between −7°F and +154°F, refer to Chapter 12, Section 2.

D_r = reference meter tube internal diameter at T_r.
T_f = temperature of the fluid at flowing conditions.
T_r = reference temperature of the meter tube internal diameter.

Note. α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F (20°C).

The meter tube internal diameter, D_r, calculated at T_r is the diameter determined in accordance with the requirements contained in Chapter 14.3, Part 2.

1.7 Empirical Coefficient of Discharge

Empirical coefficients of discharge for flange-tapped orifice meters have been determined from experimental data by comparing the measured and theoretical flow rates. A major factor in the definition of the experimental patterns for this orifice research was dynamic similarity. Using Reynolds' Law of Similarity, experimental correlations can be applied to dynamically similar meters.

To accurately predict the coefficient of discharge, C_d(FT), for a flange-tapped orifice meter manufactured to the specifications of this standard, certain parameters concerning the orifice meter and the fluid must be known. The relationships between these functions can be simplified for application to commercial use. In fact, the coefficient of discharge can be shown to depend on a number of parameters, the major ones being the Reynolds number (Re_D), sensing tap location, meter tube diameter (D), and β ratio:

$$C_d = f(Re_D, \text{Sensing tap location}, D, \beta)$$

In 1978, Jean Stolz presented an equation form that correlates the near vicinity taps for orifice meters based on the near field static wall pressure gradient. A complete discussion of the bases of the equation is beyond the scope of this standard. However, the bibliography contained in Appendix 1-A will allow the reader to further explore this technical discussion.

1.7.1 REGRESSION DATA BASE

Working jointly, a group of technical experts from the United States, Europe, Canada, Norway, and Japan have developed an equation using the Stolz linkage form that fits the Regression Data Set more accurately than have previously published equations. The new equation was developed from a significantly larger data base than was previously used for discharge coefficient equation development.

The Regression Data Set consists of data taken on four fluids (oil, water, natural gas, and air) from different sources, 11 different laboratories, on 12 different meter tubes of differing origins and more than 100 orifice plates of differing origins. The data provided a pipe Reynolds number range from accepted turbulent flow of 4000 to 36,000,000 on which to select the best model. The orifice configurations included flange, corner, and radius taps. Nominal pipe sizes investigated were 2, 3, 4, 6, and 10 inches, in compliance with ANSI/API 2530 specifications. Nominal β ratios used in the equation determination were 0.100, 0.200, 0.375, 0.500, 0.575, 0.660, and 0.750.

The bivariate data (C_d, Re_D) were measured in a manner appropriate for the test fluid and laboratory. The method of determining mass flow rate, expansion factor, fluid density, and fluid viscosity varied with the laboratory apparatus and test fluid.

Rather than including possibly erroneous data in the equation regression, the API/GPA/A.G.A. technical experts envisioned two classes of data sets for orifice research—regression and comparison. At a meeting of interested international orifice metering experts in November 1988, it was mutually agreed that the Regression Data Set be defined as follows:

> The Regression Data Set shall consist of those data points contained in the API/GPA and EC discharge coefficient experiments which were performed on orifice plates whose diameter was greater than 0.45 inch (11.4mm) and if the pipe Reynolds number was equal to or greater than 4000 (turbulent flow regime).
>
> Data which does not satisfy these criteria shall be included in the Comparison Data Set.

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Oklahoma State University Data Base (303 flange-tapped points), the 1983 NBS Boulder Experiments, the Foxboro–Columbus–Daniel 1000-Point Data Base, and the Japanese Water Data Base.

The exclusion for orifice bore diameters less than 0.45 inch (11.4 millimeters) was due to the increased uncertainty associated with the relative sharpness of the orifice plate upstream edge.

The Regression Data Set, as defined above, consists of data generated on orifice meters equipped with corner, radius, and flange tappings. The number of regression data points are summarized as follows:

Tapping	No of points
Flange	5,734
Corner	2,298
Radius	2,160
Total	10,192

The empirical data associated with the API/GPA Data Base and the EC Data Base are the highest quality and largest quantity available today.

Detailed information on the experiments, regression data, statistical fit, and other pertinent information may be found in Chapter 14.3, Part 4, or the references contained in Appendix 1-A.

1.7.2 EMPIRICAL COEFFICIENT OF DISCHARGE EQUATION FOR FLANGE-TAPPED ORIFICE METERS

The concentric, square-edged, flange-tapped orifice meter coefficient of discharge, C_d(FT), equation, developed by Reader-Harris/Gallagher (RG), is structured into distinct linkage terms and is considered to best represent the current regression data base. The equation is applicable to nominal pipe sizes of 2 inches (50 millimeters) and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d_r, is greater than 0.45 inch (11.4 millimeters); and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For diameter ratios and pipe Reynolds numbers below the limit stated, refer to 1.12.4.1. The RG coefficient of discharge equation for an orifice meter equipped with flange taps is defined as follows:

$$C_d(\mathrm{FT}) = C_i(\mathrm{FT}) + 0.000511\left[\frac{10^6\beta}{Re_D}\right]^{0.7} + (0.0210 + 0.0049A)\beta^4 C \quad (1\text{-}9)$$

$$C_i(\mathrm{FT}) = C_i(\mathrm{CT}) + Tap\ Term \quad (1\text{-}10)$$

$$C_i(\mathrm{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \quad (1\text{-}11)$$

$$Tap\ Term = Upstrm + Dnstrm \quad (1\text{-}12)$$

$$Upstrm = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \quad (1\text{-}13)$$

$$Dnstrm = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \quad (1\text{-}14)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \quad (1\text{-}15)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4}, 0.0\right) \quad (1\text{-}16)$$

$$M_2 = \frac{2L_2}{1 - \beta} \quad (1\text{-}17)$$

Date of Issue: June 1993
Affected Publication: Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 1, "General Equations and Uncertainty Guidelines" of the *Manual of Petroleum Measurement Standards*, Third Edition, September 1990

ERRATA

On page 1, the last sentence of 1.1.1 should read as follows:

U.S. customary [Inch-Pound (IP)] and International System of Units (SI) units are included.

On page 13, Equations 1-16 and 1-17 should read as follows:

$$M_1 = \max\left(2.8 - \frac{D_r}{N_4},\ 0.0\right) \qquad (1\text{-}16)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (1\text{-}17)$$

On page 14, the nomenclature should read as follows (that is, D_r should be inserted in the list):

Where:

β = diameter ratio
= d/D.
$C_d(FT)$ = coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
$C_i(FT)$ = coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
$C_i(CT)$ = coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f.
D = meter tube internal diameter calculated at T_f.
D_r = meter tube internal diameter at reference temperature, T_r.
e = Napierian constant = 2.71828.
$L_1 = L_2$ = dimensionless correction for the tap location
= N_4/D, for flange taps.
N_4 = 1.0 when D_r is in inches
= 25.4 when D_r is in millimeters.
Re_D = pipe Reynolds number.

$$A = \left[\frac{19{,}000\beta}{Re_D}\right]^{0.8} \quad (1\text{-}18)$$

$$C = \left[\frac{10^6\beta}{Re_D}\right]^{0.35} \quad (1\text{-}19)$$

Where:

β = diameter ratio
= d/D.
$C_d(FT)$ = coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter.
$C_i(FT)$ = coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter.
$C_i(CT)$ = coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f.
D = meter tube internal diameter calculated at T_f.
e = Napierian constant
= 2.71828.
L_1 = dimensionless correction for the tap location
= L_2
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches
= 25.4 when D is in millimeters.
Re_D = pipe Reynolds number.

1.7.3 REYNOLDS NUMBER (Re_D)

The RG equation uses pipe Reynolds number as the correlating parameter to represent the change in the orifice plate coefficient of discharge, C_d, with reference to the fluid's mass flow rate (its velocity through the orifice), the fluid density, and the fluid viscosity.

The pipe Reynolds number can be calculated using the following equation:

$$Re_D = \frac{4\,q_m}{\pi\,\mu\,D} \quad (1\text{-}20)$$

The pipe Reynolds number equation used in this standard is in a simplified form that combines the numerical constants and unit conversion constants:

$$Re_D = \frac{N_2 q_m}{\mu D} \quad (1\text{-}21)$$

For the Reynolds number equations presented above, the symbols are described as follows:

D = meter tube internal diameter calculated at flowing temperature (T_f).
μ = absolute viscosity of fluid.
N_2 = unit conversion factor.
π = universal constant
= 3.14159.
q_m = mass flow rate.
Re_D = pipe Reynolds number.

The unit conversion factor, N_2, for the Reynolds number equations is defined and presented in 1.11.

1.7.4 FLOW CONDITIONS

1.7.4.1 General

The condition of the meter tube, the mating of the piping sections, the ΔP sensing tap holes, the straight lengths of pipe preceding and following the primary element, and so forth, are factors that influence the flowing conditions. Although some factors may be considered insignificant for commercial purposes, flowing conditions can influence field accuracy.

To assure accuracy within the uncertainty stated, certain flow condition limitations must be followed:

a. The flow shall approach steady-state mass flow conditions on fluids that are considered clean, single phase, homogeneous, and Newtonian.
b. The fluid shall not undergo any change of phase as it passes through the orifice.
c. The flow shall be subsonic through the orifice and the meter tube.
d. The Reynolds number shall be within the specified limitations of the empirical coefficients.
e. No bypass of flow around the orifice shall occur at any time.

1.7.4.2 Law of Similarity

The empirical coefficients calculated from the equations in this standard are valid if dynamic similarity exists between the metering installation and the experimental data base. Technically, this approach is termed the Law of Similarity.

Dynamic similarity is the underlying principle for present-day theoretical and experimental fluid mechanics. The principle states that two geometrically similar meters with identical initial flow directions shall display geometrically similar streamlines.

The mechanical specifications for the meter tube, the orifice plate, the orifice flanges or fitting, the differential pressure sensing taps, the upstream and downstream piping requirements, the flow straightener (if applicable), and the thermowell must be adhered to, as stated in the standard, to assure geometric similarity.

Geometric similarity requires that the experimental flow system be a scale model of the field installations. The experimental pattern's design identifies sensitive dimensional regions to explore, measure, and empirically fit. A proper experimental pattern for orifice meters allows the user to extrapolate to larger meter tube diameters without increasing the uncertainty.

Dynamic similarity implies a correspondence of fluid forces between the two metering systems. The Reynolds number is a measure of the ratio of the inertial to viscous forces. For the orifice meter, the inertial to viscous forces are the forces considered significant within the application limitations of this standard. As a result, the Reynolds number is the term that correlates dynamic similarity in all empirical coefficient of discharge equations. In fact, the Reynolds number correlation provides a rational basis for extrapolation of the empirical equation, provided the physics of the fluid does not change. For instance, the physics associated with subsonic flow is not similar to that associated with sonic flow.

For the empirical data base, undisturbed flow conditions (flow pattern and fully developed velocity profile) were achieved through the use of straight lengths of meter tube both upstream and downstream from the orifice and the use of flow straighteners. For both the API/GPA and EC experiments, an undisturbed flow condition was defined as the equivalent of a symmetrical, approximately swirl-free velocity profile located approximately 45 pipe diameters downstream of a Sprenkle flow conditioner, in circular pipes with an average internal surface wall roughness, R_a, of approximately 150 microinches.

1.7.5 PULSATING FLOW

Reliable measurements of flow cannot be obtained with an orifice meter when appreciable pulsations are present at the point of measurement. Currently, no satisfactory theoretical or empirical adjustment for orifice measurement in pulsating flow applications exists that, when applied to custody transfer measurement, will maintain the measurement accuracy predicted by this standard.

1.7.5.1 Sources

Pulsations in a pipeline, originating from a reciprocating device, a rotary device, valve actions, piping configuration, or another similar source, consist of sudden changes in the velocity, pressure, and density of the fluid flowing. The most common sources of pulsation are the following:

a. Reciprocating compressors, engines, or impeller-type boosters.
b. Pumping or improperly sized pressure regulators and loose or worn valves.
c. Irregular movement of quantities of water or oil condensates in the line.
d. Intermitters on wells, automatic drips, or separator dumps.
e. Dead-ended piping tee junctions and similar cavities.

1.7.5.2 Pulsation Reduction

To obtain reliable measurements, it is necessary to suppress pulsation. In general, the following practices have been effective in diminishing pulsation and/or its effect on orifice flow measurement:

a. Locating the meter tube in a more favorable location with regard to the source of the pulsation, such as the inlet side of regulators, or increasing the distance from the source of the pulsation.
b. Inserting capacity tanks (volume), flow restrictions, or specially designed filters in the line between the source of pulsation and the meter tube to reduce the amplitude of the pulsation.
c. Using short-coupled impulse tubing and/or manifolds of approximately the same size as the pressure taps to the differential pressure measurement instrument.
d. Operating at differentials as high as is practicable by replacing the orifice plate in use with a smaller orifice bore plate or by concentrating flow in a multiple meter tube installation through a limited number of tubes.
e. Using smaller sized meter tubes and keeping essentially the same orifice diameter while maintaining the highest practical limit of the differential pressure.

Considerable study and experimentation have been conducted to evaluate the requirements and methods necessary to achieve pulsation reduction. This material is outside the scope of this standard and may be found in many publications that are readily available.

1.7.5.3 Pulsation Instruments

Instruments, both mechanical and electronic, have been developed that indicate the presence of pulsation. These devices are used to determine the effectiveness of pulsation suppression practices.

1.8 Empirical Expansion Factor (Y) for Flange-Tapped Orifice Meters

Expansibility research on water, air, steam, and natural gas using orifice meters equipped with various sensing taps is the basis for the present expansion factor equation. The empirical research compared the flow for an incompressible fluid with that of several compressible fluids.

The expansion factor, Y, was defined as follows:

$$Y = \frac{C_{d_1}}{C_{d_2}} \quad (1\text{-}22)$$

Where:

C_{d_1} = coefficient of discharge from compressible fluids tests.
C_{d_2} = coefficient of discharge from incompressible fluids tests.

Buckingham derived the empirical expansion factor equations for orifice meters equipped with various sensing taps based on the following correlation:

$$Y = f(\beta, k, x) \tag{1-23}$$

Where:

β = diameter ratio (d/D).
k = isentropic exponent.
x = ratio of differential pressure to absolute static pressure.

Compressible fluids expand as they flow through a square-edged orifice. For practical applications, it is assumed that the expansion follows a polytropic, ideal, one-dimensional path.

This assumption defines the expansion as reversible and adiabatic (no heat gain or loss). Within practical operating ranges of differential pressure, flowing pressure, and temperature, the expansion factor equation is insensitive to the value of the isentropic exponent. As a result, the assumption of a perfect or ideal isentropic exponent is reasonable for field applications. This approach was adopted by Buckingham and Bean in their correlation. They empirically developed the upstream expansion factor (Y_1) using the downstream temperature and upstream pressure.

Within the limits of this standard's application, it is assumed that the temperatures of the fluid at the upstream and downstream differential sensing taps are identical for the expansion factor calculation.

The application of the expansion factor is valid as long as the following dimensionless pressure ratio criteria are followed:

$$0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.20$$

Or,

$$0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0$$

Where:

ΔP = orifice differential pressure.
N_3 = unit conversion factor.
P_f = absolute static pressure at the pressure tap.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.

Although use of the upstream or downstream expansion factor equation is a matter of choice, the upstream expansion factor is recommended because of its simplicity. If the upstream expansion factor is chosen, then the determination of the flowing fluid compressibility should be based on the upstream absolute static pressure, P_{f_1}. Likewise, if the downstream expansion factor is selected, then the determination of the flowing fluid compressibility should be based on the downstream absolute static pressure, P_{f_2}.

The expansion factor equation for flange taps is applicable over a β range of 0.10–0.75.

1.8.1 UPSTREAM EXPANSION FACTOR (Y_1)

The upstream expansion factor requires determination of the upstream static pressure, the diameter ratio, and the isentropic exponent.

If the absolute static pressure is taken at the upstream differential pressure tap, then the value of the expansion factor, Y_1, shall be calculated as follows:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{k} \quad (1\text{-}24)$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \quad (1\text{-}25)$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \quad (1\text{-}26)$$

Where:

ΔP = orifice differential pressure.
k = isentropic exponent.
N_3 = unit conversion factor.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_1/k = upstream acoustic ratio.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.

1.8.2 DOWNSTREAM EXPANSION FACTOR (Y_2)

The downstream expansion factor requires determination of the downstream static pressure, the upstream static pressure, the downstream compressibility factor, the upstream compressibility factor, the diameter ratio, and the isentropic exponent. The value of the downstream expansion factor, Y_2, shall be calculated using the following equation:

$$Y_2 = Y_1\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \quad (1\text{-}27)$$

Or,

$$Y_2 = \left[1 - (0.41 + 0.35\beta^4)\frac{x_1}{k}\right]\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \quad (1\text{-}28)$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \quad (1\text{-}29)$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \quad (1\text{-}30)$$

Where:

ΔP = orifice differential pressure.
k = isentropic exponent.
N_3 = unit conversion factor.
P_{f_1} = absolute static pressure at the upstream pressure tap.
P_{f_2} = absolute static pressure at the downstream pressure tap.

x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_1/k = upstream acoustic ratio.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
Y_2 = expansion factor based on the absolute static pressure measured at the downstream tap.
Z_{f_1} = fluid compressibility at the upstream pressure tap.
Z_{f_2} = fluid compressibility at the downstream pressure tap.

1.9 In-Situ Calibration

1.9.1 GENERAL

The statement of the uncertainty of the empirical coefficient of discharge for concentric, square-edged orifice meters, C_d, is predicated on compliance with the requirements of this standard.

For accurate measurement applications, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. Deviations from the standard's specifications (for example, eccentricity, steps between adjacent sections of pipe, prerun lengths with or without a flow conditioner, post-run lengths, and pipe wall roughness) will invalidate the uncertainty statement.

To assure the accuracy of such flow measurements, the user may wish to calibrate the meter in situ. This is particularly suggested for orifice meters under 2 inches (50 millimeters) nominal pipe size. *In situ* is defined as being under normal operating conditions, with the actual approach piping configuration, using the actual fluid with the actual orifice plate and recording system in place.

Calibration of an orifice meter in situ requires the use of a primary mass flow system. This primary mass flow system may be portable or permanently installed. A master meter that has been calibrated with a primary mass flow standard can also be used for in-situ calibration.

The in-situ calibration should be performed with a primary mass flow system (or master meter) with an overall uncertainty less than the overall uncertainty of q_{m_i} of the meter being calibrated. Refer to the working uncertainty equation given in 1.12.

To perform an in-situ calibration, the primary mass flow system (or master meter) should be installed either upstream or downstream of the pipe fitting nearest to the meter tube or meter tube manifold so that it provides a calibration of the meter in its normal flowing configuration (that is, velocity profile). In-situ calibration should be performed at the normal flow rate, temperature, and pressure of the meter station. Additionally, in-situ calibration may be performed over the range of flow rates, temperatures, and pressures to assure a higher confidence level over the complete range of flowing conditions.

1.9.2 METER CORRECTION FACTOR

The in-situ calibration can provide a meter factor (MF) that may be used to correct the calculated mass flow rate as determined by Equation 1-1, if agreed upon by the parties. The MF is defined as follows:

$$MF = \frac{q_{m_p}}{q_{m_i}} = \frac{q_{m_p}}{q_{v_i}\rho_{t,p}} \tag{1-31}$$

Where:

q_{m_p} = mass flow rate determined by the primary mass flow system (or master meter).
q_{m_i} = mass flow rate indicated by the orifice meter being calibrated.
q_{v_i} = volumetric flow rate indicated by the orifice meter being calibrated.
$\rho_{t,p}$ = density (mass) of fluid at the meter at flowing conditions.

Alternatively, the results may be used to identify installations that exceed the uncertainty estimated using 1.12. If the MF falls outside the $0.9 \leq MF \leq 1.1$ limits, the system should be investigated until the physical cause for the deviation has been identified and corrected.

When the meter factors are determined over a range of operating conditions, several values of MF may result. A plot of MF versus pipe Reynolds number (Re_D) should provide a single curve that may be used for determining MF corrections.

If the MF is applied to the metered quantities for custody transfer purposes, then in-situ calibration should be periodically repeated to ensure accurate measurement. Additional in-situ calibrations should be performed when physical changes to the metering system or significantly different operating conditions are encountered.

1.10 Fluid Physical Properties

Certain fluid physical properties are required to solve the orifice flow equation.

For the mass flow equation, the following fluid properties are required:

a. The viscosity at flowing conditions, μ.
b. The fluid density at flowing conditions, $\rho_{t,p}$.
c. The isentropic exponent, k, for compressible fluids.

For the standard volumetric flow equation, the density at base conditions, ρ_b, is required for solution.

1.10.1 VISCOSITY (μ)

The absolute (or dynamic) viscosity of the fluid at flowing conditions is required to compute the pipe Reynolds number. Fluid viscosities may be measured experimentally or computed from empirical equations.

For high Reynolds number applications, viscosity variations are usually ignored, since a sensitivity analysis indicates negligible effect in the flow computation. For low Reynolds number applications, accurate viscosity values and their variation with composition, temperature, and pressure may have a significant affect on the flow computation.

1.10.2 DENSITY ($\rho_{t,p}$, ρ_b)

Appropriate values for the density of the fluid, $\rho_{t,p}$ and ρ_b, can be obtained using one of two methods:

a. Empirical density correlation. The empirical density value may be calculated by an equation of state or another technically qualified expression.
b. On-line density meters. An on-line density meter can measure the fluid density at operating conditions (or base conditions).

For on-line density meter applications where the density at flowing conditions (or base conditions) is greater than 0.30 gram per cubic centimeter, refer to Chapter 14.6 for the installation, operation, and calibration of these devices.

For on-line density meter applications where the density at flowing conditions (or base conditions) is less than 0.30 gram per cubic centimeter, refer to the manufacturers' recommendations for the installation, operation, and calibration of these devices. The manufacturer should be able to demonstrate that operation of the on-line density measurement device will not interfere with the basic operation of the orifice meter.

From a practical standpoint, the fluid temperature differences between the upstream sensing tap, the downstream sensing tap, and the temperature sensing device are assumed to be insignificant when the temperature device is installed as required in Chapter 14.3, Part 2. For fluids whose density changes rapidly with changes in flowing temperature, for low fluid velocities, and/or to minimize ambient temperature and heat transfer effects, the user may wish to thermally insulate the meter tube between the primary element and the temperature device.

1.10.3 ISENTROPIC EXPONENT (k)

The isentropic exponent, k, is required in the solution of the empirical expansion factor (Y) equation.

As a compressible fluid flows through the reduced area of an orifice plate bore, it undergoes a contraction and then an expansion. The expansion, which results in a change in the static pressure, is assumed to follow a polytropic path expressed by the following relationship:

$$\frac{P_f}{\left[\rho_{t,p}\right]^n} = \text{Constant} \tag{1-32}$$

Where:

P_f = absolute static pressure.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
n = polytropic exponent.

However, if the expansion is assumed to be relatively rapid (that is, short in length) and the pressure change relatively small in magnitude, the polytropic relationship can be replaced by an idealized (reversible and adiabatic) one-dimensional isentropic expansion relationship of the following form:

$$\frac{P_f}{\left[\rho_{t,p}\right]^k} = \text{Constant} \tag{1-33}$$

Where:

P_f = absolute static pressure.
$\rho_{t,p}$ = density of the fluid at flowing conditions (P_f, T_f).
k = isentropic exponent.

The real compressible fluid isentropic exponent, k_r, is a function of the fluid and the pressure and temperature. For an ideal gas, the isentropic exponent, k_i, is equal to the ratio of its specific heats (c_p/c_v) and is independent of pressure. A perfect gas is an ideal gas that has constant specific heats. The perfect gas isentropic exponent, k_p, is equal to k_i evaluated at base conditions. It has been found that for many applications, the value of k_r, is nearly identical to the value of k_i, which is nearly identical to k_p. From a practical standpoint, the flow equation is not particularly sensitive to small variations in the isentropic exponent. Therefore, the perfect gas isentropic exponent, k_p, is often used in the flow equations. This greatly simplifies the calculations. This approach was adopted by Buckingham in his correlation for the expansion factor.

1.11 Unit Conversion Factors

1.11.1 ORIFICE FLOW EQUATION

The values for the unit conversion factor, N_1, for the orifice flow rate equation are summarized in Table 1-2. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.2 REYNOLDS NUMBER EQUATION

The values for the unit conversion factor, N_2, for the Reynolds number equation are summarized in Table 1-3. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.3 EXPANSION FACTOR EQUATION

The values for the unit conversion factor, N_3, for the expansion factor equation are summarized in Table 1-4. The table contains common engineering units, along with their corresponding conversion factor value.

1.11.4 FLOW RATE PER UNIT OF TIME CONVERSION

To convert the mass or volume flow rate per unit of time to another unit of time, the following multiplication factors are applicable:

From	To	Multiplying Factor
Units per second	Units per minute	60
Units per second	Units per hour	3,600
Units per second	Units per day	86,400

Table 1-2—Orifice Flow Rate Equation: Unit Conversion Factor (N_1)

Mass Rate

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}$$

Volumetric Rate at Flowing (Actual) Conditions

$$q_v = \frac{q_m}{\rho_{t,p}} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_{t,p}}$$

Volumetric Rate at Base Conditions

$$Q_v = \frac{q_m}{\rho_b} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_b}$$

Where:

	IP Units	SI Units	
π	3.141593	3.141593	Universal constant
g_c	32.1740	NA	lbm-ft/(lbf-sec²)
g_c	NA	1.0000	kg·m/(N·sec²)
d	Feet	Meters	
ΔP	lbf/ft²	Pa	
$\rho_{t,p}$	lbm/ft³	kg/m³	
ρ_b	lbm/ft³	kg/m³	
q_m	lbm/sec	kg/sec	
q_v	ft³/sec	m³/sec	
Q_v	Sft³/sec	Nm³/sec	
N_1	6.30025 E+00 6.30025	1.11072 E+00 1.11072	

	U.S. Units	U.S. Units	U.S. Units	Metric Units	Metric Units	
π	3.14159	3.14159	3.14159	3.14159	3.14159	Universal constant
g_c	32.1740	32.1740	32.1740	NA	NA	lbm-ft/ (lbf-sec²)
g_c	NA	NA	NA	1.0000	1.0000	kg·m/ (N·sec²)
d	Inches	Inches	Inches	Millimeters	Millimeters	
ΔP	lbf/in²	in H_2O_{60}	in H_2O_{68}	Millibar	kPa	
$\rho_{t,p}$	lbm/ft³	lbm/ft³	lbm/ft³	kg/m³	kg/m³	
ρ_b	lbm/ft³	lbm/ft³	lbm/ft³	kg/m³	kg/m³	
q_m	lbm/sec	lbm/sec	lbm/sec	kg/sec	kg/sec	
q_v	ft³/sec	ft³/sec	ft³/sec	m³/sec	m³/sec	
Q_v	Sft³/sec	Sft³/sec	Sft³/sec	Nm³/sec	Nm³/sec	
N_1	5.25021 E–01 0.525021	9.97424 E–02 0.0997424	9.97019 E–02 0.0997019	3.51241 E–04 0.000351241	3.51241 E–05 0.0000351241	

Table 1-3—Reynolds Number Equation: Unit Conversion Factor (N_2)

$$Re_D = \frac{4q_m}{\pi\mu D} \quad \text{or} \quad Re_D = \frac{N_2 q_m}{\mu D}$$

Where:

	IP Units	SI Units	
q_m	lbm/sec	kg/sec	
π	3.14159	3.14159	Universal constant
μ	lbm/ft-sec	kg/m sec	SI Unit equal to Pa-sec
D	Feet	Meters	
N_2	1.27324 E+00 1.27324	1.27324 E+00 1.27324	

	U.S. Units	U.S. Units	Metric Units	Metric Units	
q_m	lbm/sec	lbm/sec	kg/sec	kg/sec	
π	3.14159	3.14159	3.14159	3.14159	Universal constant
μ	Centipoise	Poise	Centipoise	Poise	
D	Inches	Inches	Millimeters	Millimeters	
N_2	2.27375 E+04 22,737.5	22.7375 E+01 227.375	1.27324 E+06 127,324	1.27324 E+04 12,732.4	

1.12 Practical Uncertainty Guidelines

The most important assumption underlying the calculation of the orifice discharge coefficient equation is that laboratories' systematic equipment biases are randomized within the data base. This means that there is no bias in the equation's ability to represent reality due to equipment variety in the various laboratories. Such an assumption of randomization has precedent in ISO 5168, established in 1978, and a 1939 paper by Rossini and Deming. This allows the use of results from the world's finest laboratories without requiring that experimental equipment be identical.

Table 1-4—Empirical Expansion Factor Equation: Unit Conversion Factor (N_3)

$$x = \frac{\Delta P}{N_3 P}$$

	IP Units	SI Units
ΔP	lbf/ft^2	Pascals
P	lbf/ft^2	Pascals
N_3	1.00000 E+00 1.00000	1.00000 E+00 1.00000

	U.S. Units	U.S. Units	U.S. Units
ΔP	lbs/in^2	in H_2O_{60}	in H_2O_{68}
P	lbs/in^2	lbs/in^2	lbs/in^2
N_3	1.00000 E+00 1.00000	2.77070 E+01 27.7070	2.77300 E+01 27.7300

	Metric Units	Metric Units	Metric Units
ΔP	Kilopascals	Millibar	Millibar
P	Megapascals	Bar	Megapascals
N_3	1.00000 E+03 1000.00	1.00000 E+03 1000.00	1.00000 E–02 0.0100000

Every effort has been made to remove residual bias from the representation of the experimental data by the equation for mass flow. Consequently, the subsequent precision statements are valid for an individual orifice meter installation for which physical characteristics and measurements of these characteristics are maintained within the precision that is used to determine the contributions to imprecision in mass flow measurement caused by various factors.

In accordance with prudent statistical and engineering practice, the estimated orifice flow rate uncertainty shall be calculated at the 95-percent confidence level.

1.12.1 GENERAL

Many factors associated with an orifice installation influence the overall error in flow measurement. These errors are due to uncertainties about the following:

a. Representation of reality by the mass flow equation.
b. Uncertainty about actual physical properties of the fluid being measured.
c. Imprecision in the measurement of important installation parameters (such as orifice diameter and β ratio)

Examples of the calculations of the overall uncertainty as it depends on these major categories are given below. For ease of understanding, graphical summaries are presented where feasible.

1.12.2 UNCERTAINTY OVER A FLOW RANGE

From a practical standpoint, the accuracy envelope for an orifice meter is usually estimated using the uncertainty assigned to the differential pressure sensing device. This technique realistically estimates the uncertainty associated with the designer's flow range.

An accuracy envelope incorporates the influence quantities associated with the ΔP sensing device. The significant quantities include ambient temperature effects, static pressure effects, long-term drift, hysteresis, linearity, repeatability, and the calibration standard's uncertainty.

For some applications, parallel orifice meters are required to meet the user's desired uncertainty and rangeability. In addition, the designer may choose to install stacked ΔP devices calibrated for different ranges to minimize uncertainty while maximizing rangeability for a given orifice plate, as shown in Figure 1-3.

1.12.3 UNCERTAINTY OF FLOW RATE

The overall uncertainty is the quadrature sum (square root of the sum of the squares) of the uncertainties associated with the pertinent variables:

$$q_m = f(C_d, Y, \Delta P, d, D, \rho_{t,p})$$

For practical considerations, the pertinent variables are assumed to be independent to provide a simpler uncertainty calculation. In fact, no significant change in the uncertainty estimate will occur if the user applies the simplified uncertainty equations presented below.

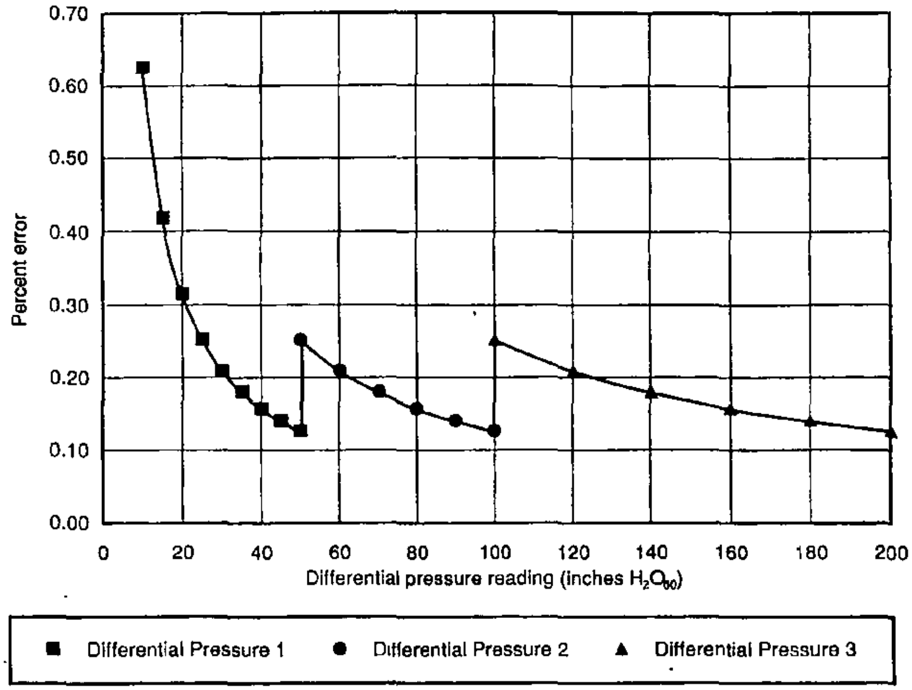
The total uncertainty of the flow rate through an orifice meter may be calculated by one of two methods:

a. Empirical coefficient of discharge using flange-tapped orifice meters.
b. In-situ calibration using orifice meters.

1.12.3.1 Uncertainty Using Empirical Coefficient of Discharge for Flange-Tapped Orifice Meter

The basic flow equation used is as follows:

$$q_m = C_d E_v Y (\pi / 4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P}$$



Note: The precision of the differential pressure device used in this example is ±0.25 percent of full scale.

Figure 1-3—Contribution to Flow Error due to Differential Pressure Instrumentation

Where:

E_v = velocity of approach factor

$$= \frac{1}{\sqrt{1-\beta^4}}.$$

β = diameter ratio (d/D).

Using differentiation, one can show that

$$(\delta q_m / q_m) = S_{C_d}(\delta C_d / C_d) + S_{E_v}(\delta E_v / E_v) + S_Y(\delta Y / Y) + S_d(\delta d / d)$$
$$+ S_{\rho_{t,p}}(\delta \rho_{t,p} / \rho_{t,p}) + S_{\Delta P}(\delta \Delta P / \Delta P) \qquad (1\text{-}34)$$

Where:

S = sensitivity coefficient of the particular variable.

Therefore,

$$S_{C_d} \text{ and } S_Y = 1.0$$

And,

$$S_d = 2$$
$$S_{\rho_{t,p}} = \tfrac{1}{2}$$
$$S_{\Delta P} = \tfrac{1}{2}$$

By continuing this process to put $\delta E_v/E_v$ in terms of $\delta d/d$ and $\delta D/D$, it can be shown that

$$(\delta E_v / E_v) = \frac{2\beta^4}{1 - \beta^4}[(\delta d / d) - (\delta D / D)] \quad (1\text{-}35)$$

Assuming that independent estimates are available for $\delta C_d/C_d$, $\delta Y/Y$, $\delta d/d$, and $\delta D/D$ and substituting for $\delta E_v/E_v$ gives us the following working equation for the uncertainty of the mass flow rate:

$$(\delta q_m / q_m) = \left\{(\delta C_d / C_d)^2 + (\delta Y / Y)^2 + \left[\frac{2}{1 - \beta^4}\right]^2 (\delta d / d)^2 + \left[\frac{-2\beta^4}{1 - \beta^4}\right]^2 (\delta D / D)^2 + \tfrac{1}{4}(\delta \rho_{t,p} / \rho_{t,p})^2 + \tfrac{1}{4}(\delta \Delta P / \Delta P)^2\right\}^{0.5} \quad (1\text{-}36)$$

1.12.3.2 Uncertainty Using an In-Situ Calibration

When the orifice meter has been calibrated in situ, the practical working formula for the uncertainty of the mass flow rate can be expressed as follows:

$$(\delta q_m / q_m) = \left[(\delta \mathrm{MF} / \mathrm{MF})^2 + \tfrac{1}{4}(\delta \Delta P / \Delta P)^2 + \tfrac{1}{4}(\delta \rho_{t,p} / \rho_{t,p})^2\right]^{0.5} \quad (1\text{-}37)$$

The meter factor (MF) term is estimated from the combination of the primary mass flow uncertainty, the master meter uncertainty, and the precision of the orifice meter calibration. Note that the meter factor (MF) determined for the orifice plate and tube is a combination of several possible errors. No additional uncertainty is necessary for installation conditions or expansion factor.

1.12.4 TYPICAL UNCERTAINTIES

For precise metering applications, such as custody transfer, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. In the following sections, the typical uncertainties expressed can be obtained only through compliance with the specifications of the standard.

1.12.4.1 Empirical Coefficient of Discharge

The estimated uncertainty of the empirical coefficient of discharge for concentric, square-edged, flange-tapped orifice meters that are in compliance with this standard is a function of the Reynolds number and the diameter ratio (β). At very high Reynolds numbers the uncertainty is only a function of the diameter ratio (β). This uncertainty estimate is shown graphically in Figure 1-4. As the Reynolds number decreases, the uncertainty of the orifice plate coefficient of discharge increases. The ratio of the uncertainty at a given Reynolds number to the uncertainty at infinite Reynolds number is shown graphically in Figure 1-5. The overall uncertainty of the empirical coefficient of discharge is the product of the value read from Figure 1-4 and the value read from Figure 1-5. The values for Figure 1-4 may be approximated by the following:

For $\beta > 0.175$,

$$\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT}) = 0.5600 - 0.2550\beta + 1.9316\beta^8 \quad (1\text{-}38)$$

For $\beta \leq 0.175$,

$$\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT}) = 0.7000 - 1.0550\beta \quad (1\text{-}39)$$

The values for Figure 1-5 may be approximated by the following:

$$\delta C_d(\mathrm{FT}) / \delta C_i(\mathrm{FT}) = 1 + 1.7895\left(\frac{4000}{Re_D}\right)^{0.8} \quad (1\text{-}40)$$

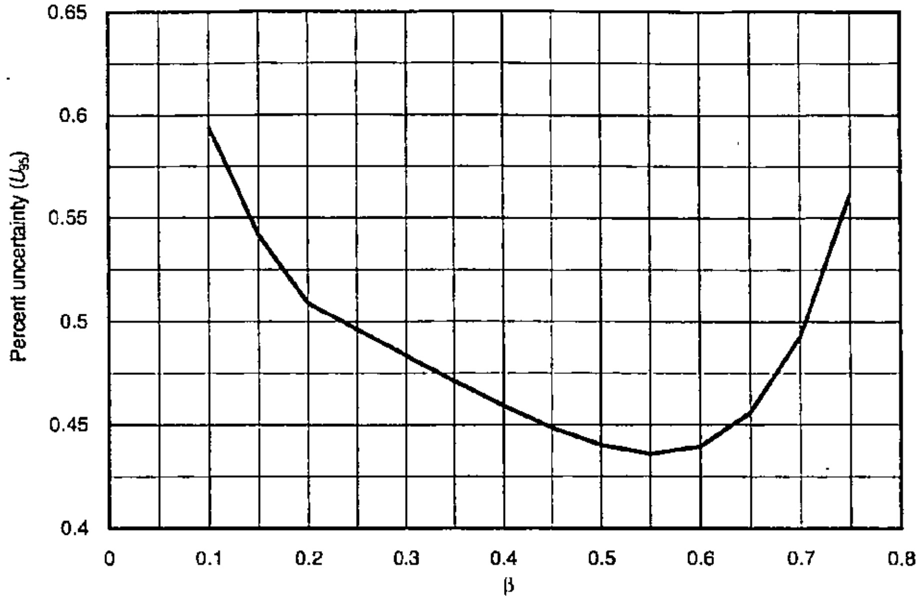


Figure 1-4—Empirical Coefficient of Discharge: Uncertainty at Infinite Reynolds Number

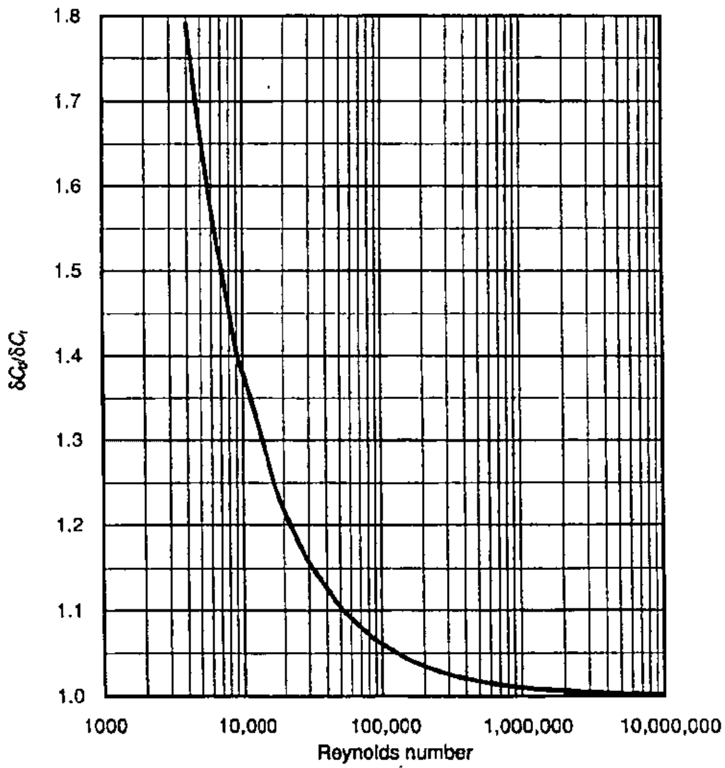


Figure 1-5—Relative Change in Uncertainty: Dependence on Reynolds Number

These estimates for the uncertainty were developed using the regression data base discussed in 1.7.1. Orifice plates with bore diameters less than 0.45 inch (11.4 millimeters), installed according to Chapter 14.3, Part 2, may have coefficient of discharge [C_d(FT)] uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness. These types of problems are discussed further in Chapter 14.3, Part 2. Deviations from the installation specifications in Chapter 14.3, Part 2, will invalidate this uncertainty statement.

1.12.4.2 Empirical Expansion Factor for Flange–Tapped Orifice Meters

The values of Y computed by the empirical equations are subject to a tolerance varying from 0, when $x = 0$, to ± 0.5 percent, when $x = 0.2$. For larger values of x, a somewhat larger uncertainty may be expected.

An alternative approach for determining the uncertainty for the expansion factor, which has been proposed in the international community, stipulates that when β, ΔP, P_f, and k are assumed to be known without error, the percentage uncertainty of the value of Y is estimated by

$$\pm 4\left[\frac{\Delta P}{N_3 P_f}\right] \text{ when } \beta \le 0.750$$

The expansion factor uncertainty is presented in Table 1-5. For fluids that are not compressible, the expansion factor equals 1.000 by definition, and the estimated uncertainty is zero.

Table 1-5—Uncertainty Statement for Empirical Expansion Factor

		Common U.S. Units							
		Expansion Factor Uncertainty (%) When P_f (psia) Equals							
ΔP (inches H_2O_{60})	psid	50	100	250	500	750	1000	1250	1500
10	0.36	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	1.80	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	3.61	0.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	5.41	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	7.22	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	9.02	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	10.83	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03
		Common SI Units							
		Expansion Factor Uncertainty (%) When P_f (MPa) Equals							
ΔP (inches H_2O_{60})	kPa	0.3	0.7	1.7	3.4	5.2	6.9	8.6	10.3
10	2.49	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
50	12.44	0.14	0.07	0.03	0.01	0.01	0.01	0.01	0.00
100	24.88	0.29	0.14	0.06	0.03	0.02	0.01	0.01	0.01
150	37.33	0.43	0.22	0.09	0.04	0.03	0.02	0.02	0.01
200	49.77	0.58	0.29	0.12	0.06	0.04	0.03	0.02	0.02
250	62.21	0.72	0.36	0.14	0.07	0.05	0.04	0.03	0.02
300	74.65	0.87	0.43	0.17	0.09	0.06	0.04	0.03	0.03

Notes:
1. Orifice plates having bore diameters less than 0.45 inch (11.4 millimeters), installed according to Chapter 14 3, Part 2, may have coefficient of discharge (C_d) uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness.
2. The relative uncertainty level depicted in Figure 1-6 assumes a swirl-free inlet velocity profile.

1.12.4.3 Installation Conditions

To assure accurate flow measurement, the fluid should enter the orifice plate with a fully developed flow profile, free from swirl or vortices. Such a condition is best achieved through the use of flow conditioners and adequate lengths of straight pipe preceding and following the orifice plate.

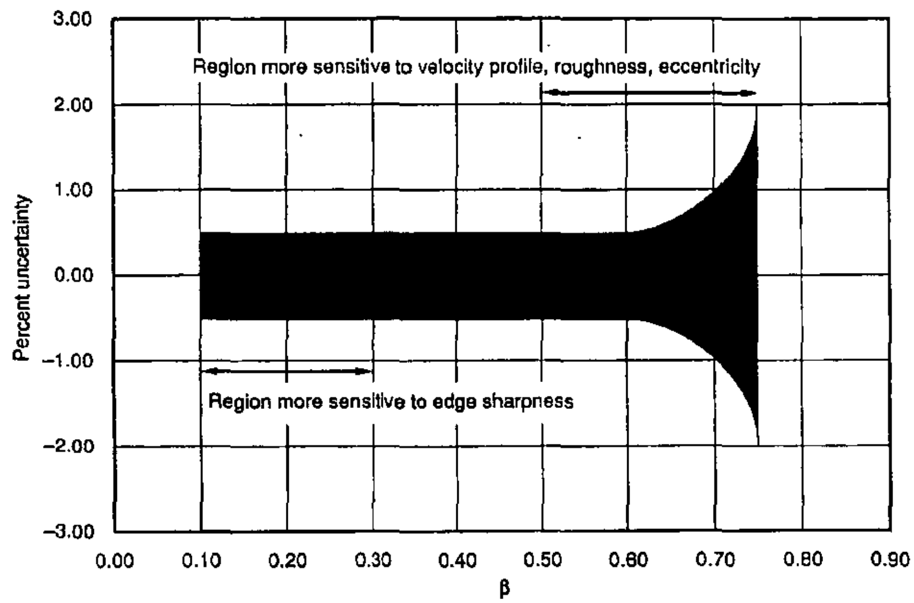
For various technical reasons, the uncertainty associated with installation conditions is difficult to quantify. Therefore, Figure 1-6 has been provided as a general guide. This figure represents a combined practical uncertainty level attributed to the following parameters:

a. Empirical coefficient of discharge.
b. Installation conditions, such as velocity profile and swirl.
c. Mechanical specifications, such as pipe wall roughness, plate eccentricity, and orifice plate bore edge sharpness.

Figure 1-6 depicts the prospective combined uncertainty level as a function of diameter ratio (β). It is apparent from the figure that the lowest relative combined uncertainty levels occur over a diameter ratio range of 0.10–0.60.

The approach length (upstream meter tube), piping configuration, and flow conditioning recommendations presented in Chapter 14.3, Part 2, are essentially unchanged from the second (1985) edition of the standard. Substantial research programs in these areas are currently under way by the API, the EC,[4] and the GRI.[5] A restatement of the orifice meter

[4]Commission of the European Communities, rue de la Loi 200, B-1049, Brussels, Belgium.
[5]Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, Illinois 60631.



Notes:
1. Orifice plates whose bore diameters are less than 0.45 inch (11.4 millimeters), installed according to Chapter 14, Section 3, Part 2, may have coefficient of discharge uncertainties as great as 3.0 percent. This large uncertainty is due to problems with edge sharpness.
2. The relative uncertainty level shown in the figure assumes a swirl-free inlet velocity profile.

Figure 1-6—Practical Uncertainty Levels

uncertainty will naturally follow the conclusion of the current research and may offer a basis for future changes in this standard.

1.12.4.4 Orifice Plate Bore Diameter

The plate diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the plate diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

For example, if the four measurements for d_m are 20.005, 20.002, 19.995, and 19.9980, then the mean value is 20.000.

The deviations from the mean are +0.005, +0.002, –0.005, and –0.002, so

$$\delta d_m = \left[\frac{\sum_{i=1}^{n}\left(\delta d_{m_i}\right)^2}{n-1}\right]^{0.5}$$

$$= \pm\left[\frac{(0.005)^2 + (0.002)^2 + (-0.005)^2 + (-0.002)^2}{3}\right]^{0.5}$$

$$= \pm 0.0044$$

$$\frac{\delta d_m}{d_m} = \pm\frac{0.0044}{20.00}$$

$$= \pm 0.00022 \times 100$$

$$= \pm 0.022 \text{ percent} \qquad (1\text{-}41)$$

1.12.4.5 Meter Tube Internal Diameter

The plate diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the plate diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

For example, if the four measurements for D_m are 20.050, 20.020, 19.950, and 19.980, then the mean value is 20.000.

The deviations from the mean are +0.05, +0.02, –0.05, and –0.02, so

$$\delta D_m = \left[\frac{\sum_{i=1}^{n}\left(\delta D_{m_i}\right)^2}{n-1}\right]^{0.5}$$

$$= \pm\left[\frac{(0.05)^2 + (0.02)^2 + (-0.05)^2 + (-0.02)^2}{3}\right]^{0.5}$$

$$= \pm 0.044$$

$$\frac{\delta D_m}{D_m} = \pm\frac{0.044}{20.00}$$

$$= \pm 0.0022 \times 100$$

$$= \pm 0.22 \text{ percent} \qquad (1\text{-}42)$$

1.12.4.6 Differential Pressure Device

Performance specifications for the differential pressure device must be provided by the manufacturer. The user selects a device based on its performance specifications and the desired uncertainty associated with the application.

When considering the uncertainty, care should be taken to take into account the effects of ambient temperature, humidity, static pressure, driving mechanism, and response time on the user-selected device.

1.12.4.7 Fluid Density

When an empirical correlation is used to predict a liquid density, the uncertainty should be estimated based on the stated uncertainty of the correlation and the estimated uncertainty of the variables required to calculate the density. The following example for proplyene, calculated using the method of Chapter 11.3.3.2, demonstrates this procedure.

Proplyene is being metered at 60°F and 800 pounds per square inch absolute. The stated uncertainty of the Chapter 11.3.3.2 method for calculating the density of proplyene is ±0.24 percent. The stated uncertainty of the temperature measurement is ±0.5°F. The stated uncertainty of the pressure measurement is ±4 pounds per square inch absolute. The uncertainty in the density is calculated according to the following formula:

$$(\delta\rho_{t,p}/\rho_{t,p}) = \left\{(\delta\rho_{t,p}/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial T_f}\right]^2_{P_f}(\delta T_f/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial P_f}\right]^2_{T_f}(\delta P_f/\rho_{t,p})^2\right\}^{0.5} \quad (1\text{-}43)$$

Using this method, the following calculated values can be used to estimate $(\partial\rho_{t,p}/\partial T_f)_{P_f}$ and $(\partial\rho_{t,p}/\partial P_f)_{T_f}$:

T_f (°F)	P_f (psia)	Density (lb/ft³)
60	800	33.3413
60	780	33.3215
60	820	33.3611
58	800	33.4445
62	800	33.2376

$$\left[\frac{\partial\rho_{t,p}}{\partial T_f}\right]_{P_f} \cong (33.2376 - 33.4445)/4 = -0.052$$

$$\left[\frac{\partial\rho_{t,p}}{\partial P_f}\right]_{T_f} \cong (33.3611 - 33.3215)/40 = -0.00099$$

Then,

$$\delta\rho_{t,p}/\rho_{t,p} \cong \pm\left[(0.0024)^2 + (-0.052)^2\left(\frac{0.5}{33.3413}\right)^2 + (0.00099)^2\left(\frac{4}{33.3413}\right)^2\right]^{0.5}$$

$$= \pm\left[0.0024^2 + 0.0008^2 + 0.0001^2\right]^{0.5}$$

$$= \pm 0.0025 \text{ or } \pm 0.25 \text{ percent}$$

Therefore, the estimated overall uncertainty in the proplyene density is ±0.25 percent.

When on-line density meters are used, the uncertainty should be estimated based on the calibration technique, density differences between the orifice and density meter locations, and the density meter manufacturer's recommendations.

1.12.5 EXAMPLE UNCERTAINTY CALCULATIONS

Example uncertainty calculations for liquid and gas flows are presented in 1.12.5.1 and 1.12.5.2.

1.12.5.1 Example Uncertainty Estimate for Liquid Flow Calculation

An example of the effect of uncertainties is provided in Table 1-6, using the following flow equation:

Table 1-6—Example Uncertainty Estimate for Liquid Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient	0.45	1.0	0.2025
d	Orifice diameter (Table 2-1)	0.05	$2/(1-\beta^4)$	0.0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1-\beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0.0625
ρ	Density	0.45	0.5	0.0506
Sum of squares				0.3281
Square root of sum of squares				0.5728

Note: As the table shows, the overall liquid flow measurement uncertainty at a 95-percent confidence level is ±0.57 percent.

$$q_m = C_d E_v Y(\pi/4)d^2 \sqrt{2g_c \rho_{t,p} \Delta P}$$

The following assumptions and conditions were selected for the calculation:

a. The fluid flowing is proplyene. The liquid density will be calculated using the Chapter 11.3.3.2 method. The viscosity will be estimated using Procedure 11A5.1 from the API *Technical Data Book—Petroleum Refining*. The expansion factor will be assumed to be 1.0.
b. A 4-inch meter with a β ratio of 0.5, a static pressure of 800 pounds per square inch absolute, a flowing temperature of 60°F, and a differential pressure of 50 inches of water (60°F) is selected for the calculation.
c. For each variable, the uncertainty listed represents random error only.

As a result of the first two assumptions, the estimated values of the required physical properties are as follows:

$\rho_{t,p}$ = 33.3413 lbm/ft³.
$\delta\rho_{t,p}/\rho_{t,p}$ = 0.25 percent (as shown in liquid density sensitivity section).
μ = 0.0956 centipoise = 0.0000643 lbm/ft-sec.

As a result of the calculations for the flow rate,

C_d(FT) = 0.603659.
q_m = 10.148 lbm/sec.
Re_D = 603,400.
δC_i(FT)/C_d(FT) = ±0.44 percent (from Figure 1-4).
δC_d(FT)/δC_i(FT) = 1.02 (from Figure 1-5).

This gives

δC_d(FT)/C_d(FT) = 1.02 × ±0.44 = ±0.45 percent.

1.12.5.2 Example Uncertainty Estimate for Natural Gas Flow Calculation

For natural gas flow, fluid density is defined as follows:

$$\rho_{t,p} = \frac{G_i Mr_{air} P_f}{Z_f R T_f} \quad (1\text{-}44)$$

Where:

G_i = ideal gas relative density (specific gravity) of the gas (Mr_{gas}/Mr_{air}).
Mr_{air} = molar mass of air.
Mr_{gas} = molar mass of the gas.
P_f = static pressure of fluid.

R = universal gas constant.
T_f = temperature of the fluid at flowing conditions.
Z_f = fluid compressibility at flowing conditions.

The fluid density uncertainty term, $\frac{1}{4}(\delta\rho_{t,p}/\rho_{t,p})^2$ in 1.12.3.1 is replaced by the following terms for natural gas application:

$$\left[\tfrac{1}{2}(\delta G_i/G_i)\right]^2 + \left[\tfrac{1}{2}(\delta P_f/P_f)\right]^2 + \left[-\tfrac{1}{2}(\delta Z_f/Z_f)\right]^2 + \left[-\tfrac{1}{2}(\delta T_f/T_f)\right]^2$$

An example of the effect of uncertainties is provided in Table 1-7, using the following gas flow equation:

$$q_m = C_d E_v Y(\pi/4)d^2 \sqrt{2g_c \frac{G_i Mr_{air} P_f}{Z_f R T_f} \Delta P} \qquad (1\text{-}45)$$

The following assumptions and conditions were selected for the calculation:

a. For each variable, the uncertainty listed represents random error only.
b. A 4-inch meter with a β ratio of 0.5 and static and differential pressures equal to 250 pounds per square inch absolute and 50 inches of water, respectively, was selected for the calculation.

Note: The precision of the ΔP device used in this example was ±0.25 percent of full scale.

Table 1-7—Example Uncertainty Estimate for Natural Gas Flow Calculation

		Uncertainty, U_{95}(%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient (Figure 1-4)	0.44	1	0.1936
Y	Expansion factor (Table 1-5)	0.03	1	0.0009
d	Orifice diameter (Table 2-1)	0.05	$2/(1-\beta^4)$	0.0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1-\beta^4)$	0.0110
ΔP	Differential pressure	0.50	0.5	0.0625
P	Static pressure	0.50	0.5	0.0625
Z	Compressibility factor (A.G.A. 8)	0.1	−0.5	0.0025
T	Flowing temperature	0.25	−0.5	0.0156
G	Relative density	0.60	0.5	0.0900
Sum of squares				0.4500
Square root of sum of squares				0.6700

Note: As the table shows, the overall gas flow measurement uncertainty at a 95-percent confidence level is ±0.67 percent.

On page 23, the last line of Table 1-3 should read as follows:

22,737.5 227.375 1,273,240 12,732.4

On page 25, S_E should be added to the following line:

Therefore,

$$S_E, S_{C_d}, \text{ and } S_Y = 1.0$$

On page 26, Equations 1-38 and 1-39 should read as follows:

$$100\,[\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT})] = 0.5600 - 0.2550\beta + 1.9316\beta^8 \quad (1\text{-}38)$$

$$100\,[\delta C_i(\mathrm{FT}) / C_d(\mathrm{FT})] = 0.7000 - 1.0550\beta \quad (1\text{-}39)$$

On page 33, Table 1-7 should read as follows:

Table 1-7—Example Uncertainty Estimate for Natural Gas Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Basic discharge coefficient (Figure 1-4)	0.44	1	0.1936
Y	Expansion factor (Table 1-5)	0.03	1	0.0009
d	Orifice diameter (Table 2-1)	0.05	$2/(1 - \beta^4)$	0.0114
D	Pipe diameter (2.5.1.3)	0.25	$-2\beta^4/(1 - \beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0.0625
P	Static pressure	0.50	0.5	0.0625
Z	Compressibility factor (A.G.A. 8)	0.1	−0.5	0.0025
T	Flowing temperature	0.25	−0.5	0.0156
G	Relative density	0.60	0.5	0.0900
Sum of squares				0.4401
Square root of sum of squares				0.6634

Note: As the table shows, the overall gas flow measurement uncertainty at a 95-percent confidence level is ±0.67 percent.

On page 14, Equation 1-19 should read as follows:

$$C = \left[\frac{10^6}{Re_D}\right]^{0.35}$$

On page 17, the second equation for the dimensionless pressure ratio should read as follows:

$$0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0$$

On page 26, Equation 1-40 should read as follows:

$$\delta C_d(\text{FT}) / \delta C_i(\text{FT}) = 1 + 0.7895\left(\frac{4000}{Re_D}\right)^{0.8}$$

On page 30, the first two paragraphs under 1.12 4.5 should read as follows (that is, the words meter tube *should replace the word* plate*):*

The meter tube diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in Chapter 14.3, Part 2.

If the dimensional measurements are available, the meter tube diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

NOTICE TO USERS OF PART 1

Chapter 14.3, Part 4, "Background; Development, Implementation Procedure, and Subroutine Documentation for Empirical Flange-Tapped Discharge Coefficient Equation" will provide the calculation procedure necessary to obtain uniform answers. Users of Part 1 may find it desirable to obtain Part 4 before attempting to program the equations contained in Part 1.

APPENDIX 1-A—REFERENCES

Note: This appendix is not a part of this standard but is included for informational purposes only.

The following references are pertinent to the discussions contained in Part 1.

1-A.1 Discharge Coefficient Studies

1-A.1.1 API/GPA EXPERIMENTAL PROGRAM

Britton, C. L., Caldwell, S., and Seidl, W., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in White Mineral Oil Over a Low Reynolds Number Range," American Petroleum Institute, Washington, D.C., 1988.

"Coefficients of Discharge for Concentric, Square-Edged, Flange-Tapped Orifice Meters: Equation Data Set—Supporting Documentation for Floppy Diskettes," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J. R., Cleveland, W. G., Baumgarten, G. P., and Woo, S., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in Water Over a Reynolds Number Range of 600 to 2,700,000" (Technical Note 1264), National Institute of Standards and Technology, Washington, D.C., 1989.

1-A.1.2 EC EXPERIMENTAL PROGRAM

Hobbs, J. M., "Experimental Data for the Determination of Basic 100mm Orifice Meter Discharge Coefficients" (Report EUR 10027), Commission of the European Communities, Brussels, 1985.

Hobbs, J. M., "The EEC Orifice Plate Project: Part I. Traceabilities of Facilities Used and Calculation Methods Employed" (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

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1-A.1.3 OSU EXPERIMENTAL PROGRAM

Beitler, S. R., "The Flow of Water Through Orifices" (Bulletin 89), Engineering Experiment Station, Ohio State University, Columbus, 1935.

Fling, W. A., "API Orifice Meter Program" (Paper 83-T-23), *Operating Section Proceedings*, American Gas Association, Arlington, Virginia, 1983, pp. 308–311.

1-A.1.4 EMPIRICAL COEFFICIENT EQUATIONS

Beaty, R. E., Fling, W. A., Gallagher, J. E., Hoglund, P. A., Tessandier, R. G., and West, K. I., "The API/GPA Experimental Data Base," Paper presented at the American Gas Association Distribution/Transmission Conference, New Orleans, May 22–24, 1989.

Gallagher, J. E., "The A.G.A. Report No. 3 Orifice Plate Discharge Coefficient Equation," Paper presented at the Second International Symposium on Fluid Flow Measurement, Calgary, June 6–8, 1990.

Stolz, J., "A Universal Equation for the Calculation of Discharge Coefficient of Orifice Plates," *Flow Measurement of Fluids*, North-Holland, Amsterdam, 1978.

1-A.2 Expansion Factor Studies

Bean, H. S., "Values of Discharge Coefficients of Square-Edged Orifices: Comparison of Results Obtained by Tests Using Gases with Those Obtained by Tests Using Water," *American Gas Association Monthly*, July 1935, Volume 17, p. 259.

Buckingham, E., "Note on Contraction Coefficients for Jets of Gas," *National Bureau of Standards Journal of Research*, May 1931, Volume 6, RP 303, p. 765.

Buckingham, E., "Notes on the Orifice Meter: The Expansion Factor for Gases," *National Bureau of Standards Journal of Research*, July 1932, Volume 9, RP 459, p. 61.

Murdock, J. W., and Folts, C. J., "Experimental Evaluation of Expansion Factors for Steam," *Transactions of the ASME*, July 1953, Volume 75, No. 5, p. 953.

Smith, Jr., Edward S., "Quantity-Rate Fluid Meters" (Paper 719), Paper presented at the World Engineering Congress, Tokyo, 1929.

1-A.3 Conversion Constants

Manual of Petroleum Measurement Standards, Chapter 15, "Guidelines for the Use of the International System of Units (SI) in the Petroleum and Allied Industries" (2nd ed.), American Petroleum Institute, Washington, D.C., December 1980.

1-A.4 Uncertainty Estimation

ASME MFC-2M, *Measurement Uncertainty for Fluid Flow in Closed Conduits*, American Society of Mechanical Engineers, New York, 1988.

ISO 5168, *Measurement Uncertainty for Fluid Flow in Closed Conduits*, International Standards Organization, Geneva, 1978.

Rossini, F. D., and Deming, W. E., *Journal of the Washington Academy of Sciences*, 1939, Volume 29, p. 416.

1–A.5 Material Properties

ASME B46.1, *Surface Texture (Surface Roughness, Waviness and Lay*, American Society of Mechanical Engineers, New York, 1985.

ASME PTC 19.5, *Application, Part II of Fluid Meters: Interim Supplement on Instruments and Apparatus*, American Society of Mechanical Engineers, New York, 1972.

Metals Handbook (Desk Edition), American Society for Metals, Metals Park, Ohio, 1985.

1–A.6 Boundary–Layer Theory

Schlichting, H., *Boundary-Layer Theory* (7th ed.), McGraw-Hill, New York, 1979.

APPENDIX 1-B—DISCHARGE COEFFICIENTS FOR FLANGE-TAPPED ORIFICE METERS

Note: This appendix is not a part of this standard but is included for informational purposes only.

Table 1-B-1—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 2-Inch (50-Millimeter) Meter [D = 1.939 Inches (49.25 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.60014	0.59940	0.59883	0.59873	0.59862	0.59860	0.59858	0.59857	0.59857	0.59857
0.04	0.60102	0.59981	0.59890	0.59873	0.59854	0.59851	0.59847	0.59847	0.59846	0.59846
0.06	0.60178	0.60016	0.59895	0.59872	0.59848	0.59844	0.59839	0.59838	0.59837	0.59837
0.08	0.60248	0.60050	0.59901	0.59873	0.59843	0.59838	0.59832	0.59831	0.59830	0.59829
0.10	0.60315	0.60083	0.59908	0.59875	0.59840	0.59834	0.59827	0.59826	0.59824	0.59824
0.12	0.60381	0.60116	0.59916	0.59879	0.59839	0.59832	0.59824	0.59823	0.59821	0.59821
0.14	0.60448	0.60150	0.59927	0.59886	0.59841	0.59832	0.59823	0.59821	0.59820	0.59819
0.16	0.60515	0.60187	0.59940	0.59894	0.59844	0.59835	0.59825	0.59823	0.59820	0.59820
0.18	0.60586	0.60226	0.59955	0.59905	0.59850	0.59840	0.59828	0.59826	0.59824	0.59823
0.20	0.60660	0.60269	0.59974	0.59919	0.59859	0.59848	0.59835	0.59832	0.59829	0.59829
0.22	0.60738	0.60315	0.59996	0.59936	0.59871	0.59858	0.59844	0.59841	0.59838	0.59837
0.24	0.60823	0.60367	0.60022	0.59957	0.59886	0.59872	0.59856	0.59853	0.59849	0.59848
0.26	0.60914	0.60423	0.60052	0.59982	0.59904	0.59889	0.59871	0.59867	0.59863	0.59862
0.28	0.61014	0.60487	0.60087	0.60011	0.59926	0.59909	0.59889	0.59885	0.59880	0.59878
0.30	0.61123	0.60557	0.60127	0.60045	0.59952	0.59933	0.59911	0.59906	0.59900	0.59898
0.32	0.61243	0.60635	0.60173	0.60084	0.59982	0.59962	0.59936	0.59931	0.59923	0.59921
0.34	0.61375	0.60722	0.60224	0.60128	0.60017	0.59994	0.59965	0.59959	0.59950	0.59948
0.36	0.61522	0.60818	0.60282	0.60178	0.60056	0.60030	0.59998	0.59990	0.59980	0.59978
0.38	0.61683	0.60926	0.60347	0.60234	0.60100	0.60071	0.60034	0.60026	0.60014	0.60011
0.40	0.61862	0.61044	0.60419	0.60296	0.60149	0.60117	0.60075	0.60065	0.60051	0.60047
0.42	0.62059	0.61175	0.60499	0.60365	0.60202	0.60167	0.60119	0.60108	0.60091	0.60087
0.44	0.62276	0.61319	0.60586	0.60440	0.60261	0.60221	0.60167	0.60154	0.60134	0.60129
0.46	0.62515	0.61476	0.60682	0.60522	0.60324	0.60279	0.60218	0.60203	0.60180	0.60174
0.48	0.62777	0.61647	0.60784	0.60610	0.60391	0.60341	0.60271	0.60254	0.60228	0.60221
0.50	0.63063	0.61833	0.60895	0.60703	0.60462	0.60406	0.60327	0.60307	0.60278	0.60270
0.52	0.63374	0.62034	0.61012	0.60803	0.60536	0.60473	0.60384	0.60361	0.60327	0.60318
0.54	0.63712	0.62249	0.61136	0.60906	0.60612	0.60541	0.60441	0.60415	0.60376	0.60366
0.56	0.64077	0.62479	0.61265	0.61014	0.60688	0.60609	0.60497	0.60467	0.60423	0.60411
0.58	0.64470	0.62722	0.61399	0.61123	0.60763	0.60675	0.60549	0.60516	0.60465	0.60451
0.60	0.64890	0.62979	0.61535	0.61233	0.60836	0.60738	0.60596	0.60558	0.60501	0.60486
0.62	0.65337	0.63246	0.61671	0.61341	0.60903	0.60794	0.60636	0.60593	0.60529	0.60511
0.64	0.65811	0.63524	0.61806	0.61445	0.60963	0.60842	0.60665	0.60617	0.60545	0.60525
0.66	0.66309	0.63809	0.61937	0.61542	0.61012	0.60878	0.60681	0.60628	0.60546	0.60523
0.68	0.66829	0.64098	0.62061	0.61629	0.61047	0.60899	0.60680	0.60621	0.60529	0.60504
0.70	0.67369	0.64389	0.62174	0.61703	0.61066	0.60902	0.60660	0.60593	0.60491	0.60463
0.72	0.67925	0.64679	0.62274	0.61762	0.61064	0.60884	0.60615	0.60542	0.60428	0.60396
0.74	0.68494	0.64964	0.62358	0.61802	0.61040	0.60842	0.60546	0.60464	0.60338	0.60303
0.75	0.68781	0.65103	0.62394	0.61815	0.61019	0.60812	0.60501	0.60415	0.60282	0.60245

Table 1-B-2—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 3-Inch (75-Millimeter) Meter [D = 2.900 Inches (73.66 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59763	0.59688	0.59632	0.59622	0.59611	0.59609	0.59606	0.59606	0.59606	0.59605
0.04	0.59859	0.59737	0.59646	0.59629	0.59611	0.59607	0.59604	0.59603	0.59602	0.59602
0.06	0.59942	0.59780	0.59659	0.59636	0.59612	0.59607	0.59603	0.59602	0.59601	0.59601
0.08	0.60019	0.59821	0.59672	0.59645	0.59615	0.59609	0.59603	0.59602	0.59601	0.59601
0.10	0.60094	0.59861	0.59687	0.59655	0.59620	0.59613	0.59606	0.59605	0.59603	0.59603
0.12	0.60167	0.59902	0.59703	0.59666	0.59626	0.59619	0.59611	0.59609	0.59608	0.59608
0.14	0.60241	0.59944	0.59721	0.59680	0.59635	0.59627	0.59618	0.59616	0.59614	0.59614
0.16	0.60316	0.59989	0.59742	0.59697	0.59647	0.59638	0.59627	0.59625	0.59623	0.59623
0.18	0.60394	0.60036	0.59766	0.59716	0.59661	0.59650	0.59639	0.59637	0.59634	0.59634
0.20	0.60475	0.60086	0.59792	0.59737	0.59677	0.59666	0.59653	0.59651	0.59648	0.59647
0.22	0.60561	0.60140	0.59822	0.59763	0.59697	0.59684	0.59670	0.59667	0.59664	0.59663
0.24	0.60652	0.60199	0.59855	0.59791	0.59720	0.59706	0.59690	0.59687	0.59683	0.59682
0.26	0.60751	0.60263	0.59893	0.59824	0.59746	0.59730	0.59713	0.59709	0.59704	0.59703
0.28	0.60857	0.60333	0.59935	0.59860	0.59775	0.59758	0.59738	0.59734	0.59729	0.59728
0.30	0.60973	0.60410	0.59983	0.59901	0.59808	0.59790	0.59767	0.59762	0.59756	0.59755
0.32	0.61099	0.60495	0.60035	0.59947	0.59846	0.59825	0.59800	0.59794	0.59787	0.59785
0.34	0.61238	0.60589	0.60093	0.59998	0.59887	0.59864	0.59835	0.59829	0.59820	0.59818
0.36	0.61391	0.60691	0.60158	0.60054	0.59933	0.59907	0.59874	0.59867	0.59857	0.59854
0.38	0.61558	0.60804	0.60229	0.60116	0.59982	0.59954	0.59917	0.59908	0.59896	0.59893
0.40	0.61742	0.60929	0.60306	0.60184	0.60037	0.60005	0.59963	0.59953	0.59939	0.59935
0.42	0.61945	0.61064	0.60391	0.60257	0.60095	0.60059	0.60012	0.60001	0.59984	0.59980
0.44	0.62167	0.61213	0.60483	0.60337	0.60158	0.60118	0.60064	0.60051	0.60032	0.60027
0.46	0.62410	0.61374	0.60581	0.60422	0.60224	0.60179	0.60118	0.60103	0.60081	0.60075
0.48	0.62676	0.61548	0.60687	0.60512	0.60294	0.60244	0.60175	0.60157	0.60131	0.60125
0.50	0.62966	0.61737	0.60799	0.60608	0.60366	0.60310	0.60232	0.60212	0.60182	0.60174
0.52	0.63280	0.61939	0.60917	0.60707	0.60440	0.60377	0.60289	0.60266	0.60232	0.60223
0.54	0.63620	0.62155	0.61040	0.60810	0.60515	0.60444	0.60344	0.60318	0.60279	0.60269
0.56	0.63987	0.62383	0.61166	0.60914	0.60588	0.60509	0.60397	0.60367	0.60323	0.60311
0.58	0.64380	0.62625	0.61295	0.61019	0.60658	0.60570	0.60444	0.60410	0.60360	0.60346
0.60	0.64800	0.62877	0.61425	0.61121	0.60723	0.60625	0.60483	0.60445	0.60388	0.60373
0.62	0.65246	0.63138	0.61552	0.61219	0.60780	0.60671	0.60512	0.60470	0.60405	0.60387
0.64	0.65716	0.63406	0.61674	0.61310	0.60826	0.60704	0.60527	0.60479	0.60407	0.60386
0.66	0.66209	0.63679	0.61788	0.61389	0.60856	0.60722	0.60524	0.60471	0.60389	0.60366
0.68	0.66723	0.63953	0.61889	0.61453	0.60868	0.60719	0.60499	0.60439	0.60348	0.60322
0.70	0.67253	0.64223	0.61974	0.61498	0.60855	0.60691	0.60447	0.60381	0.60279	0.60250
0.72	0.67797	0.64486	0.62038	0.61519	0.60814	0.60633	0.60363	0.60289	0.60176	0.60144
0.74	0.68348	0.64736	0.62075	0.61510	0.60740	0.60541	0.60243	0.60161	0.60035	0.59999
0.75	0.68624	0.64855	0.62083	0.61494	0.60689	0.60480	0.60167	0.60081	0.59948	0.59911

Table 1-B-3—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 4-Inch (100-Millimeter) Meter [D = 3.826 Inches (97.18 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59764	0.59689	0.59633	0.59623	0.59612	0.59610	0.59607	0.59607	0.59607	0.59607
0.04	0.59861	0.59739	0.59648	0.59631	0.59613	0.59610	0.59606	0.59605	0.59605	0.59605
0.06	0.59945	0.59784	0.59662	0.59640	0.59616	0.59611	0.59606	0.59605	0.59605	0.59604
0.08	0.60024	0.59826	0.59677	0.59650	0.59620	0.59615	0.59609	0.59608	0.59606	0.59606
0.10	0.60100	0.59868	0.59693	0.59661	0.59626	0.59620	0.59613	0.59612	0.59610	0.59610
0.12	0.60175	0.59910	0.59711	0.59675	0.59635	0.59627	0.59619	0.59618	0.59616	0.59616
0.14	0.60250	0.59954	0.59731	0.59690	0.59645	0.59637	0.59628	0.59626	0.59624	0.59624
0.16	0.60326	0.60000	0.59754	0.59708	0.59658	0.59649	0.59639	0.59637	0.59635	0.59634
0.18	0.60405	0.60048	0.59779	0.59729	0.59674	0.59664	0.59652	0.59650	0.59647	0.59647
0.20	0.60488	0.60099	0.59807	0.59752	0.59692	0.59681	0.59668	0.59666	0.59663	0.59662
0.22	0.60575	0.60155	0.59838	0.59779	0.59713	0.59701	0.59686	0.59684	0.59680	0.59680
0.24	0.60667	0.60215	0.59873	0.59809	0.59737	0.59723	0.59708	0.59704	0.59701	0.59700
0.26	0.60767	0.60280	0.59912	0.59842	0.59765	0.59749	0.59732	0.59728	0.59723	0.59722
0.28	0.60874	0.60352	0.59955	0.59880	0.59795	0.59779	0.59759	0.59755	0.59749	0.59748
0.30	0.60991	0.60430	0.60004	0.59922	0.59830	0.59811	0.59789	0.59784	0.59778	0.59776
0.32	0.61118	0.60516	0.60057	0.59969	0.59868	0.59847	0.59822	0.59816	0.59809	0.59807
0.34	0.61258	0.60610	0.60116	0.60021	0.59910	0.59887	0.59858	0.59852	0.59843	0.59841
0.36	0.61410	0.60713	0.60181	0.60078	0.59956	0.59930	0.59898	0.59891	0.59880	0.59878
0.38	0.61578	0.60827	0.60252	0.60140	0.60006	0.59978	0.59941	0.59932	0.59920	0.59917
0.40	0.61763	0.60951	0.60330	0.60207	0.60060	0.60028	0.59987	0.59977	0.59963	0.59959
0.42	0.61965	0.61086	0.60414	0.60280	0.60118	0.60082	0.60035	0.60023	0.60007	0.60003
0.44	0.62187	0.61233	0.60504	0.60358	0.60180	0.60140	0.60086	0.60073	0.60054	0.60048
0.46	0.62429	0.61393	0.60601	0.60442	0.60245	0.60200	0.60139	0.60123	0.60101	0.60095
0.48	0.62694	0.61567	0.60705	0.60530	0.60312	0.60262	0.60192	0.60175	0.60149	0.60142
0.50	0.62983	0.61753	0.60814	0.60623	0.60381	0.60325	0.60246	0.60226	0.60197	0.60189
0.52	0.63296	0.61952	0.60928	0.60719	0.60451	0.60388	0.60300	0.60277	0.60243	0.60234
0.54	0.63634	0.62164	0.61047	0.60817	0.60521	0.60450	0.60350	0.60324	0.60285	0.60275
0.56	0.63999	0.62389	0.61168	0.60915	0.60588	0.60509	0.60396	0.60367	0.60323	0.60310
0.58	0.64389	0.62625	0.61290	0.61013	0.60651	0.60563	0.60436	0.60403	0.60352	0.60338
0.60	0.64806	0.62871	0.61411	0.61106	0.60707	0.60609	0.60467	0.60429	0.60372	0.60356
0.62	0.65247	0.63124	0.61528	0.61194	0.60753	0.60643	0.60484	0.60442	0.60377	0.60359
0.64	0.65713	0.63384	0.61638	0.61272	0.60785	0.60664	0.60486	0.60438	0.60365	0.60345
0.66	0.66201	0.63645	0.61737	0.61335	0.60800	0.60665	0.60467	0.60413	0.60332	0.60309
0.68	0.66708	0.63905	0.61820	0.61381	0.60792	0.60643	0.60422	0.60362	0.60271	0.60245
0.70	0.67230	0.64160	0.61884	0.61403	0.60756	0.60591	0.60347	0.60280	0.60178	0.60149
0.72	0.67764	0.64403	0.61921	0.61396	0.60686	0.60504	0.60234	0.60160	0.60046	0.60014
0.74	0.68303	0.64629	0.61926	0.61354	0.60577	0.60377	0.60078	0.59996	0.59869	0.59834
0.75	0.68573	0.64733	0.61915	0.61318	0.60505	0.60295	0.59981	0.59895	0.59762	0.59725

Table 1-B-4—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 6-Inch (150-Millimeter) Meter [D = 5.761 Inches (146.33 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59765	0.59691	0.59635	0.59624	0.59613	0.59611	0.59609	0.59608	0.59608	0.59608
0.04	0.59864	0.59742	0.59651	0.59634	0.59616	0.59613	0.59609	0.59608	0.59608	0.59607
0.06	0.59950	0.59788	0.59667	0.59644	0.59620	0.59616	0.59611	0.59610	0.59609	0.59609
0.08	0.60030	0.59832	0.59683	0.59656	0.59626	0.59621	0.59615	0.59614	0.59613	0.59612
0.10	0.60107	0.59876	0.59701	0.59669	0.59635	0.59628	0.59621	0.59620	0.59618	0.59618
0.12	0.60184	0.59920	0.59721	0.59685	0.59645	0.59637	0.59629	0.59628	0.59626	0.59626
0.14	0.60260	0.59965	0.59743	0.59702	0.59657	0.59649	0.59640	0.59638	0.59636	0.59636
0.16	0.60339	0.60013	0.59767	0.59722	0.59672	0.59663	0.59653	0.59651	0.59649	0.59648
0.18	0.60419	0.60063	0.59794	0.59744	0.59690	0.59679	0.59668	0.59666	0.59663	0.59663
0.20	0.60503	0.60116	0.59824	0.59770	0.59710	0.59698	0.59686	0.59683	0.59680	0.59680
0.22	0.60592	0.60173	0.59857	0.59798	0.59733	0.59720	0.59706	0.59703	0.59700	0.59699
0.24	0.60686	0.60235	0.59894	0.59830	0.59758	0.59745	0.59729	0.59726	0.59722	0.59721
0.26	0.60786	0.60302	0.59934	0.59865	0.59787	0.59772	0.59755	0.59751	0.59746	0.59745
0.28	0.60895	0.60374	0.59979	0.59904	0.59820	0.59803	0.59783	0.59779	0.59773	0.59772
0.30	0.61013	0.60454	0.60029	0.59948	0.59855	0.59837	0.59814	0.59810	0.59803	0.59802
0.32	0.61141	0.60540	0.60083	0.59995	0.59894	0.59874	0.59849	0.59843	0.59836	0.59834
0.34	0.61281	0.60635	0.60143	0.60048	0.59937	0.59914	0.59886	0.59879	0.59871	0.59868
0.36	0.61434	0.60739	0.60208	0.60105	0.59984	0.59958	0.59926	0.59918	0.59908	0.59905
0.38	0.61602	0.60852	0.60279	0.60167	0.60034	0.60005	0.59968	0.59960	0.59948	0.59945
0.40	0.61786	0.60976	0.60356	0.60234	0.60087	0.60055	0.60014	0.60004	0.59990	0.59986
0.42	0.61988	0.61111	0.60439	0.60306	0.60144	0.60108	0.60061	0.60049	0.60033	0.60029
0.44	0.62210	0.61257	0.60528	0.60382	0.60204	0.60164	0.60110	0.60097	0.60078	0.60073
0.46	0.62452	0.61415	0.60623	0.60464	0.60266	0.60221	0.60160	0.60145	0.60123	0.60117
0.48	0.62715	0.61586	0.60723	0.60549	0.60330	0.60280	0.60211	0.60193	0.60167	0.60161
0.50	0.63002	0.61769	0.60829	0.60637	0.60395	0.60339	0.60260	0.60240	0.60211	0.60203
0.52	0.63313	0.61965	0.60938	0.60727	0.60460	0.60396	0.60308	0.60285	0.60251	0.60242
0.54	0.63649	0.62172	0.61050	0.60819	0.60523	0.60452	0.60352	0.60326	0.60287	0.60276
0.56	0.64011	0.62391	0.61163	0.60910	0.60582	0.60502	0.60390	0.60360	0.60316	0.60303
0.58	0.64398	0.62620	0.61276	0.60997	0.60634	0.60546	0.60419	0.60385	0.60335	0.60321
0.60	0.64810	0.62858	0.61386	0.61079	0.60678	0.60579	0.60437	0.60399	0.60342	0.60326
0.62	0.65247	0.63101	0.61489	0.61153	0.60709	0.60600	0.60440	0.60398	0.60333	0.60315
0.64	0.65707	0.63349	0.61583	0.61214	0.60724	0.60602	0.60424	0.60376	0.60303	0.60283
0.66	0.66188	0.63596	0.61663	0.61258	0.60718	0.60582	0.60384	0.60330	0.60248	0.60226
0.68	0.66688	0.63839	0.61723	0.61279	0.60685	0.60535	0.60314	0.60254	0.60162	0.60137
0.70	0.67201	0.64073	0.61758	0.61272	0.60618	0.60453	0.60207	0.60140	0.60038	0.60010
0.72	0.67724	0.64291	0.61762	0.61230	0.60512	0.60329	0.60057	0.59983	0.59869	0.59837
0.74	0.68250	0.64487	0.61726	0.61144	0.60358	0.60156	0.59856	0.59773	0.59647	0.59611
0.75	0.68512	0.64575	0.61690	0.61083	0.60260	0.60048	0.59733	0.59646	0.59513	0.59476

Table 1-B-5—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 8-Inch (200-Millimeter) Meter [D = 7.625 Inches (193.68 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59766	0.59691	0.59635	0.59625	0.59614	0.59612	0.59610	0.59609	0.59609	0.59609
0.04	0.59865	0.59744	0.59652	0.59636	0.59617	0.59614	0.59610	0.59610	0.59609	0.59609
0.06	0.59952	0.59791	0.59669	0.59647	0.59623	0.59618	0.59613	0.59612	0.59612	0.59611
0.08	0.60033	0.59835	0.59687	0.59659	0.59630	0.59624	0.59618	0.59617	0.59616	0.59616
0.10	0.60111	0.59880	0.59706	0.59674	0.59639	0.59632	0.59625	0.59624	0.59623	0.59622
0.12	0.60189	0.59925	0.59727	0.59690	0.59650	0.59643	0.59635	0.59633	0.59632	0.59631
0.14	0.60266	0.59971	0.59749	0.59708	0.59664	0.59655	0.59646	0.59645	0.59643	0.59642
0.16	0.60345	0.60020	0.59775	0.59729	0.59680	0.59670	0.59660	0.59658	0.59656	0.59656
0.18	0.60427	0.60071	0.59803	0.59753	0.59698	0.59688	0.59677	0.59674	0.59672	0.59671
0.20	0.60511	0.60125	0.59833	0.59779	0.59719	0.59708	0.59695	0.59693	0.59690	0.59689
0.22	0.60601	0.60183	0.59867	0.59808	0.59743	0.59731	0.59717	0.59714	0.59710	0.59710
0.24	0.60695	0.60246	0.59905	0.59841	0.59770	0.59756	0.59740	0.59737	0.59733	0.59733
0.26	0.60797	0.60313	0.59947	0.59877	0.59800	0.59785	0.59767	0.59763	0.59759	0.59758
0.28	0.60906	0.60387	0.59992	0.59917	0.59833	0.59816	0.59796	0.59792	0.59787	0.59786
0.30	0.61024	0.60467	0.60042	0.59961	0.59869	0.59851	0.59828	0.59823	0.59817	0.59816
0.32	0.61153	0.60554	0.60097	0.60010	0.59909	0.59888	0.59863	0.59857	0.59850	0.59848
0.34	0.61293	0.60649	0.60157	0.60062	0.59952	0.59929	0.59901	0.59894	0.59885	0.59883
0.36	0.61447	0.60753	0.60223	0.60120	0.59999	0.59973	0.59941	0.59933	0.59923	0.59920
0.38	0.61615	0.60866	0.60294	0.60182	0.60049	0.60020	0.59983	0.59975	0.59963	0.59960
0.40	0.61799	0.60990	0.60371	0.60248	0.60102	0.60070	0.60028	0.60018	0.60004	0.60001
0.42	0.62001	0.61124	0.60453	0.60320	0.60158	0.60122	0.60075	0.60063	0.60047	0.60043
0.44	0.62222	0.61270	0.60541	0.60395	0.60217	0.60177	0.60123	0.60110	0.60091	0.60086
0.46	0.62464	0.61427	0.60635	0.60475	0.60278	0.60233	0.60172	0.60157	0.60134	0.60128
0.48	0.62727	0.61597	0.60734	0.60559	0.60340	0.60290	0.60220	0.60203	0.60177	0.60170
0.50	0.63013	0.61778	0.60837	0.60645	0.60403	0.60346	0.60268	0.60248	0.60218	0.60210
0.52	0.63323	0.61972	0.60943	0.60732	0.60464	0.60401	0.60312	0.60289	0.60255	0.60246
0.54	0.63658	0.62177	0.61052	0.60820	0.60523	0.60452	0.60352	0.60326	0.60287	0.60277
0.56	0.64018	0.62393	0.61161	0.60906	0.60578	0.60498	0.60386	0.60356	0.60312	0.60299
0.58	0.64403	0.62618	0.61269	0.60989	0.60625	0.60536	0.60410	0.60376	0.60325	0.60312
0.60	0.64814	0.62851	0.61372	0.61065	0.60662	0.60563	0.60421	0.60383	0.60326	0.60310
0.62	0.65248	0.63089	0.61468	0.61131	0.60686	0.60576	0.60416	0.60373	0.60309	0.60291
0.64	0.65706	0.63330	0.61554	0.61182	0.60691	0.60569	0.60390	0.60342	0.60270	0.60249
0.66	0.66183	0.63570	0.61623	0.61215	0.60673	0.60538	0.60339	0.60285	0.60203	0.60180
0.68	0.66679	0.63804	0.61671	0.61224	0.60627	0.60476	0.60255	0.60195	0.60103	0.60078
0.70	0.67188	0.64027	0.61691	0.61201	0.60544	0.60378	0.60132	0.60065	0.59963	0.59934
0.72	0.67705	0.64233	0.61676	0.61140	0.60418	0.60234	0.59962	0.59888	0.59774	0.59742
0.74	0.68225	0.64413	0.61619	0.61032	0.60240	0.60037	0.59736	0.59654	0.59527	0.59492
0.75	0.68484	0.64491	0.61571	0.60957	0.60128	0.59916	0.59599	0.59513	0.59379	0.59342

Table 1-B-6—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 10-Inch (250-Millimeter) Meter [D = 9.562 Inches (242.87 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59625	0.59614	0.59612	0.59610	0.59610	0.59609	0.59609
0.04	0.59866	0.59745	0.59653	0.59637	0.59618	0.59615	0.59611	0.59611	0.59610	0.59610
0.06	0.59953	0.59792	0.59671	0.59649	0.59624	0.59620	0.59615	0.59614	0.59613	0.59613
0.08	0.60035	0.59838	0.59689	0.59662	0.59632	0.59627	0.59621	0.59620	0.59618	0.59618
0.10	0.60114	0.59883	0.59709	0.59677	0.59642	0.59635	0.59628	0.59627	0.59626	0.59625
0.12	0.60192	0.59928	0.59730	0.59694	0.59654	0.59646	0.59638	0.59637	0.59635	0.59635
0.14	0.60270	0.59976	0.59754	0.59713	0.59668	0.59660	0.59651	0.59649	0.59647	0.59647
0.16	0.60350	0.60025	0.59780	0.59734	0.59685	0.59676	0.59665	0.59663	0.59661	0.59661
0.18	0.60432	0.60076	0.59808	0.59758	0.59704	0.59694	0.59682	0.59680	0.59678	0.59677
0.20	0.60517	0.60131	0.59840	0.59785	0.59726	0.59714	0.59702	0.59699	0.59696	0.59696
0.22	0.60607	0.60190	0.59874	0.59816	0.59750	0.59738	0.59724	0.59721	0.59718	0.59717
0.24	0.60702	0.60253	0.59913	0.59849	0.59778	0.59764	0.59748	0.59745	0.59741	0.59740
0.26	0.60804	0.60321	0.59955	0.59886	0.59808	0.59793	0.59775	0.59772	0.59767	0.59766
0.28	0.60914	0.60395	0.60001	0.59926	0.59842	0.59825	0.59805	0.59801	0.59796	0.59795
0.30	0.61032	0.60475	0.60052	0.59971	0.59879	0.59860	0.59838	0.59833	0.59827	0.59825
0.32	0.61161	0.60563	0.60107	0.60019	0.59919	0.59898	0.59873	0.59867	0.59860	0.59858
0.34	0.61302	0.60658	0.60167	0.60072	0.59962	0.59939	0.59911	0.59904	0.59896	0.59893
0.36	0.61456	0.60763	0.60233	0.60130	0.60009	0.59983	0.59951	0.59944	0.59933	0.59931
0.38	0.61624	0.60876	0.60304	0.60192	0.60059	0.60030	0.59994	0.59985	0.59973	0.59970
0.40	0.61809	0.61000	0.60381	0.60259	0.60112	0.60080	0.60038	0.60028	0.60014	0.60011
0.42	0.62010	0.61134	0.60463	0.60330	0.60168	0.60132	0.60085	0.60073	0.60057	0.60053
0.44	0.62231	0.61279	0.60551	0.60405	0.60226	0.60186	0.60132	0.60119	0.60100	0.60095
0.46	0.62473	0.61436	0.60643	0.60484	0.60286	0.60241	0.60180	0.60165	0.60143	0.60137
0.48	0.62735	0.61605	0.60741	0.60566	0.60347	0.60297	0.60228	0.60210	0.60185	0.60178
0.50	0.63021	0.61785	0.60843	0.60651	0.60409	0.60352	0.60274	0.60253	0.60224	0.60216
0.52	0.63331	0.61977	0.60947	0.60737	0.60468	0.60405	0.60316	0.60293	0.60259	0.60250
0.54	0.63665	0.62181	0.61054	0.60822	0.60525	0.60454	0.60354	0.60328	0.60289	0.60278
0.56	0.64024	0.62395	0.61161	0.60906	0.60577	0.60497	0.60384	0.60355	0.60310	0.60298
0.58	0.64408	0.62618	0.61265	0.60985	0.60621	0.60532	0.60405	0.60371	0.60321	0.60307
0.60	0.64817	0.62848	0.61365	0.61057	0.60654	0.60555	0.60412	0.60374	0.60317	0.60301
0.62	0.65250	0.63083	0.61457	0.61118	0.60672	0.60562	0.60402	0.60360	0.60295	0.60277
0.64	0.65706	0.63320	0.61536	0.61164	0.60672	0.60549	0.60371	0.60323	0.60250	0.60229
0.66	0.66182	0.63555	0.61599	0.61190	0.60647	0.60511	0.60312	0.60258	0.60176	0.60153
0.68	0.66675	0.63784	0.61639	0.61190	0.60592	0.60441	0.60219	0.60159	0.60067	0.60042
0.70	0.67181	0.64000	0.61650	0.61158	0.60499	0.60332	0.60086	0.60019	0.59916	0.59888
0.72	0.67696	0.64198	0.61624	0.61085	0.60361	0.60176	0.59903	0.59829	0.59715	0.59683
0.74	0.68212	0.64369	0.61553	0.60963	0.60167	0.59964	0.59663	0.59580	0.59453	0.59418
0.75	0.68468	0.64441	0.61497	0.60880	0.60047	0.59834	0.59517	0.59430	0.59297	0.59259

Table 1-B-7—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 12-Inch (300-Millimeter) Meter [D = 11.374 Inches (288.90 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59626	0.59615	0.59613	0.59610	0.59610	0.59609	0.59609
0.04	0.59867	0.59745	0.59654	0.59637	0.59619	0.59616	0.59612	0.59611	0.59611	0.59611
0.06	0.59954	0.59793	0.59672	0.59650	0.59625	0.59621	0.59616	0.59615	0.59614	0.59614
0.08	0.60037	0.59839	0.59691	0.59663	0.59634	0.59628	0.59622	0.59621	0.59620	0.59620
0.10	0.60116	0.59885	0.59711	0.59679	0.59644	0.59637	0.59630	0.59629	0.59628	0.59627
0.12	0.60194	0.59931	0.59733	0.59696	0.59656	0.59649	0.59641	0.59639	0.59638	0.59637
0.14	0.60273	0.59978	0.59757	0.59716	0.59671	0.59663	0.59654	0.59652	0.59650	0.59650
0.16	0.60353	0.60028	0.59783	0.59738	0.59688	0.59679	0.59669	0.59667	0.59665	0.59664
0.18	0.60435	0.60080	0.59812	0.59762	0.59708	0.59698	0.59686	0.59684	0.59681	0.59681
0.20	0.60521	0.60135	0.59844	0.59790	0.59730	0.59719	0.59706	0.59704	0.59701	0.59700
0.22	0.60611	0.60194	0.59879	0.59820	0.59755	0.59743	0.59728	0.59726	0.59722	0.59722
0.24	0.60707	0.60258	0.59918	0.59854	0.59783	0.59769	0.59753	0.59750	0.59746	0.59746
0.26	0.60809	0.60326	0.59960	0.59891	0.59814	0.59799	0.59781	0.59777	0.59773	0.59772
0.28	0.60919	0.60401	0.60007	0.59932	0.59848	0.59831	0.59811	0.59807	0.59802	0.59800
0.30	0.61038	0.60481	0.60058	0.59977	0.59885	0.59866	0.59844	0.59839	0.59833	0.59832
0.32	0.61167	0.60569	0.60113	0.60026	0.59925	0.59905	0.59880	0.59874	0.59867	0.59865
0.34	0.61308	0.60665	0.60174	0.60079	0.59969	0.59946	0.59918	0.59911	0.59902	0.59900
0.36	0.61462	0.60769	0.60240	0.60137	0.60016	0.59990	0.59958	0.59951	0.59940	0.59938
0.38	0.61630	0.60883	0.60311	0.60199	0.60066	0.60037	0.60001	0.59992	0.59980	0.59977
0.40	0.61815	0.61006	0.60388	0.60265	0.60119	0.60087	0.60045	0.60035	0.60021	0.60018
0.42	0.62017	0.61140	0.60470	0.60336	0.60175	0.60139	0.60092	0.60080	0.60064	0.60059
0.44	0.62237	0.61285	0.60557	0.60411	0.60233	0.60193	0.60139	0.60126	0.60107	0.60101
0.46	0.62479	0.61442	0.60649	0.60490	0.60292	0.60247	0.60186	0.60171	0.60149	0.60143
0.48	0.62741	0.61610	0.60747	0.60572	0.60353	0.60302	0.60233	0.60216	0.60190	0.60183
0.50	0.63027	0.61790	0.60847	0.60655	0.60413	0.60357	0.60278	0.60258	0.60229	0.60221
0.52	0.63336	0.61982	0.60951	0.60740	0.60472	0.60408	0.60320	0.60297	0.60263	0.60254
0.54	0.63670	0.62184	0.61056	0.60825	0.60527	0.60456	0.60356	0.60330	0.60291	0.60280
0.56	0.64028	0.62397	0.61162	0.60907	0.60577	0.60498	0.60385	0.60355	0.60311	0.60299
0.58	0.64412	0.62619	0.61264	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64821	0.62847	0.61362	0.61053	0.60650	0.60551	0.60408	0.60370	0.60313	0.60297
0.62	0.65253	0.63080	0.61451	0.61111	0.60665	0.60555	0.60395	0.60352	0.60288	0.60270
0.64	0.65708	0.63315	0.61527	0.61154	0.60661	0.60538	0.60360	0.60312	0.60239	0.60219
0.66	0.66182	0.63548	0.61586	0.61176	0.60632	0.60496	0.60296	0.60243	0.60161	0.60138
0.68	0.66674	0.63773	0.61621	0.61171	0.60572	0.60421	0.60199	0.60139	0.60047	0.60021
0.70	0.67179	0.63985	0.61627	0.61133	0.60473	0.60306	0.60059	0.59992	0.59890	0.59861
0.72	0.67692	0.64178	0.61594	0.61053	0.60327	0.60142	0.59869	0.59795	0.59680	0.59649
0.74	0.68206	0.64343	0.61514	0.60922	0.60124	0.59921	0.59619	0.59536	0.59410	0.59374
0.75	0.68461	0.64412	0.61453	0.60834	0.59999	0.59785	0.59468	0.59381	0.59247	0.59210

Table 1-B-8—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 16-Inch (400-Millimeter) Meter [D = 14.688 Inches (373.08 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59610	0.59610	0.59610
0.04	0.59868	0.59746	0.59655	0.59638	0.59620	0.59617	0.59613	0.59612	0.59612	0.59611
0.06	0.59956	0.59794	0.59673	0.59651	0.59627	0.59622	0.59617	0.59617	0.59616	0.59615
0.08	0.60038	0.59841	0.59692	0.59665	0.59635	0.59630	0.59624	0.59623	0.59622	0.59621
0.10	0.60118	0.59887	0.59713	0.59681	0.59646	0.59640	0.59633	0.59631	0.59630	0.59630
0.12	0.60197	0.59934	0.59736	0.59699	0.59659	0.59652	0.59644	0.59642	0.59641	0.59640
0.14	0.60276	0.59982	0.59760	0.59719	0.59675	0.59666	0.59657	0.59655	0.59654	0.59653
0.16	0.60356	0.60032	0.59787	0.59742	0.59692	0.59683	0.59673	0.59671	0.59669	0.59668
0.18	0.60439	0.60084	0.59817	0.59767	0.59713	0.59702	0.59691	0.59689	0.59686	0.59686
0.20	0.60526	0.60140	0.59849	0.59795	0.59735	0.59724	0.59711	0.59709	0.59706	0.59705
0.22	0.60616	0.60200	0.59885	0.59826	0.59761	0.59749	0.59734	0.59732	0.59728	0.59728
0.24	0.60712	0.60264	0.59924	0.59860	0.59789	0.59776	0.59760	0.59757	0.59753	0.59752
0.26	0.60815	0.60333	0.59967	0.59898	0.59821	0.59806	0.59788	0.59784	0.59780	0.59779
0.28	0.60925	0.60408	0.60014	0.59940	0.59855	0.59839	0.59819	0.59815	0.59809	0.59808
0.30	0.61044	0.60489	0.60066	0.59985	0.59893	0.59874	0.59852	0.59847	0.59841	0.59840
0.32	0.61174	0.60577	0.60122	0.60034	0.59934	0.59913	0.59888	0.59882	0.59875	0.59873
0.34	0.61315	0.60673	0.60183	0.60088	0.59978	0.59955	0.59926	0.59920	0.59911	0.59909
0.36	0.61469	0.60777	0.60249	0.60146	0.60025	0.59999	0.59967	0.59960	0.59949	0.59947
0.38	0.61638	0.60891	0.60320	0.60208	0.60075	0.60047	0.60010	0.60001	0.59989	0.59986
0.40	0.61823	0.61015	0.60397	0.60275	0.60128	0.60096	0.60055	0.60045	0.60031	0.60027
0.42	0.62025	0.61149	0.60479	0.60345	0.60184	0.60148	0.60101	0.60089	0.60073	0.60069
0.44	0.62246	0.61294	0.60566	0.60420	0.60242	0.60201	0.60148	0.60134	0.60115	0.60110
0.46	0.62487	0.61450	0.60658	0.60498	0.60301	0.60256	0.60195	0.60179	0.60157	0.60151
0.48	0.62749	0.61618	0.60754	0.60579	0.60361	0.60310	0.60241	0.60223	0.60198	0.60191
0.50	0.63035	0.61798	0.60854	0.60662	0.60420	0.60363	0.60285	0.60265	0.60235	0.60227
0.52	0.63343	0.61988	0.60957	0.60746	0.60478	0.60414	0.60325	0.60302	0.60269	0.60259
0.54	0.63677	0.62190	0.61061	0.60829	0.60532	0.60461	0.60360	0.60334	0.60295	0.60285
0.56	0.64035	0.62402	0.61164	0.60909	0.60580	0.60500	0.60387	0.60358	0.60313	0.60301
0.58	0.64418	0.62622	0.61265	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64826	0.62848	0.61360	0.61051	0.60647	0.60548	0.60405	0.60367	0.60310	0.60294
0.62	0.65258	0.63079	0.61446	0.61106	0.60659	0.60549	0.60389	0.60346	0.60281	0.60264
0.64	0.65711	0.63312	0.61519	0.61145	0.60651	0.60528	0.60350	0.60302	0.60229	0.60208
0.66	0.66185	0.63541	0.61573	0.61162	0.60617	0.60481	0.60281	0.60228	0.60146	0.60123
0.68	0.66675	0.63763	0.61603	0.61152	0.60551	0.60400	0.60178	0.60118	0.60026	0.60000
0.70	0.67179	0.63971	0.61602	0.61107	0.60445	0.60278	0.60031	0.59964	0.59862	0.59833
0.72	0.67690	0.64158	0.61562	0.61019	0.60291	0.60106	0.59833	0.59758	0.59644	0.59612
0.74	0.68202	0.64316	0.61473	0.60878	0.60078	0.59874	0.59572	0.59489	0.59362	0.59327
0.75	0.68456	0.64382	0.61406	0.60784	0.59947	0.59733	0.59415	0.59328	0.59194	0.59157

Table 1-B-9—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 20-Inch (500-Millimeter) Meter [D = 19.000 Inches (482.60 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59868	0.59747	0.59656	0.59639	0.59621	0.59617	0.59614	0.59613	0.59612	0.59612
0.06	0.59957	0.59796	0.59674	0.59652	0.59628	0.59623	0.59619	0.59618	0.59617	0.59616
0.08	0.60040	0.59842	0.59694	0.59667	0.59637	0.59631	0.59626	0.59624	0.59623	0.59623
0.10	0.60120	0.59889	0.59715	0.59683	0.59648	0.59642	0.59635	0.59633	0.59632	0.59632
0.12	0.60199	0.59936	0.59738	0.59701	0.59662	0.59654	0.59646	0.59645	0.59643	0.59643
0.14	0.60279	0.59984	0.59763	0.59722	0.59677	0.59669	0.59660	0.59658	0.59656	0.59656
0.16	0.60360	0.60035	0.59790	0.59745	0.59696	0.59686	0.59676	0.59674	0.59672	0.59672
0.18	0.60443	0.60088	0.59821	0.59771	0.59716	0.59706	0.59695	0.59693	0.59690	0.59690
0.20	0.60529	0.60144	0.59854	0.59799	0.59740	0.59729	0.59716	0.59713	0.59710	0.59710
0.22	0.60620	0.60204	0.59890	0.59831	0.59766	0.59753	0.59739	0.59737	0.59733	0.59732
0.24	0.60717	0.60269	0.59930	0.59866	0.59795	0.59781	0.59765	0.59762	0.59758	0.59757
0.26	0.60820	0.60338	0.59973	0.59904	0.59827	0.59812	0.59794	0.59790	0.59786	0.59785
0.28	0.60930	0.60413	0.60020	0.59946	0.59862	0.59845	0.59825	0.59821	0.59816	0.59814
0.30	0.61050	0.60495	0.60072	0.59992	0.59900	0.59881	0.59859	0.59854	0.59848	0.59846
0.32	0.61180	0.60583	0.60129	0.60041	0.59941	0.59920	0.59895	0.59890	0.59882	0.59880
0.34	0.61321	0.60680	0.60190	0.60095	0.59985	0.59962	0.59934	0.59927	0.59919	0.59917
0.36	0.61476	0.60784	0.60256	0.60153	0.60033	0.60007	0.59975	0.59967	0.59957	0.59955
0.38	0.61645	0.60898	0.60328	0.60216	0.60083	0.60054	0.60018	0.60009	0.59997	0.59994
0.40	0.61830	0.61022	0.60404	0.60283	0.60136	0.60104	0.60063	0.60053	0.60039	0.60035
0.42	0.62032	0.61156	0.60486	0.60353	0.60192	0.60156	0.60109	0.60097	0.60081	0.60077
0.44	0.62253	0.61301	0.60574	0.60428	0.60249	0.60209	0.60156	0.60142	0.60123	0.60118
0.46	0.62494	0.61458	0.60665	0.60506	0.60308	0.60263	0.60202	0.60187	0.60165	0.60159
0.48	0.62756	0.61625	0.60762	0.60587	0.60368	0.60317	0.60248	0.60231	0.60205	0.60198
0.50	0.63042	0.61804	0.60861	0.60669	0.60427	0.60370	0.60292	0.60272	0.60242	0.60234
0.52	0.63350	0.61995	0.60963	0.60752	0.60484	0.60420	0.60331	0.60309	0.60275	0.60265
0.54	0.63684	0.62196	0.61066	0.60834	0.60537	0.60466	0.60365	0.60339	0.60300	0.60290
0.56	0.64042	0.62407	0.61169	0.60913	0.60584	0.60504	0.60391	0.60361	0.60317	0.60305
0.58	0.64424	0.62626	0.61268	0.60987	0.60622	0.60533	0.60406	0.60372	0.60321	0.60308
0.60	0.64832	0.62851	0.61361	0.61052	0.60648	0.60548	0.60406	0.60368	0.60310	0.60295
0.62	0.65263	0.63081	0.61445	0.61105	0.60657	0.60547	0.60387	0.60344	0.60279	0.60262
0.64	0.65716	0.63311	0.61515	0.61141	0.60647	0.60524	0.60345	0.60297	0.60224	0.60204
0.66	0.66189	0.63539	0.61567	0.61155	0.60609	0.60473	0.60273	0.60219	0.60137	0.60115
0.68	0.66679	0.63758	0.61593	0.61141	0.60539	0.60388	0.60166	0.60105	0.60014	0.59988
0.70	0.67181	0.63963	0.61588	0.61091	0.60428	0.60261	0.60014	0.59947	0.59844	0.59816
0.72	0.67691	0.64146	0.61542	0.60997	0.60268	0.60083	0.59809	0.59735	0.59620	0.59589
0.74	0.68201	0.64300	0.61446	0.60850	0.60048	0.59844	0.59541	0.59459	0.59332	0.59296
0.75	0.68455	0.64363	0.61376	0.60752	0.59912	0.59698	0.59380	0.59293	0.59159	0.59122

Table 1-B-10—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 24-Inch (600-Millimeter) Meter [D = 23.000 Inches (584.20 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59869	0.59747	0.59656	0.59639	0.59621	0.59618	0.59614	0.59613	0.59613	0.59613
0.06	0.59957	0.59796	0.59675	0.59653	0.59628	0.59624	0.59619	0.59618	0.59617	0.59617
0.08	0.60041	0.59843	0.59695	0.59668	0.59638	0.59632	0.59626	0.59625	0.59624	0.59624
0.10	0.60121	0.59890	0.59716	0.59684	0.59649	0.59643	0.59636	0.59635	0.59633	0.59633
0.12	0.60201	0.59937	0.59739	0.59703	0.59663	0.59656	0.59648	0.59646	0.59645	0.59644
0.14	0.60280	0.59986	0.59765	0.59724	0.59679	0.59671	0.59662	0.59660	0.59658	0.59658
0.16	0.60361	0.60037	0.59793	0.59747	0.59698	0.59689	0.59678	0.59676	0.59674	0.59674
0.18	0.60445	0.60090	0.59823	0.59773	0.59719	0.59709	0.59697	0.59695	0.59693	0.59692
0.20	0.60532	0.60147	0.59856	0.59802	0.59743	0.59731	0.59719	0.59716	0.59713	0.59713
0.22	0.60623	0.60207	0.59893	0.59834	0.59769	0.59757	0.59742	0.59740	0.59736	0.59736
0.24	0.60720	0.60272	0.59933	0.59869	0.59798	0.59785	0.59769	0.59766	0.59762	0.59761
0.26	0.60823	0.60342	0.59977	0.59908	0.59830	0.59815	0.59798	0.59794	0.59789	0.59788
0.28	0.60934	0.60417	0.60024	0.59950	0.59866	0.59849	0.59829	0.59825	0.59820	0.59818
0.30	0.61054	0.60499	0.60076	0.59996	0.59904	0.59885	0.59863	0.59858	0.59852	0.59851
0.32	0.61184	0.60587	0.60133	0.60046	0.59945	0.59925	0.59900	0.59894	0.59887	0.59885
0.34	0.61325	0.60684	0.60195	0.60100	0.59990	0.59967	0.59938	0.59932	0.59923	0.59921
0.36	0.61480	0.60789	0.60261	0.60158	0.60037	0.60012	0.59980	0.59972	0.59962	0.59959
0.38	0.61649	0.60903	0.60333	0.60221	0.60088	0.60059	0.60023	0.60014	0.60002	0.59999
0.40	0.61834	0.61027	0.60410	0.60288	0.60141	0.60109	0.60068	0.60058	0.60044	0.60040
0.42	0.62036	0.61161	0.60492	0.60358	0.60197	0.60161	0.60114	0.60102	0.60086	0.60082
0.44	0.62257	0.61306	0.60579	0.60433	0.60255	0.60215	0.60161	0.60148	0.60129	0.60123
0.46	0.62498	0.61463	0.60671	0.60511	0.60314	0.60269	0.60208	0.60192	0.60170	0.60164
0.48	0.62761	0.61630	0.60767	0.60592	0.60373	0.60323	0.60253	0.60236	0.60210	0.60203
0.50	0.63046	0.61809	0.60866	0.60674	0.60432	0.60375	0.60297	0.60276	0.60247	0.60239
0.52	0.63355	0.61999	0.60968	0.60757	0.60488	0.60425	0.60336	0.60313	0.60279	0.60270
0.54	0.63688	0.62200	0.61070	0.60838	0.60541	0.60470	0.60369	0.60343	0.60304	0.60294
0.56	0.64046	0.62411	0.61172	0.60917	0.60587	0.60507	0.60394	0.60365	0.60320	0.60308
0.58	0.64429	0.62629	0.61271	0.60989	0.60624	0.60535	0.60408	0.60375	0.60324	0.60310
0.60	0.64836	0.62854	0.61363	0.61054	0.60649	0.60550	0.60407	0.60369	0.60312	0.60296
0.62	0.65267	0.63083	0.61446	0.61105	0.60658	0.60547	0.60387	0.60345	0.60280	0.60262
0.64	0.65720	0.63313	0.61515	0.61140	0.60646	0.60523	0.60344	0.60296	0.60223	0.60202
0.66	0.66192	0.63539	0.61565	0.61153	0.60607	0.60470	0.60270	0.60216	0.60135	0.60112
0.68	0.66682	0.63757	0.61589	0.61137	0.60534	0.60383	0.60160	0.60100	0.60008	0.59983
0.70	0.67184	0.63960	0.61581	0.61084	0.60421	0.60253	0.60006	0.59939	0.59837	0.59808
0.72	0.67693	0.64142	0.61533	0.60987	0.60257	0.60072	0.59798	0.59724	0.59610	0.59578
0.74	0.68203	0.64293	0.61433	0.60836	0.60034	0.59829	0.59526	0.59444	0.59317	0.59281
0.75	0.68456	0.64355	0.61361	0.60736	0.59895	0.59681	0.59363	0.59276	0.59142	0.59105

Table 1-B-11—Discharge Coefficients for Flange-Tapped Orifice Meters: Nominal 30-Inch (750-Millimeter) Meter [D = 29.000 Inches (736.60 Millimeters)]

	Pipe Reynolds Number (Re_D)									
β	4000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59616	0.59614	0.59611	0.59611	0.59611	0.59610
0.04	0.59869	0.59748	0.59657	0.59640	0.59622	0.59618	0.59615	0.59614	0.59613	0.59613
0.06	0.59958	0.59797	0.59676	0.59653	0.59629	0.59625	0.59620	0.59619	0.59618	0.59618
0.08	0.60041	0.59844	0.59696	0.59668	0.59639	0.59633	0.59627	0.59626	0.59625	0.59625
0.10	0.60122	0.59891	0.59717	0.59685	0.59651	0.59644	0.59637	0.59636	0.59634	0.59634
0.12	0.60202	0.59939	0.59741	0.59704	0.59665	0.59657	0.59649	0.59648	0.59646	0.59646
0.14	0.60282	0.59988	0.59767	0.59726	0.59681	0.59673	0.59664	0.59662	0.59660	0.59660
0.16	0.60363	0.60039	0.59795	0.59749	0.59700	0.59691	0.59681	0.59679	0.59676	0.59676
0.18	0.60447	0.60093	0.59825	0.59776	0.59721	0.59711	0.59700	0.59698	0.59695	0.59695
0.20	0.60534	0.60150	0.59859	0.59805	0.59745	0.59734	0.59721	0.59719	0.59716	0.59715
0.22	0.60626	0.60210	0.59896	0.59837	0.59772	0.59760	0.59746	0.59743	0.59739	0.59739
0.24	0.60723	0.60275	0.59936	0.59872	0.59802	0.59788	0.59772	0.59769	0.59765	0.59764
0.26	0.60826	0.60345	0.59980	0.59911	0.59834	0.59819	0.59801	0.59798	0.59793	0.59792
0.28	0.60937	0.60421	0.60028	0.59954	0.59870	0.59853	0.59833	0.59829	0.59824	0.59822
0.30	0.61057	0.60503	0.60081	0.60000	0.59908	0.59890	0.59867	0.59863	0.59856	0.59855
0.32	0.61188	0.60592	0.60138	0.60050	0.59950	0.59929	0.59904	0.59899	0.59891	0.59889
0.34	0.61329	0.60689	0.60199	0.60105	0.59995	0.59972	0.59943	0.59937	0.59928	0.59926
0.36	0.61484	0.60794	0.60266	0.60163	0.60043	0.60017	0.59985	0.59977	0.59967	0.59965
0.38	0.61653	0.60908	0.60338	0.60226	0.60093	0.60065	0.60028	0.60020	0.60008	0.60005
0.40	0.61838	0.61032	0.60415	0.60293	0.60147	0.60115	0.60073	0.60063	0.60049	0.60046
0.42	0.62041	0.61166	0.60497	0.60364	0.60203	0.60167	0.60120	0.60108	0.60092	0.60087
0.44	0.62262	0.61312	0.60584	0.60439	0.60260	0.60220	0.60166	0.60153	0.60134	0.60129
0.46	0.62503	0.61468	0.60676	0.60517	0.60319	0.60274	0.60213	0.60198	0.60176	0.60170
0.48	0.62766	0.61635	0.60772	0.60597	0.60379	0.60328	0.60259	0.60241	0.60216	0.60209
0.50	0.63051	0.61814	0.60871	0.60679	0.60437	0.60380	0.60302	0.60282	0.60252	0.60244
0.52	0.63360	0.62005	0.60973	0.60762	0.60493	0.60430	0.60341	0.60318	0.60284	0.60275
0.54	0.63693	0.62205	0.61075	0.60843	0.60545	0.60474	0.60374	0.60348	0.60309	0.60298
0.56	0.64051	0.62415	0.61177	0.60921	0.60591	0.60512	0.60399	0.60369	0.60325	0.60312
0.58	0.64434	0.62634	0.61275	0.60993	0.60628	0.60539	0.60412	0.60378	0.60328	0.60314
0.60	0.64841	0.62858	0.61366	0.61057	0.60652	0.60553	0.60410	0.60372	0.60315	0.60299
0.62	0.65272	0.63086	0.61448	0.61107	0.60660	0.60549	0.60389	0.60346	0.60282	0.60264
0.64	0.65724	0.63315	0.61516	0.61141	0.60646	0.60523	0.60344	0.60296	0.60223	0.60203
0.66	0.66197	0.63540	0.61564	0.61152	0.60606	0.60469	0.60269	0.60215	0.60133	0.60111
0.68	0.66686	0.63757	0.61587	0.61134	0.60531	0.60380	0.60158	0.60097	0.60006	0.59980
0.70	0.67188	0.63959	0.61577	0.61080	0.60416	0.60248	0.60001	0.59934	0.59831	0.59803
0.72	0.67697	0.64139	0.61526	0.60980	0.60249	0.60064	0.59790	0.59716	0.59601	0.59570
0.74	0.68206	0.64289	0.61424	0.60825	0.60022	0.59818	0.59515	0.59432	0.59305	0.59270
0.75	0.68459	0.64349	0.61350	0.60724	0.59882	0.59668	0.59349	0.59262	0.59128	0.59091

APPENDIX 1-C—ADJUSTMENTS FOR INSTRUMENT CALIBRATION AND USE

Note: This appendix is not a part of this standard but is included for informational purposes only.

This appendix discusses the need to consider the determination of flow rate from a holistic viewpoint. To build, operate, and maintain the facility properly, the user must have defined the desired uncertainty for the designer.

The accuracy of the metered quantities depends on a combination of the following:

a. The design, installation, and operation of the orifice metering facility.
b. The choice of measurement equipment (charts, transmitters, smart transmitters, analog/digital converters, data loggers, and so forth).
c. The means of data transmission (analog, pneumatic, digital, manual).
d. The calculation procedure and means of computation (chart integration, flow computer, mainframe, minicomputer, personal computer, and so forth).
e. The effects on the operating/calibration equipment of ambient temperature, fluid temperature and pressure, response time, local gravitational forces, atmospheric pressure, and the like.
f. The traceability chain associated with the portable field standards.

The uncertainty depends not just on the hardware but also on the hardware's performance, the software's performance, the method of calibration, the calibration equipment, the calibration procedures, and the human factor.

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters

Part 2—Specification and Installation Requirements

THIRD EDITION, FEBRUARY 1991

AGA	American Gas Association	Report No. 3, Part 2
GPA	Gas Processors Association	GPA 8185-90, Part 2

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005

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Chapter 14—Natural Gas Fluids Measurement

SECTION 3—CONCENTRIC, SQUARE-EDGED ORIFICE METERS

PART 2—SPECIFICATION AND INSTALLATION REQUIREMENTS

2.1 Construction and Installation Requirements

This document outlines the various design parameters that must be taken into consideration when designing metering facilities using orifice meters. The mechanical tolerances found in this document encompass a wide range of diameter ratios for which experimental results are available. In this document there are several sections in which the tolerances for the mechanical specifications have been changed, relative to previous editions.

Use of the calculation procedures and techniques shown in the Manual of Petroleum Measurement Standards, *Chapter 14, Section 3, Parts 1 and 3, with existing equipment is recommended, since these represent significant improvements over the previous methods. However, the uncertainty levels for flow measurement using existing equipment may be different from those quoted in Part 1.*

Use of orifice meters at the extremes of their diameter ratio (β_r) ranges should be avoided whenever possible. Good metering design and practice tends to be somewhat conservative. This means that the use of the tightest tolerances in the mid-diameter ratio (β_r) ranges would have the highest probability of producing the best measurement. An indication of this is found in the section on uncertainty in Part 1.

This standard is based on diameter ratios (β_r) between 0.10 and 0.75. Minimum uncertainty of the orifice plate coefficient of discharge (C_d) is achieved with diameter ratios (β_r) between 0.2 and 0.6 and orifice bore diameters greater than or equal to 0.45 inch. Diameter ratios (β_r) and orifice bore diameters outside of this range may be used; however, the user should consult the uncertainty section of Part 1 for limitations.

Achieving the best level of measurement uncertainty begins with but is not limited to proper design. Two other aspects of the measurement process must accompany the design effort; otherwise it is of little value. These aspects are the application of the metering system and the maintenance of the meters, neither of which is considered directly in this standard. They are, however, implied. These aspects cannot be governed by a single standard, since they cover metering applications that can differ widely in flow rate, type of fluid, and operational requirements. The user must therefore determine the best meter selection for application and level of maintenance for the measurement system under consideration.

2.2 Symbols

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

Symbol	Represented Quantity
C_d	Orifice plate coefficient of discharge.
d	Orifice plate bore diameter calculated at flowing temperature, T_f.
d_m	Orifice plate bore diameter measured at T_m.
d_r	Orifice plate bore diameter calculated at reference temperature, T_r.
D	Meter tube internal diameter calculated at flowing temperature, T_f.
D_m	Meter tube internal diameter measured at T_m.
D_r	Meter tube internal diameter calculated at reference temperature, T_r.
ΔP	Orifice differential pressure.
°F	Temperature, in degrees Fahrenheit.
°R	Temperature, in degrees Rankine.

E	Orifice plate thickness.
e	Orifice plate bore thickness.
R_a	Roughness average.
T_m	Temperature of the orifice plate and/or meter tube at time of diameter measurements.
T_r	Reference temperature of orifice plate bore diameter and/or meter tube internal diameter.
α	Linear coefficient of thermal expansion.
α_1	Linear coefficient of thermal expansion of the orifice plate material.
α_2	Linear coefficient of thermal expansion of the meter tube material.
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f.
β_m	Ratio of orifice plate bore diameter to meter tube internal diameter (d_m/D_m) calculated at temperature T_m.
β_r	Ratio of orifice plate bore diameter to meter tube internal diameter (d_r/D_r) calculated at reference temperature, T_r.
ε	Orifice plate bore eccentricity.
θ	Orifice plate bevel angle.

2.3 Definitions

This standard reflects orifice meter application to fluid flow measurement. The definitions are given to emphasize the particular meaning of the terms as used in this standard.

2.3.1 PRIMARY ELEMENT

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, and the meter tube.

2.3.1.1 Orifice Plate

The orifice plate is defined as a thin plate in which a circular concentric aperture (bore) has been machined. The orifice plate is described as a thin plate with sharp, square edge because the thickness of the plate material is small, compared with the internal diameter of the measuring aperture (bore) and because the upstream edge of the measuring aperture is sharp and square.

2.3.1.2 Orifice Plate Bore Diameter (d, d_m, d_r)

The calculated orifice plate bore diameter (d) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature (T_f), as specified in 1.6.2 of Part 1. The calculated orifice plate bore diameter (d) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter (d_m) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate (T_m) at the time of bore diameter measurements, determined as specified in 2.4.3.

The reference orifice plate bore diameter (d_r) is the internal diameter of the orifice plate measuring aperture at reference temperature (T_r), calculated as specified in 2.4.3. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

2.3.1.3 Orifice Plate Holder

The orifice plate holder is defined as a pressure containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

2.3.1.4 Meter Tube

The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in 2.5.1.

2.3.1.5 Meter Tube Internal Diameter (D, D_m, D_r)

The calculated meter tube internal diameter (D) is the inside diameter of the upstream section of the meter tube computed at flowing temperature (T_f), as specified in 1.6.3 of Part 1. The calculated meter tube internal diameter (D) is used in the diameter ratio and Reynolds number equations.

The measured meter tube internal diameter (D_m) is the inside diameter of the upstream section of the meter tube measured at the temperature of the meter tube (T_m) at the time of internal diameter measurements, as specified in 2.5.1.2.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube calculated at the reference temperature (T_r), as specified in 2.5.1.2. The reference meter tube internal diameter is the certified or stamped meter tube internal diameter.

2.3.1.6 Diameter Ratio (β, β_m, β_r)

The diameter ratio (β) is defined as the calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

The diameter ratio (β_m) is defined as the measured orifice plate bore diameter (d_m) divided by the measured meter tube internal diameter (D_m).

The diameter ratio (β_r) is defined as the reference orifice plate bore diameter (d_r) divided by the reference meter tube internal diameter (D_r).

2.3.2 PRESSURE MEASUREMENT

2.3.2.1 Tap Hole

A tap hole is a hole drilled radially in the wall of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

2.3.2.2 Flange Taps

Flange taps are a pair of tap holes positioned as follows:

a. The upstream tap center is located 1 inch upstream of the nearest plate face.
b. The downstream tap center is located 1 inch downstream of the nearest plate face.

2.3.2.3 Differential Pressure (ΔP)

The differential pressure (ΔP) is the static pressure difference measured between the upstream and the downstream flange taps.

2.3.3 TEMPERATURE MEASUREMENT (T_f, T_m, T_r)

The temperature (T_f) is the flowing fluid temperature measured at the designated upstream or downstream location, as specified in 2.6.4.

In flow measurement applications where the fluid velocity is well below sonic, it is common practice to insert a temperature sensing device positioned in the the flowing stream to obtain the flowing temperature. For practical applications, the sensed temperature is assumed to be the static temperature of the flowing fluid.

The temperature (T_m) is the measured temperature of the orifice plate and/or the meter tube at the time of the diameter measurements, as specified in 2.4.3 and 2.5.1.2.

The temperature (T_r) is the reference temperature used to determine the reference orifice plate bore diameter (d_r) and/or the reference internal meter tube diameter (D_r), as specified in 2.4.3 and 2.5.1.2.

2.3.4 ROUGHNESS AVERAGE (R_a)

The roughness average (R_a) used in this standard is that given in ANSI[1] B46.1 and is "the arithmetic average of the absolute values of the measured profile height deviation taken within the sampling length and measured from the graphical centerline."

2.4 Orifice Plate Specifications

The symbols for the orifice plate dimensions are shown in Figure 2-1.

2.4.1 ORIFICE PLATE FACES

The upstream and downstream faces of the orifice plate shall be flat. Deviations from flatness on the orifice plate of less than or equal to 1 percent of dam height (that is, 0.010 inch per inch of dam height) under static conditions are allowed. The dam height can be calculated from the formula $(D_m - d_m)/2$. This criterion for flatness applies to any two points on the orifice plate within the dimensions of the inside diameter of the pipe. The departure from flatness is illustrated in Table 2-1.

The surface roughness of the upstream and downstream faces of the orifice plate shall have no abrasions or scratches visible to the naked eye that exceed 50 microinches R_a. The

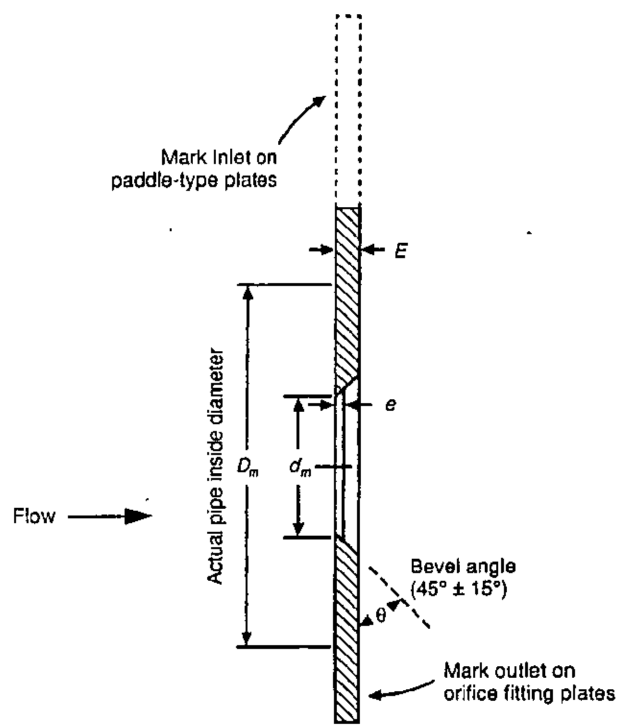


Figure 2-1—Symbols for Orifice Plate Dimensions

[1]American National Standards Institute, 1430 Broadway, New York, New York 10018.

Date of Issue: April 1994
Affected Publication: Chapter 14, "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 2, "Specification and Installation Requirements" of the *Manual of Petroleum Measurement Standards*, Third Edition, February 1991

On page 4, Figure 2-1 should appear as shown below:

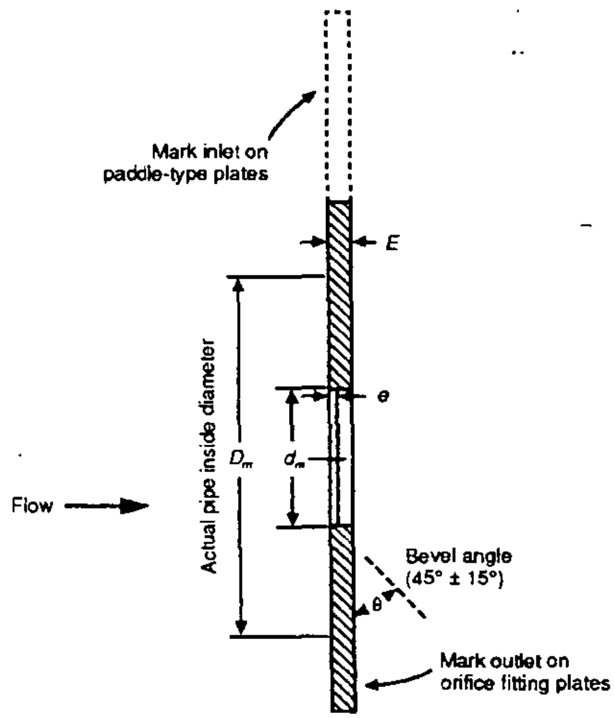
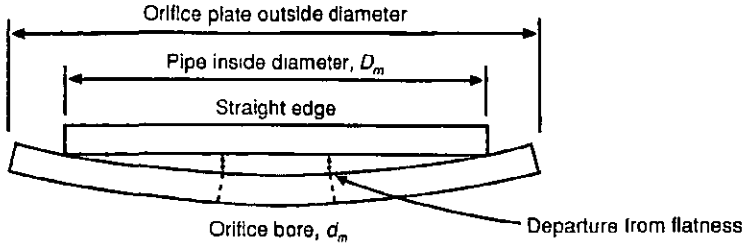


Figure 2-1—Symbols for Orifice Plate Dimensions

Table 2-1—Orifice Plate Flatness Tolerance



(MEASURED AT EDGE OF ORIFICE BORE AND WITHIN INSIDE PIPE DIAMETER)

Orifice Bore Diameter, d_m (inches)	Maximum Departure From Flatness (inches) for Nominal Meter Tube Size (inches)										
	2	3	4	6	8	10	12	16	20	24	30
0.125[a]	0.009										
0.250[a]	0.009										
0.375[a]	0.008										
0.500	0.008	0.013									
0.625	0.007	0.012	0.017								
0.750	0.007	0.012	0.016	0.027							
0.875	0.006	0.011	0.016	0.026	0.036						
1.000	0.005	0.010	0.015	0.025	0.035	0.046					
1.250	0.004	0.009	0.014	0.024	0.034	0.044	0.054				
1.500	0.003	0.008	0.013	0.023	0.033	0.043	0.053	0.067			
1.750		0.007	0.011	0.022	0.032	0.042	0.052	0.066			
2.000		0.005	0.010	0.020	0.030	0.041	0.050	0.065	0.085		
2.250		0.004	0.009	0.019	0.029	0.039	0.049	0.063	0.083		
2.500			0.008	0.018	0.028	0.038	0.048	0.062	0.082	0.102	
2.750			0.006	0.017	0.027	0.037	0.047	0.061	0.081	0.101	
3.000			0.005	0.015	0.025	0.036	0.045	0.060	0.080	0.100	0.130
3.250				0.014	0.024	0.034	0.044	0.058	0.078	0.098	0.128
3.500				0.013	0.023	0.033	0.043	0.057	0.077	0.097	0.127
3.750				0.012	0.022	0.032	0.042	0.056	0.076	0.096	0.126
4.000				0.010	0.020	0.031	0.040	0.055	0.075	0.096	0.125
4.500				0.008	0.018	0.028	0.038	0.052	0.072	0.092	0.122
5.000					0.015	0.026	0.035	0.050	0.070	0.090	0.120
5.500					0.013	0.023	0.033	0.047	0.067	0.087	0.117
6.000					0.010	0.021	0.030	0.045	0.065	0.085	0.115
6.500						0.018	0.028	0.042	0.062	0.082	0.112
7.000						0.016	0.025	0.040	0.060	0.080	0.110
7.500						0.013	0.023	0.037	0.570	0.077	0.107
8.000							0.020	0.035	0.055	0.075	0.105
8.500							0.018	0.032	0.052	0.072	0.102
9.000[b]							0.015	0.030	0.050	0.070	0.100

[a]Use of these diameters is not prohibited but may result in uncertainties greater than those specified in Chapter 14, Section 3, Part 1.
[b]For larger sizes, the maximum departure from flatness is equal to $0.005(D_m - d_m)$.

surface roughness may be verified by using an electronic-averaging-type surface roughness instrument with a cutoff value of not less than 0.03 inch. Other surface roughness devices (for example, a visual comparator) are acceptable for determination of orifice plate surface roughness if the same repeatability and reproducibility as those of the electronic-averaging-type surface roughness instrument can be demonstrated.

The plate shall be kept clean at all times and free from accumulations of dirt, ice, and other extraneous material.

2.4.2 ORIFICE PLATE BORE EDGE

The upstream edge of the orifice plate bore shall be square and sharp. The orifice plate bore edge is considered to be too dull for accurate flow measurement if the upstream edge reflects a beam of light when viewed without magnification or if the upstream edge shows a beam of light when checked with an orifice edge gauge.

An estimation of suitable sharpness can be made by comparing the orifice plate bore edge with the bore edge of a reference orifice plate of the same nominal diameter. The orifice plate bore edge being evaluated should feel and look the same as the edge of the reference orifice plate.

The upstream and downstream edges of the orifice plate bore shall be free from defects visible to the naked eye, such as flat spots, feathered texture, roughness, burrs, bumps, nicks, and notches.

If there is any doubt about whether the edge has sufficient quality for accurate metering, the orifice plate should be replaced.

2.4.3 ORIFICE PLATE BORE DIAMETER (d_m, d_r) AND ROUNDNESS

The measured orifice bore diameter, d_m, is defined as the mean (arithmetic average) of four or more evenly spaced diameter measurements. None of the four or more diameter measurements may vary from the mean value by more than the tolerances given in Table 2-2. The orifice plate temperature should be recorded at the time the bore diameter measurements are made.

The orifice plate bore diameter, d_r, is defined as the calculated reference diameter at reference temperature (T_r) and can be determined using the following equation:

$$d_r = d_m[1 + \alpha_1(T_r - T_m)] \tag{2-1}$$

Where:

α_1 = linear coefficient of thermal expansion for the orifice plate material (see Table 2-3).
d_r = orifice plate bore diameter calculated at reference temperature (T_r).
d_m = orifice plate bore diameter measured at T_m.
T_m = temperature of the orifice plate at time of diameter measurements.
T_r = reference temperature of the orifice plate bore diameter.

Note: α_1, T_m, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F.

The orifice plate bore diameter, d_r, calculated at T_r is the reference diameter used to calculate the bore diameter (d) at flowing conditions, as specified in Part 1.

2.4.4 ORIFICE PLATE BORE THICKNESS (e)

The inside surface of the orifice plate bore shall be in the form of a constant-diameter cylinder having no defects, such as grooves, ridges, pits, or lumps, visible to the naked eye. The length of the cylinder is the orifice plate bore thickness (e).

Table 2-2—Roundness Tolerance for Orifice Plate Bore Diameter, d_m

Orifice Bore Diameter, d_m (inches)	Tolerance (± inches)
≤0.250[a]	0.0003
0.251–0.375[a]	0.0004
0.376–0.500[a]	0.0005
0.501–0.625	0.0005
0.626–0.750	0.0005
0.751–0.875	0.0005
0.876–1.000	0.0005
>1.000	0.0005 inch per inch of diameter

[a]Use of diameters below 0.45 inch is not prohibited but may result in uncertainties greater than those specified in Chapter 14, Section 3, Part 1.

Table 2-3—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion, α [U.S. Units (in/in-°F)]
Type 304 and 316 stainless steel[a]	0.00000925
Monel[a]	0.00000795
Carbon steel[b]	0.00000620

Note: For flowing temperature conditions outside those stated above and for other materials, refer to the American Society for Metals *Metals Handbook*
[a]For flowing conditions between –100°F and +300°F, refer to ASME PTC 19.5.
[b]For flowing conditions between –7°F and +154°F, refer to Chapter 12, Section 2.

The minimum allowable orifice plate bore thickness (e) is defined by $e \geq 0.01d_m$ or $e > 0.005$ inch, whichever is larger.

The maximum allowable value for the orifice plate bore thickness (e) is defined by $e \leq 0.02D_m$ or $e \leq 0.125d_m$, whichever is smaller, but e shall not be greater than the orifice plate thickness (E).

2.4.5 ORIFICE PLATE THICKNESS (E)

The minimum, maximum, and recommended values of orifice plate thickness (E) for Types 304 and 316 stainless steel orifice plates are given in Table 2-4 for differential pressures not exceeding 200 inches water column and operating temperatures not exceeding 150°F. In other cases the manufacturer should be contacted for specific information on deflection (see 2.4.1) for a given diameter ratio, temperature, orifice plate material, orifice plate holder, and differential pressure.

2.4.6 ORIFICE PLATE BEVEL (θ)

The plate bevel angle (θ) is defined as the angle between the bevel and the downstream face of the plate. The allowable value for the plate bevel angle (θ) is 45 degrees ± 15 degrees.

The surface of the plate bevel shall have no defects visible to the naked eye, such as grooves, ridges, pits, or lumps.

If a bevel is required (see Table 2-4), its minimum dimension measured along the axis of the bore shall not be less than $\frac{1}{16}$ inch.

2.5 Meter Tube Specifications

2.5.1 DEFINITION

The *meter tube* is defined as the straight upstream pipe of the same diameter [length A or A' on the installation sketches (see Figures 2-5–2-9)], including the straightening vanes, if used, the orifice plate holder, and the similar downstream pipe [length B on the installation sketches (see Figures 2-5–2-9)] beyond the orifice plate. The length of the upstream and downstream pipe sections is specified in 2.6.3.1. The tolerances for the diameter and the restrictions for the inside surface of the meter tube are specified in 2.5.1.1 through 2.5.1.3. There shall be no pipe connections within these distances other than the pressure taps specified in 2.5.4 (and pipe taps as defined in Appendix 3-D of Part 3), temperature probes specified in 2.6.4, and/or straightening vane attachments, either flanged or in line.

2.5.1.1 Inside Surface

The sections of the meter tube to which the orifice plate holder is attached or the adjacent pipe sections that constitute part of the meter tube, as defined in 2.5.1, shall comply with 2.5.1.1.1 through 2.5.1.1.3.

On page 7, Table 2-3 should read as follows:

Table 2-3—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion, α [U.S. Units (in/in·°F)]
Type 304 and 316 stainless steel[a]	0.00000925
Monel[a]	0.00000795
Carbon steel[b]	0.00000620

Note: For flowing temperature conditions other than those stated in Footnotes a and b and for other materials, refer to the American Society for Metals *Metals Handbook*.
[a]For flowing conditions between –100°F and +300°F, refer to ASME PTC 19.5.
[b]For flowing conditions between –7°F and +154°F, refer to Chapter 12, Section 2.

On page 8, Table 2-4 should appear as shown on the following page:

Table 2-4—Orifice Plate Dimensions

		2	3	3	4	4	6	6	8	8	10	12	12	16	16	20	24	24	30	30
Nominal Inside Diameter (inches)																				
Published Inside Diameter		1.687		2.624	3.152						9.562					13.812				
		1.939		2 900	3.438		4.897	5.761		7.981	10.020		11.938		15 000	19 000		23 000		29.000
		2.067	2.300	3.068	3.826	4 026	5.187	6 065	7.625	8.071	10.136	11 374	12.090	14.688	15.250	19.250	22.624	23.250	28.750	29.250
Orifice Plate Thickness, E (inches)																				
Minimum		0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.175	0.175	0.175	0.175	0.240	0.240	0.240	0.370	0.370
Maximum		0.130	0.130	0.130	0.130	0.130	0.163	0.192	0.254	0.319	0.319	0.379	0.398	0.490	0.500	0 505	0.505	0.562	0.562	0.578
Recommended		0.125	0 125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.250	0.250	0.250	0.375	0.375	0.375	0.375	0.375	0.500	0.500
Orifice Bore Diameter, d_m	**$e \le 0.125d_m$**	**Maximum Orifice Edge Thickness, e (inches)**																		
0.250*	1/32	×1/32	×1/32	1/32	1/32	1/32														
0.375*	3/64			×3/64	3/64	3/64														
0.500	1/16				×1/16	1/16	1/16	1/16												
0.625	5/64					×5/64	5/64	5/64												
0.750	3/32						×3/32	3/32												
0.875	7/64							×7/64	7/64	7/64										
1.000	1/8								1/8	1/8	1/8									
1.125	9/64								×9/64	9/64	9/64									
1.250	5/32									×5/32	5/32	5/32	5/32							
1.375	11/64										11/64	11/64	11/64							
1.500	3/16										×3/16	3/16	3/16	3/16	3/16					
1.625	13/64											13/64	13/64	13/64	13/64					
1.750	7/32											×7/32	7/32	7/32	7/32					
1.875	15/64												×15/64	15/64	15/64					
2.000	1/4													1/4	1/4	1/4				
2.250	9/32													×9/32	9/32	9/32				
2.375	19/64														×19/64	19/64	19/64	19/64		
2.500	5/16															5/16	5/16	5/16		
2.750	11/32															11/32	11/32	11/32		
2.875	23/64															23/64	23/64	23/64	23/64	23/64
3.000	3/8															×3/8	3/8	3/8	3/8	3/8
3.250	13/32																13/32	13/32	13/32	13/32
3.500	7/16																×7/16	7/16	7/16	7/16
3.625	29/64																	×29/64	29/64	29/64
3.750	15/32																		15/32	15/32
4 000	1/2																		1/2	1/2
4.250	17/32																		17/32	17/32
4 500	9/16																		×9/16	9/16
4.625	37/64																			37/64
4.750	19/32																			
5.000	5/8																			

(Shaded areas in table: "Bevel not required" — upper right; "Bevel required" — lower left.)

Notes:

1. The maximum edge thickness is defined by $e < 0.02D_m$ or $e < 0.125d_m$, whichever is smaller.
2. An orifice edge thickness marked with an × is the maximum for that particular meter tube diameter and is applicable to all larger orifice diameters for that meter tube diameter.
3. Orifice diameters smaller than those marked with an × are defined by $e < 0.125d_m$.
4. Orifice plates whose edge thickness meets the value defined by $e < 0.033D_m$ need not be rebeveled unless reconditioning is required for other reasons.
5. All dimensions are in inches. For ease in machining, the next smaller values of e, in even multiples of 1/64 inch or 1/32 inch, may be used where e is given in 64ths of an inch.
6. Bidirectional flow through an orifice meter requires a specially configured meter tube and the use of an unbeveled orifice plate. Use of an unbeveled orifice plate with bore thickness, e, that exceeds the limits specified in this table is outside of the scope of this standard.
7. If a bevel is required, its minimum dimension, measured along the axis of the bore, shall not be less than 1/16 inch.
8. The use of diameters marked with an asterisk (*) may result in coefficient of discharge uncertainties larger than those specified in Chapter 14, Section 3, Part 1.
9. To prevent plate deflection, the recommended 8-inch orifice plate thickness (E) requires that the differential pressure be limited to 150 inches water column.

Table 2-4—Orifice Plate Dimensions

Nominal Inside Diameter (inches)

		2	3	3	4	4	6	6	8	8	10	12	12	16	16	20	24	24	30	30
Published Inside Diameter		1.687		2.624	3.152						9.562					18.812				
		1.939		2.900	3.438		4.897	5.761		7.981	10.020		11.938		15.000	19.000		23.000		29.000
		2.067	2.300	3.068	3.826	4.026	5.187	6.065	7.625	8.071	10.136	11.374	12.090	14.688	15.250	19.250	22.624	23.250	28.750	29.250
Orifice Plate Thickness, *E* (inches)																				
Minimum		0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.175	0.175	0.175	0.175	0.240	0.240	0.240	0.370	0.370
Maximum		0.130	0.130	0.130	0.130	0.130	0.163	0.192	0.254	0.319	0.319	0.379	0.398	0.490	0.500	0.505	0.505	0.562	0.562	0.578
Recommended		0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.250	0.250	0.250	0.375	0.375	0.375	0.375	0.375	0.500	0.500
Orifice Bore Diameter, d_m	$e \leq 0.125 d_m$	Maximum Orifice Edge Thickness, *e* (inches)																		
0.250*	1/32	×1/32	×1/32	1/32	1/32	1/32														
0.375*	3/64			×3/64	3/64	3/64														
0.500	1/16				×1/16	1/16	1/16	1/16												
0.625	5/64					×5/64	5/64	5/64												
0.750	3/32						×3/32	3/32												
0.875	7/64							×7/64	7/64	7/64										
1.000	1/8								1/8	1/8	1/8									
1.125	9/64								×9/64	9/64	9/64									
1.250	5/32									×5/32	5/32	5/32	5/32							
1.375	11/64										11/64	11/64	11/64							
1.500	3/16										×3/16	3/16	3/16	3/16	3/16					
1.625	13/64											13/64	13/64	13/64	13/64					
1.750	7/32											×7/32	7/32	7/32	7/32					
1.875	15/64												×15/64	15/64	15/64					
2.000	1/4													1/4	1/4	1/4				
2.250	9/32													×9/32	9/32	9/32				
2.375	19/64														×19/64	19/64	19/64	19/64		
2.500	5/16															5/16	5/16	5/16		
2.750	11/32															11/32	11/32	11/32		
2.875	23/64															23/64	23/64	23/64	23/64	23/64
3.000	3/8															×3/8	3/8	3/8	3/8	3/8
3.250	13/32																13/32	13/32	13/32	13/32
3.500	7/16																×7/16	7/16	7/16	7/16
3.625	29/64																	×29/64	29/64	29/64
3.750	15/32																		15/32	15/32
4.000	1/2																		1/2	1/2
4.250	17/32																		17/32	17/32
4.500	9/16																		×9/16	9/16
4.625	37/64																			37/64
4.750	19/32																			
5.000	5/8																			

Notes:

1. The maximum edge thickness is defined by $e < 0.02D_m$ or $e < 0.125d_m$, whichever is smaller
2. An orifice edge thickness marked with an × is the maximum for that particular meter tube diameter and is applicable to all larger orifice diameters for that meter tube diameter.
3. Orifice diameters smaller than those marked with an × are defined by $e < 0.125d_m$.
4. Orifice plates whose edge thickness meets the value defined by $e < 0.033D_m$ need not be rebeveled unless reconditioning is required for other reasons.
5. All dimensions are in inches. For ease in machining, the next smaller values of *e*, in even multiples of 1/64 inch or 1/32 inch, may be used where *e* is given in 64ths of an inch.
6. Bidirectional flow through an orifice meter requires a specially configured meter tube and the use of an unbeveled orifice plate. Use of an unbeveled orifice plate with bore thickness, *e*, that exceeds the limits specified in this table is outside of the scope of this standard
7. If a bevel is required, its minimum dimension, measured along the axis of the bore, shall not be less than 1/64 inch.
8. The use of diameters marked with an asterisk (*) may result in coefficient of discharge uncertainties larger than those specified in Chapter 14, Section 3, Part 1.
9. To prevent plate deflection, the recommended 8-inch orifice plate thickness (*E*) requires that the differential pressure be limited to 150 inches water column.

2.5.1.1.1 The internal surface roughness of the meter tube should be measured at approximately the same axial locations as those used to determine and verify the meter tube internal diameter (see 2.5.1.2). The values specified in Items a and b below are the arithmetic average roughnesses obtained using an electronic-averaging-type surface roughness instrument with a cutoff value of not less than 0.03 inch. Other surface roughness devices are acceptable for determination of meter tube surface roughness if the same repeatability and reproducibility as those of the electronic-averaging-type surface roughness instrument can be demonstrated. A minimum of four roughness measurements shall be made.

The mean (arithmetic average) of these four or more roughness measurements is defined as the meter tube internal surface roughness. The mean meter tube internal surface roughness may not exceed the following specifications if the uncertainty values of Part 1 are to be met:

a. 300 microinches R_a if the diameter ratios (β_r) are less than 0.6.
b. 250 microinches R_a if the diameter ratios (β_r) are greater than or equal to 0.6.

Note: The use of lower diameter ratios (β_r) reduces the effect of pipe roughness on uncertainty.

Carefully selected smooth commercial pipe may be used. To improve smoothness within the meter tube, the inside pipe walls may be machined, ground, or coated.

2.5.1.1.2 Irregularities such as grooves, scoring, or ridges resulting from seams, welding distortion, offsets, and the like, that affect the inside diameter by more than the tolerances given in 2.5.1.3 shall not be permitted. When these tolerances are exceeded, the irregularities must be corrected.

2.5.1.1.3 The interior of the meter tube shall be clean at all times and free from accumulations of contaminants (dirt, liquids, and so forth).

2.5.1.2 Meter Tube Diameter (D_m, D_r)

The measured internal diameter of the meter tube, D_m, shall be determined as specified in 2.5.1.2.1 through 2.5.1.2.5.

2.5.1.2.1 A minimum of four equally spaced individual internal diameter measurements shall be made in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these four or more individual measurements is defined as the measured meter tube internal diameter (D_m).

2.5.1.2.2 Individual check measurements of the internal diameter of the upstream section (A or A' in Figures 2-5–2-9) of the meter tube (excluding the orifice plate gasket or sealing device diameter) shall be made at a minimum of two additional cross-sections. The actual locations of the individual internal diameter check measurements, circumferentially and axially along the tube, are not specified. These individual checks should be made at points that will indicate the maximum and minimum dimensions of the internal diameter of the meter tube's upstream section.

One of these individual check measurements should be made in a region at least two pipe diameters from the face of the orifice plate or past the orifice plate holder weld or flange, whichever is the greater distance. Other individual measurements should be made at selected points within the A or A' dimension.

Individual check measurements are used to verify the uniformity of the internal diameter of the upstream section of the meter tube (see 2.5.1.3) but do not become a part of the determination of the mean meter tube internal diameter.

2.5.1.2.3 Individual check measurements of the meter tube internal diameter, D_m, shall be made in the downstream section of the meter tube in a plane 1 inch downstream from the downstream face of the orifice plate (see 2.5.1.3).

Additional individual check measurements of the internal diameter, D_m (excluding the orifice plate gasket or sealing device diameter), shall be made at a minimum of two other cross-sections in the downstream section of the meter tube (see 2.5.1.3), similar to the measurements specified in 2.5.1.2.2.

2.5.1.2.4 Meter tube internal diameters are not limited to published nominal inside pipe diameters. However, all applicable regulations and codes must be followed.

2.5.1.2.5 The meter tube temperature should be recorded at the time the internal diameter measurements are made.

The reference meter tube internal diameter, D_r, is defined as the calculated meter tube internal diameter at reference temperature (T_r) and can be determined using the following equation:

$$D_r = D_m[1 + \alpha_2(T_r - T_m)] \qquad (2\text{-}2)$$

Where:

α_2 = linear coefficient of thermal expansion for the meter tube material (see Table 2-3).
D_m = meter tube internal diameter measured at temperature (T_m).
D_r = reference meter tube internal diameter calculated at reference temperature (T_r).
T_m = temperature of the meter tube at the time of the diameter measurements.
T_r = reference temperature of the meter tube internal diameter.

Note: α_2, T_m, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F.

The meter tube internal diameter, D_r, calculated at T_r is the diameter used to calculate the meter tube internal diameter (D) at flowing conditions, as specified in Part 1.

2.5.1.3 Tolerances and Restrictions

The tolerances for the diameter and the restrictions for the internal surface of the meter tube are specified in 2.5.1.3.1 through 2.5.1.3.3.

2.5.1.3.1 Meter Tube Internal Diameter Roundness Tolerance

2.5.1.3.1.1 Within the First Mean Meter Tube Diameter (D_m) Upstream of the Orifice Plate

The absolute value of the percentage difference between the measured meter tube internal diameter, D_m, and any individual diameter measurement within a distance of one meter tube diameter, D_m, on the upstream side of the orifice plate shall not exceed 0.25 percent of D_m:

$$\left| \frac{\text{Any diameter within one } D_m - D_m}{D_m} \times 100 \right| \leq 0.25\% \qquad (2\text{-}3)$$

An example of this situation is provided in Table 2-5. All measurements within one meter tube diameter upstream of the orifice plate face are within 0.25 percent of the 2.0695 mean.

Table 2-5—Example Meter Tube Internal Diameter Roundness Tolerances: Within First Mean Meter Tube Diameter Upstream of Orifice Plate

	Meter Tube Internal Diameter Measurements (inches)				
Position	A	B	C	D	Mean, D_m
1-inch upstream plate	2.0696	2.0694	2.0694	2.0696	2.0695
Within one D_m	2.0700	2.0676	2.0671	2.0655	

2.5.1.3.1.2 All Upstream Meter Tube Individual Internal Diameter Measurements, Including Those Within One Meter Tube Diameter Upstream of the Orifice Plate

The percentage difference between the maximum measured individual internal diameter measurement and the minimum measured individual internal diameter measurement of all upstream meter tube individual internal diameter measurements, including those within the first meter tube diameter upstream of the orifice plate, shall not exceed 0.5 percent of D_m:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D_m} \times 100 \leq 0.5\% \qquad (2\text{-}4)$$

An example of this situation is provided in Table 2-6. The calculation to verify that the measurements meet the tolerance criterion is as follows:

$$\frac{2.0700 - 2.0601}{2.0695} \times 100 = 0.48\%$$

All upstream meter tube individual internal diameter measurements, including those within one meter tube diameter, D_m, upstream of the orifice plate are within 0.5 percent of D_m.

2.5.1.3.2 Meter Tube Downstream Internal Roundness Tolerance

The absolute value of the percentage difference between the measured meter tube diameter, D_m, and any individual internal diameter on the downstream side shall not exceed 0.5 percent of D_m:

$$\left|\frac{\text{Any downstream diameter} - D_m}{D_m} \times 100\right| \leq 0.5\% \qquad (2\text{-}5)$$

2.5.1.3.3 General Meter Tube Restrictions

Abrupt changes of the inside meter tube surface (shoulders, offsets, ridges, welding seams, and the like) shall not exist in meter tubes, with the exception of those allowed in 2.5.1.4.

2.5.1.4 Orifice Plate Gasket or Sealing Device Recesses and Protrusions

The orifice plate gasket or sealing device tolerances and restrictions specified in 2.5.1.4.1 through 2.5.1.4.5 shall apply at locations immediately upstream and downstream of the orifice plate face.

2.5.1.4.1 Protrusions resulting from an orifice plate gasket or sealing device that extend into the pipe bore are not permitted.

Table 2-6—Example Meter Tube Internal Diameter Roundness Tolerances: All Upstream Meter Tube Individual Internal Diameter Measurements

	Meter Tube Internal Diameter Measurements (inches)				
Position	A	B	C	D	Mean, D_m
1-inch upstream plate	2.0696	2.0694	2.0694	2.0696	2.0695
Within one D_m	2.0700	2.0676	2.0671	2.0655	
Upstream check measurement	2.0621	2.0620	2.0613	2.0601	

2.5.1.4.2 A recess resulting from an orifice plate gasket or sealing device, of 0.25 inch or less in length, as measured parallel to the pipe axis, does not require recess depth restriction, diameter ratio (β_r) limitation, or additional uncertainty.

2.5.1.4.3 A recess resulting from an orifice plate gasket or sealing device, of more than 0.25 inch but less than or equal to 0.5 inch in length, does not require diameter ratio (β_r) limitation or additional uncertainty if the depth of the recess is within the limitations of 2.5.1.3.

2.5.1.4.4 All orifice plate sealing devices shall be of the same nominal inside pipe diameter (within the limits specified in 2.5.1.4.1 through 2.5.1.4.3) as the orifice plate holder in which it is used.

2.5.1.4.5 For recesses larger than those described in 2.5.1.4.2 and 2.5.1.4.3, additional uncertainity may be required.

2.5.2 ORIFICE FLANGES

Orifice flanges for orifice meter tube installations should be constructed and attached to the pipe so that all of the mechanical specifications in 2.5.1.1 and 2.5.1.4 are met.

Any distortion of the pipe resulting from welding the flange to the pipe shall be removed by machining or grinding to meet the limitations specified in 2.5.1.3.

2.5.3 ORIFICE FITTINGS

2.5.3.1 General

Orifice fittings represent a class of orifice holders that is widely used throughout the industry. With these devices it is possible to reproduce the orifice coefficients defined by the equation in Part 1 within the same uncertainty limits as would be found for an orifice plate held between two flanges (the original test devices). To do this, these devices must be manufactured to the tolerances specified in this standard. With orifice fittings, however, some practical considerations should be recognized, and some critical inspections that are unique to these devices should be performed. The following information is based on devices that were commonly known to exist at the time this standard was developed and may not cover innovations that have become commonly known since its publication. Such innovations may be deemed to be in accordance with this standard as long as they meet all tolerances contained herein.

2.5.3.2 Attachment to Pipe

When an upstream flanged orifice fitting is used, the mean inside diameter of the meter tube connected to the inlet side shall agree with the mean inside diameter of the fitting within the tolerance given in 2.5.1.3. When the fitting is installed, the inlet side should be connected to the upstream section of the meter tube first and carefully centered; no sharp edges at this junction are allowed.

To prevent misalignment at this joint when a flanged connection has been used, two diametrically opposed bolt holes may be reamed and snug fitting bolts installed, or dowel pins may be used. Other alignment methods may be used as long as the same result is obtained.

When the upstream section of the meter tube is attached to the orifice fitting body by welding, any distortion of the pipe resulting from the welding shall be removed by machining or grinding to meet the requirements of 2.5.1.3.

2.5.3.3 Inspection Considerations

In some instances the inspection of an orifice fitting may not be as easy as the inspection of a conventional flanged orifice meter. This is true when the fitting in question is of the weld neck design and has already been connected to the meter tube. Unless the meter tube is of a large size, it may be difficult to make measurements in the vicinity of the orifice plate. To make this inspection easier, the fitting should have at least one flanged side (preferably the downstream side). The user should refer to the relevant pressure vessel and pipeline codes to determine whether this particular design may be used in a given system. All measurements of mechanical tolerances should be made after the fitting has been pressure tested at the maximum required test pressure.

2.5.3.4 Bypass Checks

In orifice fittings there is the possibility that some fluid may bypass the orifice plate. Tests shall be conducted after the meter run has been pressure tested in accordance with the relevant code to ensure the following:

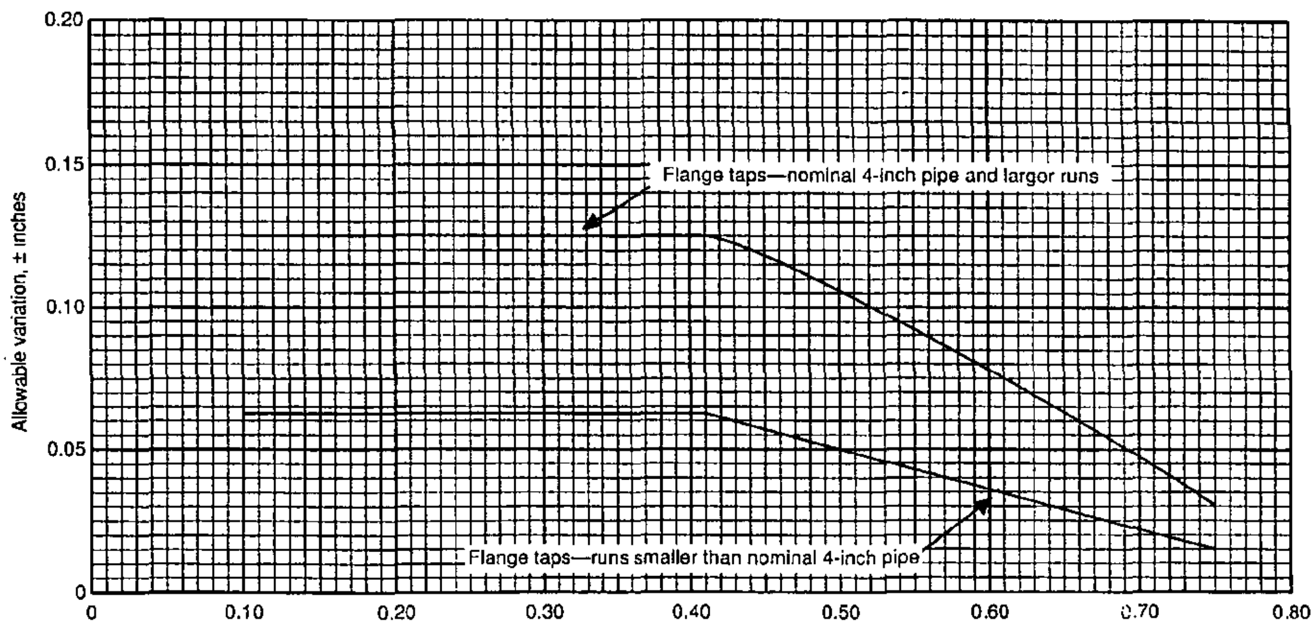
a. No differential pressure tap communication or leakage exists.
b. No holding or sealing device fluid bypass exists.

2.5.4 PRESSURE TAPS

2.5.4.1 Flange Taps

Meter tubes using flange taps shall have the center of the upstream pressure tap hole placed 1 inch from the upstream face of the orifice plate. The center of the downstream pressure tap hole shall be 1 inch from the downstream face of the orifice plate. If the pressure tap holes are located by measuring from the bearing face of a flange, allowance must be made for the gasket or plate holding device used. Each tap hole shall be located at the 1-inch dimension within the tolerances shown in Figure 2-2. It is recommended that a maximum diameter ratio (β) of 0.75 be used in the design of new installations.

Under no circumstances should there be any flow through or out of the flange tap or taps for purposes other than determining pressure and/or differential pressure. This includes flows resulting from manufacturing defects that allow for tap communication or the use of



Note: A maximum β ratio of 0.75 should be used in the design of new installations.

Figure 2-2—Allowable Variations in Pressure Tap Hole Location the flange taps as a source of fluid for other instruments. For the latter, other taps located away from the orifice plate should be used.

For flange-tapped orifice fittings, the location of the flange tap relative to the faces of the plate must be maintained. This precludes the use of either thicker or thinner plates than are specified by the original design, unless the fitting has been redrilled. Likewise, the seals or other orifice holding devices should not affect the location of the plate relative to the taps. Seal/plate combinations should be checked to ensure that the tolerance on the location of the flange taps is not exceeded.

2.5.4.2 Pressure Tap Drilling

Pressure tap holes shall be drilled radially to the meter tube; that is, the centerline of the tap hole shall intersect and form a right angle with the axis of the meter tube.

2.5.4.3 Pressure Tap Diameter

The diameter of the pressure tap holes at the inner surface of the meter tube and along the drilled length of the holes shall be ⅜ inch ± 1/64 inch for pipe with a nominal diameter of 2 or 3 inches and shall be ½ inch ± 1/64 inch for pipe with a nominal diameter of 4 inches or larger.

The pressure tap holes in the orifice plate holder may be drilled out and threaded to receive the desired size of pressure tubing connection.

The diameter of the tap hole shall not be reduced within a length equal to 2½ times the tap hole diameter, as measured from the inside surface of the meter tube.

2.5.4.4 Pressure Tap Edges

The edges of the pressure tap holes on the inner surface of the meter tube shall be free from burrs and may be slightly rounded.

2.5.5 STRAIGHTENING VANES

2.5.5.1 Design of Tube Bundle Flow Straighteners

The maximum transverse dimension, a (see Figure 2-3), of any passage through the vanes shall not exceed one-fourth the inside diameter, D_t, of the meter tube. The cross-sectional area, A, of any passage within the assembled vanes shall not exceed one-sixteenth of the cross-sectional area of the containing meter tube. The length, L, of the vanes shall be at least 10 times the maximum inside dimension, a. The length, L, shall not exceed one-half the dimension C' in Figures 2-5, 2-6, 2-7, and 2-9, or else the dimensions C' and A' in these figures must be increased. It is not necessary for all the tubes to be the same size, but their arrangement must be symmetrical.

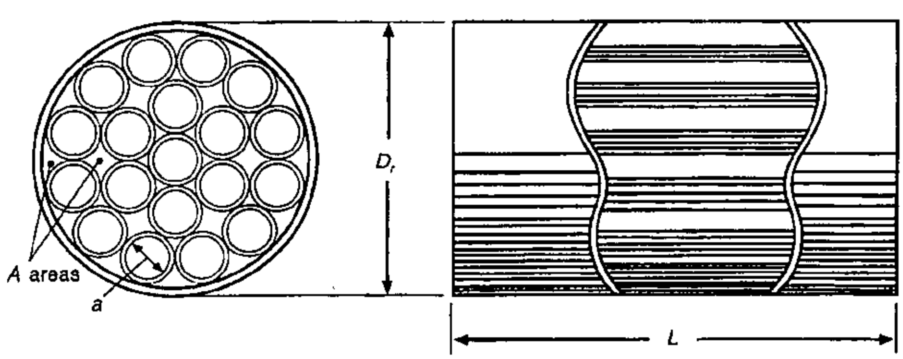


Figure 2-3—Tube Bundle Flow Straightener

2.5.5.2 Tubing

The vanes (see Figure 2-3) may be built of smooth standard-weight pipe, thin-walled tubing, or square, hexagonal, or other shaped tubing, either welded together or mounted into two end rings small enough to slip into the meter tube. Regardless of the design, the material used to make these vanes should be of uniform smoothness. The amount of passage blockage caused by the end rings should be kept as small as is practical. All tubes should be parallel, tapered as thin as is practical at both ends of each tube, and mounted axially with the pipe.

2.5.5.3 Fabrication

Straightening vanes must be sturdily fabricated. After being inserted in the meter tube, they shall be securely fastened in place to prevent their being dislodged and pushed down against the orifice plate. Secure fastening, however, should not distort the vane assembly with respect to the symmetry of the vanes within the meter tube. The vanes should be constructed to minimize the effects of swirl. Swirl can occur between the exterior tubes of the bundle and the wall of the pipe.

2.5.5.4 Other Flow Conditioners

The use of other types of flow conditioners should be based on technical performance data and mutually agreed upon by the parties involved. No specifications on the construction, installation, or uncertainty of other flow conditioners are presented in this standard.

2.6 Installation Requirements

2.6.1 GENERAL

The orifice plate coefficients of discharge (C_d) given in this standard are based on the results of many experiments conducted in both the United States and Europe. In all cases, normal flow conditions were obtained by the use of long straight lengths of meter tube, both upstream and downstream from the orifice, or by the use of flow conditioners upstream from the orifice meter (see Part 1, 1.12.4.3). To obtain the uncertainty specified on the coefficient of discharge presented in Part 1, similar fluid dynamic conditions must be attained in practice.

2.6.2 ORIFICE PLATE

2.6.2.1 Eccentricity (ε)

The orifice plate bore must be concentric with both the upstream and downstream inside wall of the orifice plate holder. The orifice plate bore eccentricity, measured parallel to the axis of the pressure taps, shall be less than or equal to the tolerance defined by the following equation:

$$\varepsilon \leq \frac{0.0025D_m}{0.1 + 2.3\beta_m^4} \tag{2-6}$$

Where:

ε = orifice plate bore eccentricity.

Table 2-7 shows some examples of the maximum allowable orifice bore eccentricity.

Orifice plate bore eccentricity perpendicular to the axis of the pressure taps may be four times the amount calculated using Equation 2-6 as long as the eccentricity in a plane at 45 degrees to and in a plane parallel to the pressure tap does not exceed the limit calculated from Equation 2-6.

For practical purposes, one method of determining the orifice plate bore eccentricity is to measure the perpendicular distance between the installed orifice plate bore edge and the

Table 2-7—Maximum Orifice Plate Bore Eccentricity Tolerances (Inches)

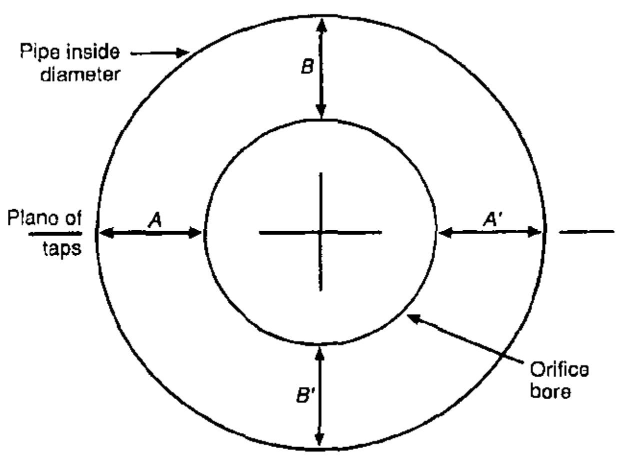
	Meter Tube Inside Diameter (inches)					
β_m	2.067	3.068	4.026	6.065	7.981	10.020
0.20	0.050	0.074	0.097	0.146	0.192	0.242
0.25	0.047	0.070	0.092	0.139	0.183	0.230
0.30	0.044	0.065	0.085	0.128	0.168	0.211
0.35	0.038	0.057	0.075	0.113	0.148	0.186
0.40	0.033	0.048	0.063	0.095	0.126	0.158
0.45	0.027	0.039	0.052	0.078	0.103	0.129
0.50	0.021	0.032	0.041	0.062	0.082	0.103
0.55	0.017[a]	0.025	0.032	0.049	0.064	0.081
0.60	0.013[a]	0.019[a]	0.025	0.033	0.050	0.063
0.65	0.010[a]	0.015[a]	0.020	0.030	0.039	0.049
0.70	0.008[a]	0.012[a]	0.015[a]	0.023	0.030	0.038

[a]For these values, a minimum eccentricity value of 0.020 inch is considered practical. This may increase the uncertainty of the orifice plate coefficient of discharge (C_d) by an additional 0.0–0.5 percent.

inside walls of the meter tube at the pressure tap location. One-half the difference between the two measurements $[(A - A')/2]$, 180 degrees apart, represents the eccentricity in one plane. This assumes that the orifice plate bore and the meter tube inside wall are round to within a tolerance smaller than the maximum allowable eccentricity limit. Two pairs of measurements, in planes parallel to and perpendicular to the pressure tap axis (see Figure 2-4), should be made to verify the orifice plate bore eccentricity. Other technically valid techniques for verifying the orifice plate bore eccentricity are acceptable.

The maximum allowable orifice plate bore eccentricity calculated using Equation 2-6 can be doubled if flange taps 180 degrees apart are connected together to obtain an average pressure. Care should be taken to ensure that equal lengths of tubing are used to connect the taps and that the connection to the differential pressure (ΔP) device is located midway between the taps.

When measurement of the eccentricity of an orifice plate installed in orifice flanges is not possible, two accurately located alignment pins should be used to support and center the orifice plate while the bolts are tightened. The eccentricity relative to the upstream side is



Note:

Horizontal eccentricity = $(A - A')/2$

Vertical eccentricity = $(B - B')/2$

Figure 2-4—Eccentricity Measurements (Sample Method) considered to be the most critical. It is therefore recommended that any alignment pins or other devices used to position the orifice plate be mounted so that the plate is centered relative to the upstream section of the meter tube and pressure tap.

Plate centering techniques are a function of the design and are only constrained by the maximum allowable eccentricity described above. In most orifice fittings, the orifice plate is held in the flowing stream by a carrier mechanism. Such mechanisms theoretically produce a repeatable eccentricity for the orifice plate. This should be checked for several operations of installing the plate in, and removing it from, the orifice fitting. The plate/carrier combination used to perform this test should be the same combination that will be used in the field. If any of the fitting's internal mechanisms are replaced, this inspection should be repeated.

2.6.2.2 Perpendicularity

The orifice plate holder should maintain the plane of the orifice plate at an angle of 90 degrees to the meter tube axis.

2.6.3 METER TUBE

2.6.3.1 Length

To assure accurate flow measurement, the fluid should enter the orifice plate with a fully developed flow profile, free from swirl or vortices. Such a condition is best achieved through the use of flow conditioners and adequate lengths of straight pipe upstream and downstream from the orifice plate. For further discussion, see Part 1, 1.12.4.3.

Any serious distortion of the flow profile will produce flow measurement errors. There are many piping configurations in which the orifice meter will not produce results within the uncertainty of this standard. Some of the more common types of piping installations have been studied with regard to their effect on metering accuracy. Figures 2-5–2-9 show the minimum lengths of meter tube required.

For installations that are not explicitly covered in the installation sketches, Figure 2-5 should be followed.

2.6.3.2 Installation Sketches

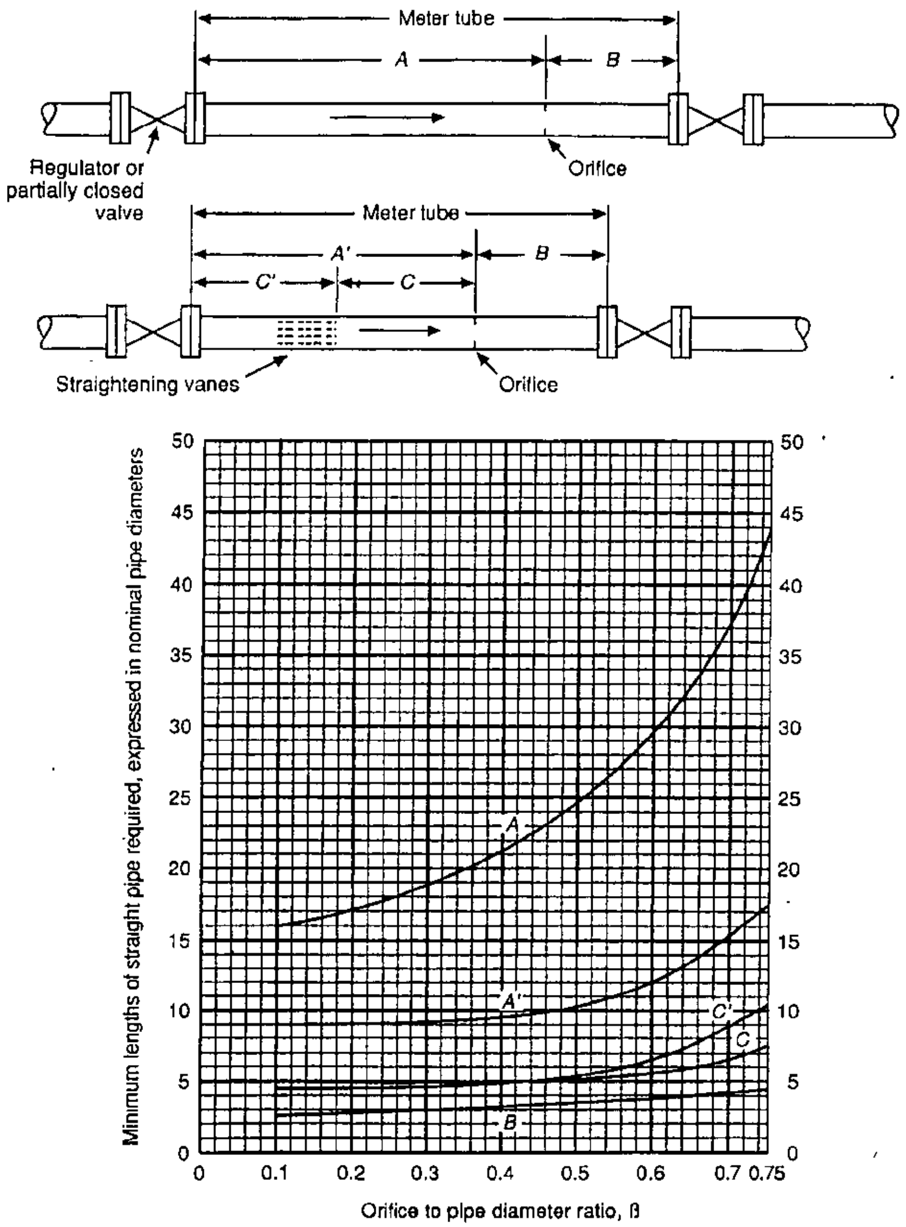
The graphs accompanying the installation sketches, Figures 2-5–2-9, indicate that the minimum length of meter tube required varies with the diameter ratio (β_r) and that longer lengths of meter tube are required for the higher diameter ratios (β_r). When the diameter of the orifice bore requires changing to meet different flowing conditions, the minimum length of the installed meter tube should be determined for the maximum diameter ratio (β_r) that may be used. The design criteria for new installations should be the lengths quoted for diameter ratios (β_r) equal to 0.75. Meter tubes longer than those shown in Figures 2-5–2-9 are desirable. When straightening vanes are used with meter tubes longer than those specified for the given diameter ratio (β_r), the dimensions C and C' should not be less than those indicated by the graphs.

The installation sketches contained in this document are essentially unchanged from those in the 1985 edition of the standard. Substantial research programs in this area are currently being conducted by API, the Commission of the European Communities, the Gas Research Institute, and Canadian researchers. At the conclusion of the required research, changes in the standard will naturally follow. In the interim, the user should consult the flow references listed in 2-A.25 of Appendix 2-A.

2.6.3.3 Requirements for Straightening Vanes

In determining whether or not straightening vanes are required, the governing factor may not always be the nearest piping fitting on the inlet end of the meter tube. For example, the last piping fitting or fittings may give no indication of the presence of swirling flows. Each individual station design may have a different set of conditions. It would therefore be impractical to set up specifications that would suit all conditions. The main consideration should be to minimize flow disturbance at the orifice plate from any upstream piping fittings. .

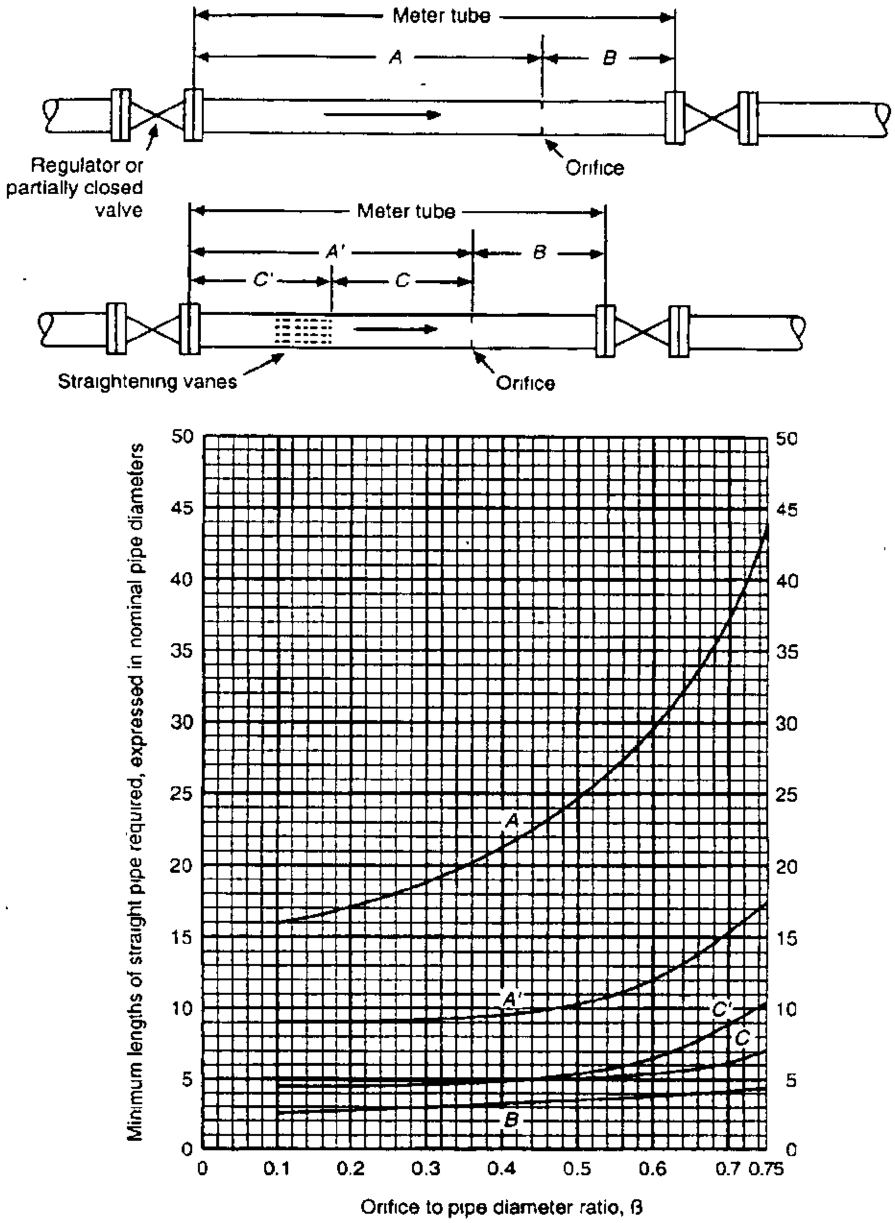
The installation of straightening vanes as shown in the installation sketches will considerably reduce the amount of straight pipe required upstream from an orifice plate. The pur-



Notes:
1. $A' - C = C'$.
2. When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.

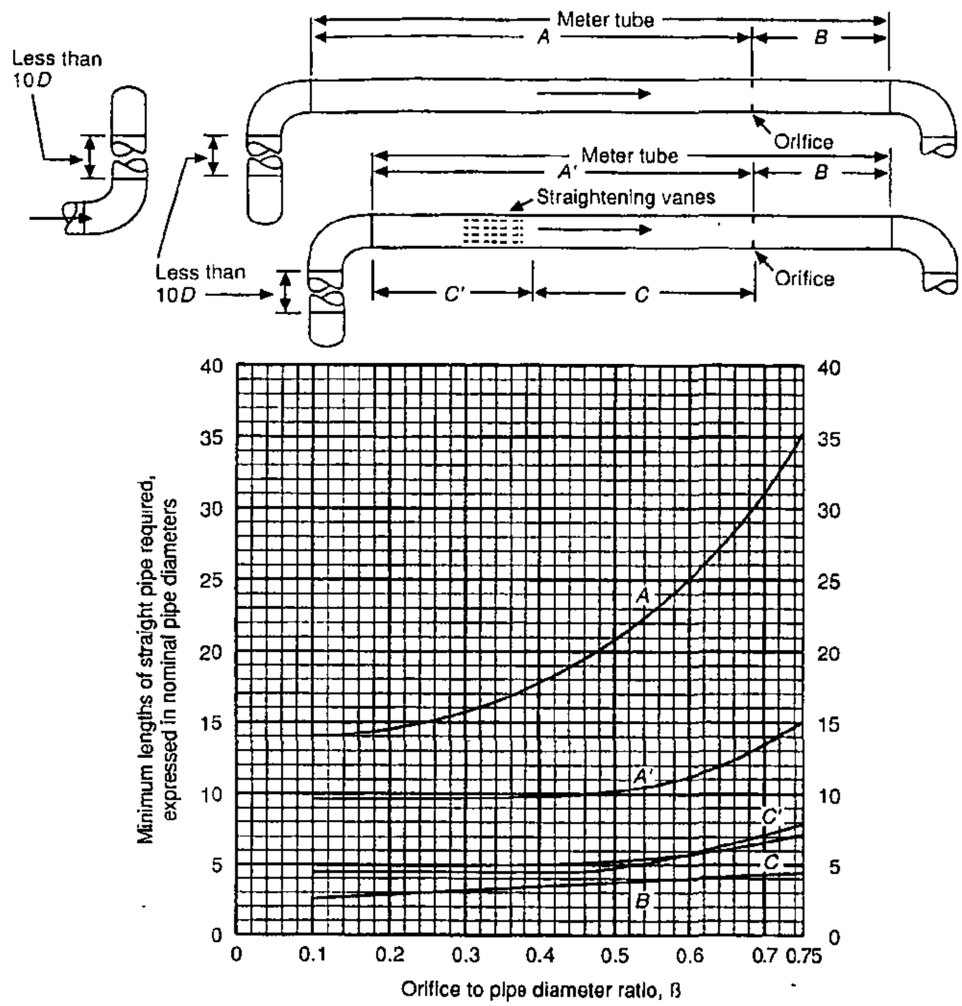
Figure 2-5—Partly Closed Valve Upstream of Meter Tube

On page 4, Figure 2-5 should appear as shown below:



Notes:
1 $A' - C = C'$.
2 When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.

Figure 2-5—Partly Closed Valve Upstream of Meter Tube

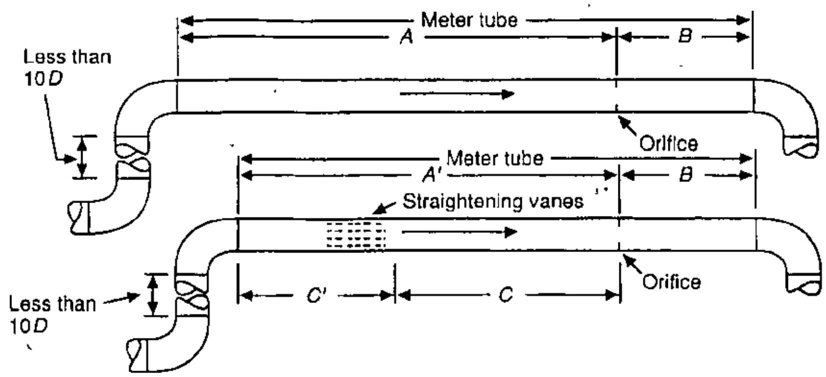


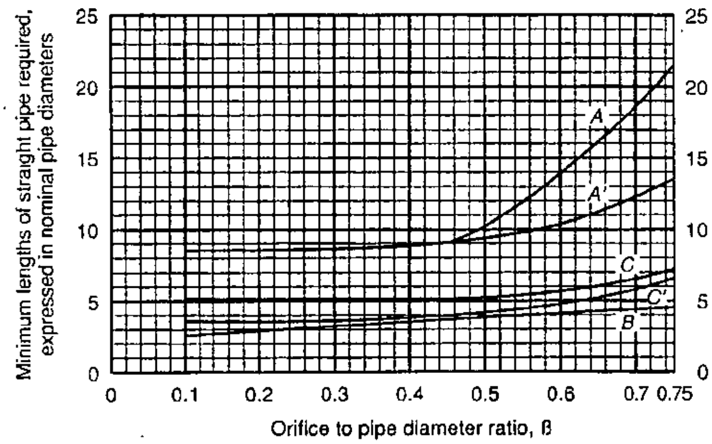
Notes:
1. $A' - C = C'$.
2. When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.
3. When the two ells shown in the sketches above are closely (less then $3D$) preceded by a third that is not in the same plane as the middle or second ell, the piping requirements indicated by A should be doubled.
4. Considerable evidence exists that swirling flows require 100 or more diameters of pipe to decay. This information is for guidance only, since no empirical data exist that accurately predict the potential increase in uncertainty due to this effect. Information on additional research and general uncertainty guide lines may be found in Chapter 14, Section 3, Part 1, 1.12.4.3.

Figure 2-6—Two Ells Not in Same Plane Upstream of Meter Tube

pose of the vanes is to reduce or eliminate the effect on the flow measurement of swirls and crosscurrents set up by the pipe fittings and valves upstream from the meter tube. When straightening vanes are installed, they should be kept clean and free from debris, which may collect against the upstream end.

The use of straightening vanes may not eliminate all profile effects and can lead to increased uncertainty. For further information, refer to the references listed in 2-A.25 of Appendix 2-A.





Note:
1. $A' - C = C'$
2. When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.

Figure 2-7—Less Than 10 Pipe Diameters Between Two Ells in Same Plane Upstream of Meter Tube

2.6.3.4 Installation With Valve or Regulator Preceding Meter Tube (Figure 2–5)

Figure 2-5 shows the basic meter tube length, which will accommodate a restriction in the pipeline upstream from the orifice plate. Meter tube lengths may be reduced under specific circumstances, as specified below. For installations that are not explicitly covered in Figures 2-6–2-9, the meter tube length shown in Figure 2-5 should be used.

Installations made within the dimensional limits of Figure 2-5 will provide adequate length for a valve that restricts the flow of fluid to be installed immediately upstream from the meter tube. This valve may be a regulator or a partially closed gate valve, a globe valve, a reduced-port ball valve, or a plug valve.

However, if the valve opening is circular, the area is equivalent to the meter tube area (that is, the valve opening is of the same pipe size and schedule as the meter tube), and the valve is in a wide-open position during the flow measurement, it may be considered as not creating any serious disturbance and may be treated as providing restriction equivalent to that resulting from an elbow immediately preceding the meter tube. Under such circumstances, consideration should be given to other fittings immediately preceding the valve in attempting to reduce lengths below the basic distances tabulated for Figure 2-5. Where there are no other fittings and the valve preceding the meter tube is wide open, Figure 2-7 shall apply in locating the wide-open valves.

2.6.3.5 Installation of Two Ells or Bends Preceding Meter Tube (Bends Not in Same Plane; Figure 2-6)

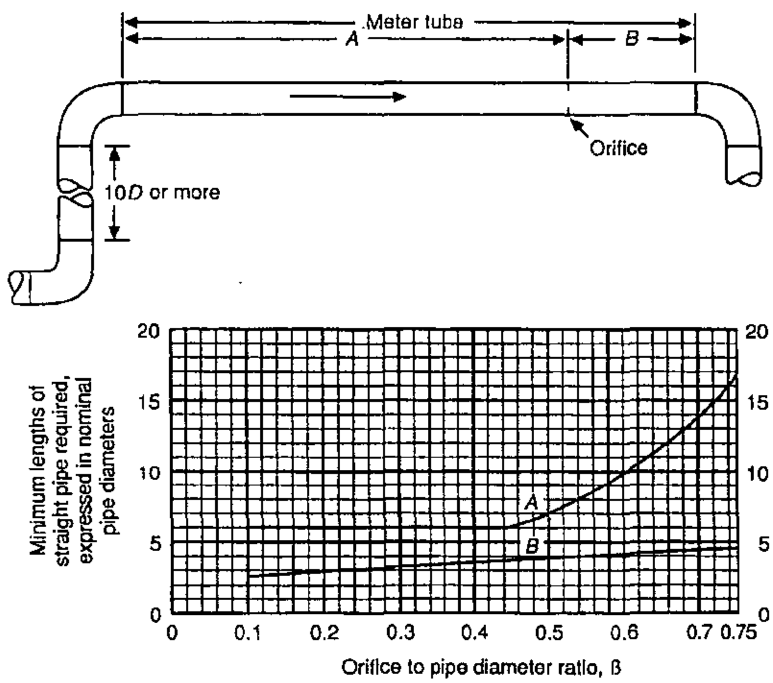
Figure 2-6 shows two ells, or bends, at right angles to each other (not in the same plane and separated by fewer than 10 diameters of straight pipe), preceding the straight run of the meter tube. With this configuration of piping fittings, the basic dimensions shown in Figure 2-5 may be reduced to those indicated in Figure 2-6.

When the two ells shown in Figure 2-6 are closely (less than $3D_r$) preceded by a third that is not in the same plane as the middle or second ell, the piping requirements shown by *A* should be doubled.

2.6.3.6 Installation of Two Ells or Bends Preceding Meter Tube (Bends in Same Plane; Figures 2-7 and 2-8)

Figure 2-7 shows two ells, or bends (in the same plane and separated by fewer than 10 diameters of straight pipe), preceding the straight run of the meter tube. With this configuration of fittings, the basic dimensions shown in Figure 2-5 may be reduced to those indicated in Figure 2-7.

Figure 2-8 shows two ells, or bends (in the same plane and separated by 10 or more diameters of straight pipe), preceding the straight run of the meter tube. With this configura-



Notes:
1. When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.
2. The straight run of pipe between the elbows must be at least 10 diameters in length. If this length is less than 10 diameters, Figure 2-7 shall be applicable.

Figure 2-8—More Than 10 Pipe Diameters Between Two Ells in Same Plane Upstream of Meter Tube tion of fittings, the basic dimensions shown in Figure 2-5 may be reduced to those indicated in Figure 2-8.

2.6.3.7 Installation of Reducer or Expander Preceding Meter Tube (Figure 2–9)

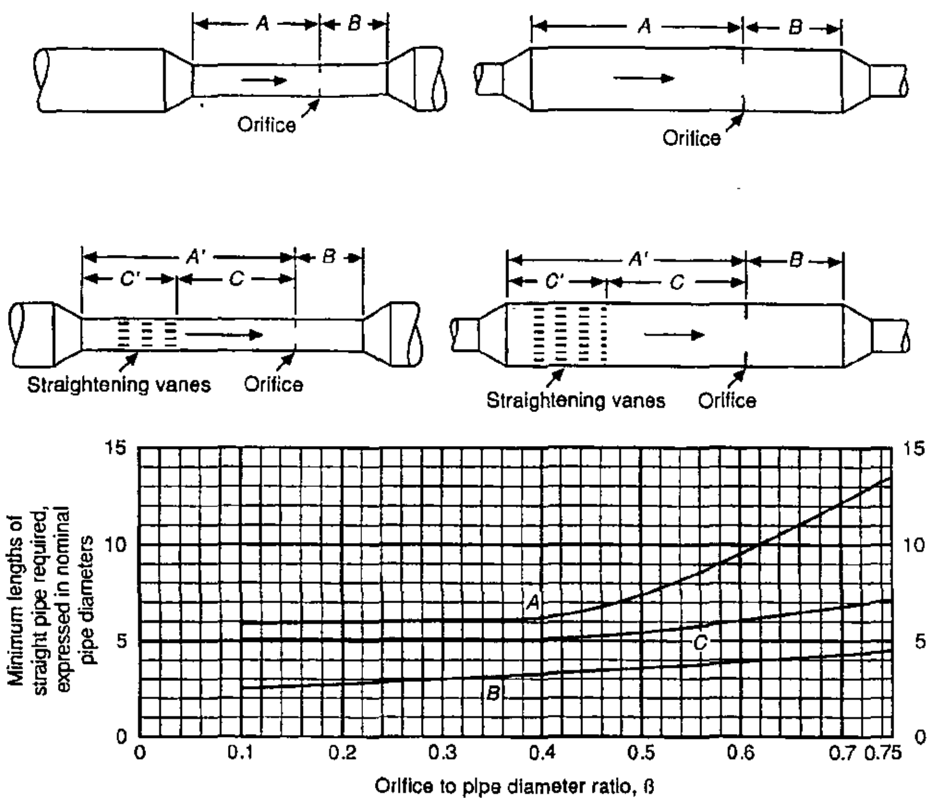
Figure 2-9 shows the use of a reducer or expander preceding the straight run of the meter tube. With this configuration of fittings, the basic or standard dimensions shown in Figure 2-5 may be reduced to those indicated in Figure 2-9. This figure applies only to concentric reducers or expanders. When eccentric reducers or expanders are used, the length of the straight run of the meter tube should be in accordance with Figure 2-5.

2.6.4 THERMOMETER WELLS

Thermometer wells should be located to sense the average temperature of the fluid at the orifice plate. The wells may be placed on the downstream side of the orifice and not closer to the plate than dimension *B* nor farther than 4*B*, as shown in Figures 2-5–2-9. If straightening vanes are used, the thermometer well may be located 12–36 inches upstream from the vane inlet.

2.6.5 INSULATION

Insulation of the meter tube may be required in the case of extreme temperature differences between the ambient temperature and the temperature of the flowing fluid and/or for fluids being metered near their critical point, where small temperature changes result in major density changes. This can be critical at low flow rates, where heat transfer effects may cause not only distorted temperature profiles but also a change in the mixed mean temperature values from the upstream to the downstream side of the meter run.



Notes:
1. Straightening vanes will not reduce lengths of straight pipe (*A*). Straightening vanes are not required because of the reducers; they are required because of other fittings that precede the reducer. Length *A* shall be increased by an amount equal to the length of the straightening vanes whenever they are used (see bottom sketches). $A' = A$ + Length of straightening vanes; $C' = A' - C$.
2. When the diameter of the orifice may require changing to meet different conditions, the lengths of straight pipe should be those required for the maximum orifice to pipe diameter ratio that may be used.
3. If the flowing fluid may be partially condensed, the expander-type installation, as well as any other configuration that might create two-phase flow in the meter tube, shall be avoided.

Figure 2-9—Reducer or Expander Upstream of Meter Tube

APPENDIX 2-A—RESEARCH PROJECTS AND TESTS CONDUCTED BETWEEN 1922 AND 1989

Note: This appendix is not a part of this standard but is included for informational purposes only.

2-A.1 Introduction

During the preparation of Chapter 14, Section 3, the committee analyzed the data from research projects and tests conducted between 1922 and 1989. Some of the projects were conducted directly under the supervision of API, Gas Processors Association (GPA), and American Gas Association (A.G.A.) personnel. Other tests were conducted by the Commission of the European Communities. Still other tests by independent investigators worldwide made significant contributions to the data base. The references described in 2-A.2 through 2-A.12 are from the original document known as A.G.A. Report No. 2. The references described in 2-A.13 through 2-A.19 were incorporated in the reference list of the document known as A.G.A. Report No. 3. The more recent references listed in 2-A.20 through 2-A.25 were part of an intense review and subsequent white paper developed by the Chapter 14, Section 3, Part 2, working group.

2-A.2 Cleveland Holder Tests (1925)

The Cleveland holder tests were conducted by the Gas Measurement Committee using a gas holder owned by the East Ohio Gas Company in Cleveland. These tests were made under the chairmanship of H. C. Cooper and the direct supervision of Professor R. S. Danforth of the Case School of Applied Science. Representatives of the National Bureau of Standards and the U.S. Bureau of Mines were present as observers. The test line consisted of orifice meter runs of 8-, 10-, and 16-inch pipe; 4-inch orifice plates were installed in each of these runs.

2-A.3 Buffalo Disturbance Tests (1926)

The Buffalo disturbance tests were conducted by the Gas Measurement Committee at the Daly Station of the Iroquois Gas Corporation, Buffalo, New York. The object of these tests was to determine the effects of disturbances produced in a gas stream by various kinds of pipeline fittings located near an orifice plate on the indications of an orifice meter.

2-A.4 Disturbance and Rate-of-Flow Tests (1927)

Disturbance and rate-of-flow tests were conducted by the Gas Measurement Committee at Daly Station of the Iroquois Gas Corporation, Buffalo, New York, under the personal supervision of Howard S. Bean. The first part of these tests was a continuation of the 1926 series described in 2-A.3. The rate-of-flow tests had two objectives:

a. To build up, by means of a series of intercomparisons, a series of relative orifice coefficient values for orifices in an 8-inch pipe that ranged in diameter from 1 inch to 6½ inches.
b. To study the effect on orifice coefficients of increasing value of the ratio of differential pressure to static pressure (h/p), that is, the ratio of the differential pressure, in inches of water, to the absolute static pressure, in pounds per square inch.

2-A.5 Rate-of-Flow, Flange Form, and Supercompressibility Tests (1928)

Rate-of-flow, flange form, and supercompressibility tests were conducted at the Daly Station of the Iroquois Gas Corporation, Buffalo, New York, by the Gas Measurement Committee under the direction of Howard S. Bean. The objects of these tests were as follows:

a. To extend the study of effects on orifice coefficients resulting from changes in the h/p ratio to orifices in 4-inch pipes.
b. To compare the relative indications obtained with recessed and unrecessed orifice flanges.
c. To determine the deviation from Boyle's Law and its effect on measuring gas by orifice meters.
d. To investigate the effect on orifice coefficients for an equal diameter ratio of changing from an 8-inch to a 4-inch line.

2-A.6 Shop Tests on Effects of Orifice Installation Conditions (1929–1930)

Shop tests on effects of orifice installation conditions were performed by the Bailey Meter Company, the Foxboro Company, the Metric Metal Works, and the Pittsburgh Equitable Meter Company for the Gas Measurement Committee in accordance with an outline prepared by Howard S. Bean. The object of these tests was to determine the effects on orifice meter indications that result from some installation conditions not covered by the disturbance tests described in 2-A.3 and 2-A.4. Additional information was desired about the following conditions:

a. Position and size of straightening vanes.
b. Position and design of thermometer wells, particularly on the upstream side of the orifice.
c. Roughness of pipe adjacent to the orifice.
d. Form of flange in which the orifice plate is held.
e. Inaccuracy in centering the orifice in the pipe.

f. The condition of the upstream edge of the orifice.
g. The ratio of the width of the orifice edge to the diameter of the orifice.

The results of these tests were reported in the article "Effect of Some Installation and Construction Conditions Upon the Indications of an Orifice Meter," *American Gas Association Monthly*, July–August 1947, Volume 29, pages 7 and 8.

2–A.7 Edgewood Tests (1922–1925)

The Edgewood tests were conducted at Edgewood Arsenal, Maryland, by the National Bureau of Standards with the cooperation of the Chemical Warfare Service, U.S. War Department, under the immediate supervision of Howard S. Bean, with the advice of Edgar Buckingham, and the assistance of Paul S. Murphy. The object of these tests was to obtain original information on the orifice discharge coefficients over as wide a range of pipe sizes, diameter ratios, pressures, and pressure ratios as was permitted by the facilities available. The setup included orifices in 4-, 6-, and 8-inch pipes. Forty-eight orifice plates were used, with orifice to pipe diameter ratios ranging from 0.108 to 0.858.

2–A.8 Chicago Holder Tests (1923–1924)

The Chicago holder tests were conducted in Chicago by the American Gas Association Committee on the Measurement of Large Volumes of Gas, under the chairmanship of M. E. Benesh. On invitation from Mr. Benesh, the National Bureau of Standards cooperated in these tests, the main object of which was to study the accuracy of several types of meters, including orifice meters used to measure large quantities of gas at pressures near atmospheric.

2–A.9 Ohio State University Steam and Water Tests (1929–1931)

Steam and water tests were conducted by the Ohio State University Engineering Experiment Station and the Bailey Meter Company at the Mechanical Engineering Laboratory of Ohio State University, under the supervision of Professors Paul Bucher and Samuel Beitler. The object of the tests was to determine the expansion factor and the coefficients of orifices measuring both steam and water. Both 3- and 6-inch lines were used and a series of orifices were tested, first using water and then steam.

2–A.10 Intercomparison of Meter Runs (1932)

An intercomparison of meter runs was conducted by the Peoples Gas Light and Coke Company at its Joliet Measuring Station, Joliet, Illinois, under the supervision of M. E. Benesh.

2–A.11 Columbus Tests (1932–1933)

The Columbus tests were conducted by the Joint Orifice Meter Committee at the Hydraulic Laboratory of Ohio State University, Columbus, Ohio, under the immediate supervision of Professor Samuel R. Beitler. Nearly 80 separate orifice plates were used in tests with 1-, 1½-, 2-, 3-, 6-, 10-, and 15-inch pipes, and in many cases, the same orifice was used in two or more different pipe sizes. The orifice pipe diameter ratio ranged from 0.04 to 0.84.

2–A.12 South Columbus Flange Form and Pressure Hole Tests (1932)

Flange form and pressure hole tests were conducted by the Joint American Gas Association–American Society of Mechanical Engineers Committee on Orifice Meters at the South Columbus Measuring Station of the Ohio Fuel Gas Company, under the immediate supervision of J. E. Overbeck, with the advice of Professor Samuel R. Beitler. The object of these tests, which were made with natural gas, was to determine more completely than had been done either at Buffalo (2-A.3 and 2-A.4) or by the shop tests (2-A.6) the effects of various sizes of internal flange recesses adjacent to the orifice plate. Both the width and the depth of the recesses were varied in the 2-, 4-, and 8-inch pipe sizes that were used in these tests. The orifice to pipe diameter ratio ranged from 0.125 to 0.75. In combination with these recesses, various diameters of pressure holes were used.

2–A.13 Rockville Tests (1949–1951)

The Rockville tests were conducted by the Joint American Gas Association–American Society of Mechanical Engineers Committee under the direction of Howard S. Bean. Tests with natural gas were performed at the Rockville, Maryland, Measuring Station of the Atlantic Seaboard Corporation to study the following:

a. The effect of plug, globe, and gate valve disturbances on measurement.
b. The effect of elbow placement disturbances (comparison with Buffalo tests).
c. The effect of orifice meter fittings, compared with conventional orifice flanges.
d. The effect of orifice tube roughness.
e. Installations of 2- and 8-inch piping.

The results of these tests were published by the American Gas Association in two interim reports, each entitled *Investigation of Orifice Meter Installation Requirements* and dated March 1951 and January 1954.

2–A.14 National Bureau of Standards Hydraulics Laboratory Tests (1950–1951)

The National Bureau of Standards Hydraulics Laboratory tests were conducted by the Joint American Gas Association–American Society of Mechanical Engineers Committee on Orifice Meters at the Hydraulics Laboratory, National Bureau of Standards, Washington, D.C., under the immediate supervision of Howard S. Bean. The object of this project was, in part, to make comparative tests with water for the roughness and orifice fitting installations used in the Rockville tests (2-A.13) and, in part, to examine the effect of pressure tap location and tap hole size. The results were reported in conjunction with those from the Rockville tests.

2–A.15 U.S. Naval Boiler and Turbine Laboratory Tests (1948–1954)

The U.S. Naval Boiler and Turbine Laboratory tests were conducted by the Bureau of Ships, U.S. Department of the Navy, in conjunction with the Joint American Gas Association–American Society of Mechanical Engineers Committee on Orifice Meters at the U.S. Naval Boiler and Turbine Laboratory in Philadelphia.

This work was conducted under the direction of James W. Murdock. The object of these tests, which were made with team, was to determine the effect of globe valves and expansion bends on orifice meter indications. Additional tests were performed to check the values of expansion factors to be used in the measurement of steam. The results of these tests were reported in a series of four interim reports published by the U.S. Naval Boiler and Turbine Laboratory. These reports were entitled *Determination of the Minimum Length of Straight Pipe Required Between Various Pipe Fittings and the Orifice Plate for Acceptable Orifice Meter Accuracy* and were dated January 1950, March 1950, May 1950, and November 1951.

2–A.16 Refugio Large–Diameter Orifice Tube Tests (1952–1953)

The Refugio large-diameter orifice tube tests, a PAR Project, were conducted by the Project NX-4 Supervising Committee, under the chairmanship of E. E. Stovall. The primary objective was to determine experimentally whether the basic orifice coefficient data contained in the American Gas Association's Gas Measurement Report No. 2 could be extrapolated for use in measuring gas accurately through large-diameter tubes. The test installation was located near Refugio, Texas, on a transmission line of the Tennessee Gas Transmission Company. The results of these tests were published by the American Gas Association in a report, *Large Diameter Orifice Tube Tests*, dated June 1954.

2–A.17 Eccentric and Segmental Orifice Tests (1948–1954)

Eccentric and segmental orifice tests were conducted under the supervision of a Subcommittee of the American Society of Mechanical Engineers' Research Committee on Fluid Meters with the cooperation of the American Gas Association's Gas Measurement Committee. The chairman of the ASME subcommittee was L. E. Gess of the Minneapolis Honeywell Company. The objective of the tests was to determine the coefficients of discharge of round orifices mounted with one edge tangent to the pipe wall and of plates with segmental orifices in them. The tests were run at Ohio State University under the supervision of Professor Samuel R. Beitler and were analyzed by Professor E. J. Lindahl of the University of Wyoming. The results of these tests were reported in two ASME papers: "Calibration of Eccentric and Segmental Orifices in 4- and 6-Inch Pipelines," *Transactions of the ASME*, 1949, Volume 71, and "Coefficients of Discharge for Eccentric and Segmental Orifices in 4-inch, 6-inch, 10-inch, and 14-inch Pipes," presented at the Annual Meeting of the American Society of Mechanical Engineers, New York, November 1954.

2–A.18 Pipe Roughness Study (1957–1960)

A pipe roughness study, a PAR Project, was conducted by the Project NW-20 Supervising Committee under the chairmanship of J. W. Murdock. W. B. Ruff, Jr., of the Southern Natural Gas Company, served as the Gas Measurement Committee representative coordinating and supervising the project. The primary purpose of this program was to determine, qualitatively and quantitatively, the effect of the character of the interior surface of orifice tubes on fluid flow measurements by orifice meters. A secondary objective was to correlate any effect on flow measurement with some physical measurement of the tube roughness (such as microinches) to the end that a recommendation could be made about the relative roughness range for satisfactory metering service. The preliminary tests were conducted at the U.S. Naval Boiler and Turbine Laboratory in Philadelphia. The full-scale tests were conducted in Birmingham, Alabama, at Southern Natural Gas Company facilities. Four-inch meter tubes were used in these tests. The results of these tests were published by the American Gas Association in the report *The Effect of Pipe Roughness on Orifice Meter Accuracy* (Catalog No. 33/PR), dated February 1960.

2–A.19 Ohio State University Flow Distortion Tests (1960–1962)

The Ohio State University flow distortion tests constituted PAR Project NY-34. The supervising committee chairman was C. W. Brown, Texas Gas Transmission Corporation. These tests were carried out at Ohio State University to determine the amount of error caused by distortion of the approach velocity profile on the coefficient of orifices. An attempt was made to eliminate swirl, so the report describes the effect of changes in the axial profile only. Six-inch orifice pipes with honed walls (roughness of about 15 microinches) were used, and the inlet profile was distorted by use of special flow disturbances and piping configurations. It was concluded that ordinary disturbances caused by piping configurations, which did not produce swirl, resulted in errors of less than 2 percent if there were at least six diameters of straight uniform pipe ahead of the orifice.

2–A.20 API Experimental Program

Britton, C. L., Caldwell, S., and Seidl, W., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square- Edged Orifice Meters in White Mineral Oil Over a Reynolds Number Range of 70 to 90,000," American Petroleum Institute, Washington, D.C., 1988.

"Coefficients of Discharge for Concentric, Square-Edged, Flange-Tapped Orifice Meters: Equation Data Set—Supporting Documentation for Floppy Diskettes," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J. R., Cleveland, W. G., Bateman, R. B., and Sindt, C. F., "Measurements of Coefficients of Discharge for Concentric, Flange-Tapped, Square-Edged Orifice Meters in Natural Gas Over a Reynolds Number Range of 25,000 to 11,600,000," American Petroleum Institute, Washington, D.C., 1988.

Whetstone, J. R., Cleveland, W. G., Baumgarten, G. P., Woo, S., and Croarkin, M. C., "Measurements of Coefficients of Discharge for Concentric Flange-Tapped Square-Edged Orifice Meters in Water Over the Reynolds Number Range 600–2,700,000" (Technical Note 1264), National Institute of Standards and Technology, Washington, D.C., June 1989.

2–A.21 EEC Experimental Program

Hobbs, J. M., "Experimental Data for the Determination of Basic 100mm Orifice Meter Discharge Coefficients" (Report EUR 10027), Commission of the European Communities, Brussels, 1985.

Hobbs, J. M., "The EEC Orifice Plate Project: Part I. Traceabilities of Facilities Used and Calculation Methods Employed" (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., "The EEC Orifice Plate Project: Part II. Critical Evaluation of Data Obtained During EEC Orifice Plate Tests" (Report PR5:EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., "The EEC Orifice Plate Project: Tables o. Valid Data for EEC Orifice Analysis" (Report EUEC/17), Commission of the European Communities, Brussels, 1987.

Hobbs, J. M., Sattary, J. A., and Maxwell, A. D., "Experimental Data for the Determination of Basic 250mm Orifice Meter Discharge Coefficients" (Report EUR 10979), Commission of the European Communities, Brussels, 1987.

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Spencer, E. A., "Study of Edge Sharpness Effects Measured During the EEC Orifice Plate Coefficient Programme" (Report EUR 11131 EN), Commission of the European Communities, Glasgow, 1987.

2–A.22 Orifice Eccentricity

Husain, Z. D., and Teyssandier, R. G., "Orifice Eccentricity Effects for Flange, Pipe and Radius (D – D/2) Taps" (ASME Paper 66-WA/FM-1), American Society of Mechanical Engineers, New York, 1966.

Husain, Z. D., and Teyssandier, R. G., "The Effect of Orifice Eccentricity in a Small Line Size," Paper presented at the International Conference on the Metering of Natural G and Liquefied Hydrocarbon Gases, London, Februa 1984.

Miller, R. W., and Kneisel, U., "Experimental Study of the Effects of Orifice Plate Eccentricity on Flow Coefficients" (ASME Paper 68-WA/FM-1), American Society of Mechanical Engineers, New York, 1968.

Norman, R., Rawat, M. S., and Jepson, P., "An Experimental Investigation into the Effects of Plate Eccentricity and Elastic Deformation on Orifice Metering Accuracy," Paper presented at the International Conference on the Metering of Natural Gas and Liquefied Hydrocarbon Gases, London, February 1984.

2–A.23 Orifice Edge/Surface Condition

Spencer, E. A., "Study of Sharpness Effects Measured During the EEC Plate Coefficient Programme" (Report EUR 11131 EN), Commission of the European Communities, Brussels, 1987.

Studzinski, W., Berg, D., Bell, D., and Richards, D., "Effects of Orifice Surface Conditions on Accuracy of Flow Rate Measurements," Paper presented at the Second International Conference on Flow Measurement, London, May 1988.

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Brennen, J. A., McFaddin, S. E., Sindt, C. F., and Wilson, R. R., "Effect of Pipe Roughness on Orifice Flow Measurement" (Technical Note 1329), National Institute of Standards and Technology, Washington, D.C., July 1989.

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McFaddin, S. E., Sindt, C. F., and Brennen, J. A., "Optimum Location of Flow Conditioners in a 4-Inch Orifice Meter" (Technical Note 1330), National Institute of Standards and Technology, Washington, D.C., July 1989.

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Smith, D. J. M., "The Effects of Flow Straighteners on Orifice Plates in Good Flow Conditions" (Paper 5.3), *Proceedings of the International Conference on Flow Measurement in the Mid 80's*, National Engineering Laboratory, East Kilbride, Scotland, June 1986.

Manual of Petroleum Measurement Standards Chapter 14—Natural Gas Fluids Measurement

Section 3—Concentric, Square-Edged Orifice Meters
Part 3—Natural Gas Applications

THIRD EDITION, AUGUST 1992

AGA American Gas Association	Report No. 3, Part 3
GPA Gas Processors Association	GPA 8185, Part 3
ANSI American National Standards Institute	ANSI/API 2530-1991, Part 3

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005

B. Location of static pressure transducer connection: upstream, downstream, or none.
C. Number of differential pressure connections.
D. Pressure tap size: ⅜ inch, ½ inch, or other.
E. Measured distance from centerline of tap hole to orifice plate surface, both upstream and downstream.
F. Condition of tap hole edge on inside diameter of meter run.
G. Manifold: manufactured or fabricated on site; full bore or restricted bore; three valves, five valves, or other.

V. Other Instrumentation
A. Measurement data on other tap connections made to the meter tube: size, location, and orientation.
B. Temperature probe: type and location.
C. Densitometer: manufacturer and type; insertion or sample line; size; inlet or outlet location.
D. Sampler: manufacturer and type; sample line size; inlet or outlet location.
E. Composition/energy analyzers: type; sample line size; inlet or outlet location.

VI. Orifice Plate Centering—Type
A. Flange: plate alignment (pins, male/female, other, or none).
B. Fitting:
1. Measurement from plate edge to pipe wall on primary pressure tap side.
2. Measurement from plate edge to pipe wall on opposite side pressure tap.
3. Difference between 1 and 2 above.
4. Measurement from plate edge to pipe wall perpendicular to primary tap.
5. Measurement from plate edge to pipe wall opposite to measurement in 4 above.
6. Difference between 4 and 5 above.

VII. Orifice Fitting Leak Test (After Hydrostatic Testing)
A. Measurement of seat width.
B. Measurement of seal width.
C. Difference between A and B above.
D. Results of pressure tap leak test.
E. Results of plate bypass leak test.
F. Type of seal and material of construction.

VIII. Orifice Plate Inspection
A. Type of plate.
B. Material of construction.
C. Manufacturer.
D. Stamped (nominal) diameter at 68°F.
E. Edge sharpness: sharp or dull.
F. Plate flatness: flat or bent (measured departure from flatness).
G. Measured roughness of plate surface.
H. Any surface film patterning for plates just removed from service?
I. Micrometer measurement of at least four inside diameters of the orifice bore.
J. Average value of the measurements in I above.
K. Measured plate thickness.
L. Other data pertinent for identification.
M. Temperature at which plate was measured.
N. Names of inspector(s) and witness(es) and date, if not the same as for meter tube.
O. Is plate beveled or unbeveled?

APPENDIX B—ORIFICE METER INSPECTION GUIDELINES

Note: This appendix is not a part of this standard but is included for informational purposes only.

The following outline is intended to provide guidelines for preparing an orifice meter inspection checklist. The outline is provided so that uniformity may be achieved in what is to be inspected. The format of the checklist is left to the user, according to company preference. Although all the items listed may not be required at every inspection, the checklist should provide the pertinent information.

Note that the outline may not include all of a particular user's required information. The minimal information specified in the outline provides a basis for evaluating the quality of the meter run and orifice plate at the time of inspection.

I. Header
  A. Company name.
  B. Date of inspection.
  C. Tube location.
  D. Flow direction.
  E. Names of inspector(s) and witness(s).
  F. Any other information required.

II. General Information
  A. Serial number.
  B. Nominal pipe diameter.
  C. Fluid measured: gas or liquid (specify name).

III. Meter Tube
  A. Type of orifice holder: flanges or fitting; single or dual chamber.
  B. Manufacturer.
  C. Serial number.
  D. Straightening vanes? yes or no; if yes:
    1. Type of vane.
    2. How fastened? pinned, welded, or flanged.
    3. Dimensions.
    4. Dimensional and quality specifications per Chapter 14.3, Part 2: pass or fail.
  E. Meter run type: single tube or multiple tube.
  F. Installation type (see Figures 2-5–2-9).
  G. Dimensional data:
    1. Length (see Figures 2-5–2-9).
    2. Upstream and downstream diameters (at least four measurements at each location):
      a. Upstream pressure tap (also calculate the average of these values).
      b. Downstream pressure tap.
      c. First pipe connection.
      d. Second pipe connection.
  H. Temperature of tube at time of measurement.
  I. Meter tube quality: cleanliness and measured roughness upstream and downstream.
  J. Average tube inside diameter at 68°F, as stamped on pipe or nameplate.
  K. Inside tube diameter used in flow computer, for calculations, and for data processing.

IV. Pressure Taps
  A. Orientation of primary differential pressure transducer connection (looking from inlet to outlet of meter tube).

Date of Issue: March 1994
Affected Publication: API Chapter 14 "Natural Gas Fluids Measurement," Section 3, "Concentric, Square-Edged Orifice Meters," Part 3, "Natural Gas Applications" of the *Manual of Petroleum Measurement Standards*, Third Edition, August 1992

ERRATA

On page 25, Equation 3-A-10 should read as follows:

$$g_l = 0.0328096[978.01855 - 0.0028247L + 0.0020299L^2 - 0.000015085L^3 - 0.000094H] \quad \text{(3-A-10)}$$

On page 33, Equation 3-B-9 should read as follows:

$$F_d = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \quad \text{(3-B-9)}$$

On page 56, the second equation under 3–C.3.1.7 should read as follows:

$$Re_D = (0.0114541)\left(\frac{Q_v(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right) = 3.32446Q_v$$

On page 57, Equation 3-6b should read as follows:

$$Q_v = 7709.61C_d(\text{FT})E_vY_1d^2\sqrt{\frac{P_{f_1}Z_sh_w}{G_rZ_{f_1}T_f}} \quad \text{(3-6b)}$$

$$= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2 \times \sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.570)(0.951308)(524.67)}}$$

$= 614{,}033$ cubic feet per hour at standard conditions

On page 57, the second equation in 3-6b should read as follows:

$$Re_D = 3.32446Q_v = 3.32446(614{,}033) = 2{,}041{,}328$$ (initial estimate of Reynolds number)

On page 57, Equation 3-20 should read as follows:

$$
\begin{aligned}
A &= \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \\
&= \left[\frac{19{,}000(0.495597)}{2{,}041{,}328}\right]^{0.8} \qquad (3\text{-}20) \\
&= 0.0135262
\end{aligned}
$$

On page 57, Equation 3-21 should read as follows:

$$
\begin{aligned}
C &= \left(\frac{10^6}{Re_D}\right)^{0.35} \\
&= \left(\frac{10^6}{2{,}041{,}328}\right)^{0.35} \qquad (3\text{-}21) \\
&= 0.778988
\end{aligned}
$$

On page 58, Equation 3-15 should read as follows:

$$
\begin{aligned}
Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \\
&= [0.0433 + 0.0712e^{-8.5/[\text{illegible}]} - 0.1145e^{-6.0/[\text{illegible}]}] \\
&\quad \times [1 - 0.23(0.0135262)](0.0642005) \qquad (3\text{-}15) \\
&= 0.000876388
\end{aligned}
$$

On page 58, Equation 3-16 should read as follows:

$$
\begin{aligned}
Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \\
&= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1} \\
&\quad \times [1 - 0.14(0.0135262)] \qquad (3\text{-}16) \\
&= -0.00152379
\end{aligned}
$$

On page 58, Equation 3-14 should read as follows:

$$
\begin{aligned}
Tap\ Term &= Upstrm + Dnstrm \\
&= 0.000876388 + (-0.00152379) \qquad (3\text{-}14) \\
&= -0.000647402
\end{aligned}
$$

On page 58, Equation 3-12 should read as follows;

$$
\begin{aligned}
C_i(\text{FT}) &= C_i(\text{CT}) + Tap\ Term \\
&= 0.602414 - 0.000647402 \qquad (3\text{-}12) \\
&= 0.601767
\end{aligned}
$$

On page 58, Equation 3-11 should read as follows:

$$
\begin{aligned}
C_d(\text{FT}) &= C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4C \\
&= 0.601767 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}328}\right]^{0.7} \qquad (3\text{-}11) \\
&\quad + [0.0210 + 0.0049(0.0135262)](0.495597)^4(0.778988) \\
&= 0.602947 \text{ (second estimate of the coefficient of discharge)}
\end{aligned}
$$

On page 58, the third to the last equation should read as follows:

Q_v = 617,048 cubic feet per hour at standard conditions
[based on $C_d(FT) = 0.602947$]

On page 58, the second to the last equation should read as follows:

$$Re_D = 3.32446Q_v = 3.32446(617{,}048)$$
$$= 2{,}051{,}351 \text{ (second estimate of Reynolds number)}$$

On page 59, the second equation should read as follows:

$$Re_D = 3.32446Q_v = 3.32446(617{,}046)$$
$$= 2{,}051{,}345 \text{ (third estimate of Reynolds number)}$$

On page 59, Equation 3-7 should read as follows:

$$Q_b = Q_v\left(\frac{P_f}{P_b}\right)\left(\frac{T_b}{T_f}\right)\left(\frac{Z_b}{Z_f}\right)$$
$$= 617{,}046\left(\frac{14.73}{14.65}\right)\left(\frac{509.67}{519.67}\right)\left(\frac{0.997839}{0.997971}\right) \qquad (3\text{-}7)$$
$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

On page 60, Equation 3-B-9 should read as follows:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}$$
$$+ \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9)$$

On page 62, the first equation should read as follows:

$$F_c = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8$$
$$+ \left(0.0433 + 0.0712e^{-8\%} - 0.1145e^{-6\%}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4}$$
$$- 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]$$
$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$
$$+ \left(0.0433 + 0.0712e^{-8\%0.07015} - 0.1145e^{-6\%0.07015}\right)[1 - 0.23(0.0137493)](0.0642005)$$
$$- 0.0116[0.491284 - 0.52(0.491284^{1.3})](0.495597)^{1.1}[1 - 0.14(0.0137493)]$$
$$= 0.601767$$

On page 62, Equation 3-B-9 should read as follows:

$$
\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1,000,000\beta}{Re_D}\right)^{0.7} \\
&\quad + \left[0.0210 + 0.0049\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1,000,000}{Re_D}\right)^{0.35} \qquad (3\text{-}B\text{-}9)\\
&= 0.000511\left(\frac{1,000,000(0.495597)}{2,000,000}\right)^{0.7} \\
&\quad + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}
$$

On page 65, the first equation should read as follows:

$$
\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_v P_s G_r}{\mu D T_s}\right) \\
&= 3.32446 Q_v \\
&= 3.32446(617,057) \\
&= 2,051,400 \text{ (second iteration)}
\end{aligned}
$$

On page 80, Equation 3-D-9 should read as follows (that is, Kpipe, *should be inserted in the equation and the second line of the equation should be deleted):*

$$Re_d = 220,858\, d F_{pv} \sqrt{\rho h_w}\ x\ (K\text{pipe}) \qquad (3\text{-}D\text{-}9)$$

On page 80, the nomenclature should read as follows (that is, Kpipe, *should be inserted in the list):*

Where:

G = specific gravity.
Kpipe = values from Table 3-D-4.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine.
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F

On page 97, Equations 3-F-4 and 3-F-5 should read as follows:

$$H_v^{id} = \phi_1(H_v^{id})_1 + \phi_2(H_v^{id})_2 + \ldots + \phi_w(H_v^{id})_w \qquad (3\text{-}F\text{-}4)$$

$$H_v^{id} = \sum_{i=1}^{w} \phi_i(H_v^{id})_i \qquad (3\text{-}F\text{-}5)$$

On page 102, the second line of Equation 3-4a should read as follows:

$$Q_b = 359.072\, C_d(FT)\, E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R\, T_f}}\ \frac{Z_b R\, T_b}{P_b G_i (28.9625)(144)}$$

CONTENTS

Chapter 14—Natural Gas Fluids Measurement

SECTION 3—CONCENTRIC, SQUARE-EDGED ORIFICE METERS

PART 3—NATURAL GAS APPLICATION

3.1 Introduction

3.1.1 APPLICATION

3.1.1.1 General

This part of Chapter 14, Section 3, has been developed as an application guide for the calculation of natural gas flow through a flange-tapped, concentric orifice meter, using the inch-pound system of units. For applications involving SI units, a conversion factor may be applied to the results (Q_m, Q_v, or Q_b) determined from the equations in 3.3. Intermediate conversion of units will not necessarily produce consistent results. As an alternative, the more universal approach specified in Chapter 14, Section 3, Part 1, should be used. The meter must be constructed and installed in accordance with Chapter 14, Section 3, Part 2.

3.1.1.2 Definition of *Natural Gas*

As used in this part, the term *natural gas* applies to fluids that for all practical purposes are considered to include both pipeline- and production-quality gas with single-phase flow and mole percentage ranges of components as given in American Gas Association (A.G.A.) Transmission Measurement Committee Report No. 8, "Compressibility and Supercompressibility for Natural Gas and Other Hydrocarbon Gases." For other hydrocarbon mixtures, the more universal approach specified in Part 1 may be more applicable. Diluents or mixtures other than those stipulated in A.G.A. Transmission Measurement Committee Report No.8 may increase the flow measurement uncertainty.

3.1.2 BASIS FOR EQUATIONS

The computation methods used in this part are consistent with those developed in Part 1 and include the Reader-Harris/Gallagher equation for flange-tapped orifice meter discharge coefficient. The equation has been modified to reflect the more common units of the inch-pound system. Since the new coefficient of discharge equation does not address pipe tap meters, the pipe tap methodology of the 1985 edition of ANSI/API 2530 has been retained for reference in Appendix 3-D.

3.1.3 ORGANIZATION OF PART 3

Chapter 14, Section 3, Part 3, is organized as follows: Symbols and units are defined in 3.2, the basic flow equation is presented in 3.3, the key equation components are defined in 3.4, and the gas properties applicable to orifice metering of natural gas are developed in 3.5. All values are assumed to be absolute. Factors to compensate for meter calibration and location are included in Appendix 3-A. The factor approach to orifice measurement is included in Appendix 3-B. Appendix 3-C covers examples to assist the user in interpreting this part. Appendix 3-D covers pipe tap meters. Appendix 3-E covers SI conversions, Appendix 3-F covers heating value calculation, and Appendix 3-G covers derivation of constants. The user is cautioned that the symbols as defined in 3.2 may be different from those used in previous orifice metering standards.

3.2 Symbols, Units, and Terminology

3.2.1 GENERAL

The symbols and units used are specific to Chapter 14, Section 3, Part 3, and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable: however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C_d	Orifice plate coefficient of discharge	—
C_d(FT)	Coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter	—
C_i(CT)	Coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter	—
C_i(FT)	Coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter	—
c_p	Specific heat at constant pressure	Btu/(lbm-°F)
c_v	Specific heat at constant volume	Btu/(lbm-°F)
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
d_r	Orifice plate bore diameter calculated at reference temperature, T_r	in
D_r	Meter tube internal diameter calculated at reference temperature, T_r	in
e	Napierian constant	2.71828
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_{pv}	Supercompressibility factor	—
G	Gas relative density (specific gravity)	—
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
k	Isentropic exponent (see 3.4.5)	—
k_i	Ideal gas isentropic exponent	—
k_p	Perfect gas isentropic exponent	—
k_r	Real gas isentropic exponent	—
m	Mass	lbm
Mr_{air}	Molar mass (molecular weight) of air	28.9625 lbm/lb-mol
Mr_{gas}	Molar mass (molecular weight) of gas	lbm/lb-mol
Mr_i	Molar mass (molecular weight) of component	lbm/lb-mol
n	Number of moles	—
N_4	Unit conversion factor (discharge coefficient)	—
P	Pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
$P_{b_{air}}$	Base pressure of air	lbf/in^2 (abs)
$P_{b_{gas}}$	Base pressure of gas	lbf/in^2 (abs)
P_f	Static pressure of fluid at the pressure tap	lbf/in^2 (abs)
P_{f1}	Absolute static pressure at the orifice upstream differential pressure tap	lbf/in^2 (abs)
P_{f2}	Absolute static pressure at the orifice downstream differential pressure tap	lbf/in^2 (abs)

P_s	Standard pressure	14.73 lbf/in^2 (abs)
Q_b	Volume flow rate at base conditions	ft^3/hr
q_m	Mass flow rate per second	lbm/sec
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard conditions	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
Re_D	Pipe Reynolds number	—
T	Temperature	°R
T_b	Base temperature	°R
$T_{b_{air}}$	Base temperature of air	°R
$T_{b_{gas}}$	Base temperature of gas	°R
T_f	Temperature of fluid at flowing conditions	°R
T_r	Reference temperature of the orifice plate bore diameter and/or meter tube inside diameter	68°F
T_s	Standard temperature	519.67°R
U_{f_1}	Flowing velocity at upstream tap	ft/sec
V	Volume	ft^3
V_b	Volume at base conditions	ft^3
V_{f_1}	Flowing volume at upstream tap	ft^3
x	Ratio of differential pressure to absolute static pressure	—
x_1	Ratio of differential pressure to absolute static pressure at the upstream pressure tap	—
x_2	Ratio of differential pressure to absolute static pressure at the downstream pressure tap	—
x/k	Acoustic ratio	—
Y	Expansion factor	—
Y_1	Expansion factor based on upstream absolute static pressure	—
Y_2	Expansion factor based on downstream absolute static pressure	—
Z	Compressibility	—
Z_b	Compressibility at base conditions	—
$Z_{b_{air}}$	Compressibility of air at 14.73 psia and 60°F	0.999590
$Z_{b_{gas}}$	Compressibility of the gas at base conditions (P_b, T_b)	—
Z_f	Compressibility at flowing conditions (P_f, T_f)	—
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_{f_2}	Compressibility at downstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
α	Linear coefficient of thermal expansion	in/in-°F
α_1	Linear coefficient of thermal expansion of the orifice plate material	in/in-°F
α_2	Linear coefficient of thermal expansion of the meter tube material	in/in-°F
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
μ	Absolute viscosity of flowing fluid	lbm/ft-sec

π	Universal constant	3.14159
ρ_b	Density of a fluid at base conditions (P_b, T_b)	lbm/ft^3
$\rho_{b_{air}}$	Density of air at base conditions (P_b, T_b)	lbm/ft^3
$\rho_{b_{gas}}$	Density of a gas at base conditions (P_b, T_b)	lbm/ft^3
ρ_s	Density of a fluid at standard conditions (P_s, T_s)	lbm/ft^3
$\rho_{t,p}$	Density of a fluid at flowing conditions (P_f, T_f)	lbm/ft^3
ρ_{t,p_1}	Density of a fluid at flowing conditions at upstream tap position (P_{f_1}, T_f)	lbm/ft^3
ρ_{t,p_2}	Density of a fluid at flowing conditions at downstream tap position (P_{f_2}, T_f)	lbm/ft^3
ϕ_i	Mole fraction of component	%/100

Note: Factors, ratios and coefficients are dimensionless.

3.2.3 TERMINOLOGY

3.2.3.1 Pressure

One pound force (lbf) per square inch pressure is defined as the force a 1-pound mass (lbm) exerts when evenly distributed on an area of 1 square inch and when acted on by the standard acceleration of free fall, 32.1740 feet per second per second.

3.2.3.2 Subscripts

The subscript 1 on the expansion factor (Y_1), the flowing density (ρ_{t,p_1}), the fluid flowing static pressure (P_{f_1}), and the fluid flowing compressibility (Z_{f_1}) indicates that these variables are to be measured, calculated, or otherwise determined relative to the fluid flowing at the conditions of the upstream differential tap. Variables related to the downstream differential pressure tap are identified by the subscript 2, including Y_2, ρ_{t,p_2}, P_{f_2}, and Z_{f_2}, and can be used in the equations with equal precision of the calculated flow rates (except for Y_2, which has a separate equation).

The subscript 1 is arbitrarily used in the equations in this part to emphasize the necessity of maintaining the relationship of these four variables to the chosen static pressure reference tap.

3.2.3.3 Temperature

The temperature of the flowing fluid (T_f) does not have a numerical subscript. This temperature is usually measured downstream of the orifice plate for minimum flow disturbance but may be measured upstream within the locations prescribed in Part 2. It is assumed that there is no difference between fluid temperatures at the two differential pressure tap locations and the measurement point, so the subscript is unnecessary.

3.2.3.4 Standard Conditions

Standard conditions are defined as a designated set of base conditions. In this part, standard conditions are defined as the absolute static pressure, P_s, of 14.73 pounds force per square inch absolute; the absolute temperature, T_s, of 519.67°R (60°F); and the fluid compressibility, Z_s, for a stated relative density (specific gravity), G.

3.2.3.5 Definitions

General definitions are covered in Parts 1 and 2. Definitions specific to Part 3 are incorporated in the text.

3.3 Flow Measurement Equations

3.3.1 GENERAL

The following equations express flow in terms of mass and volume per unit time and produce equivalent results. Since this section deals exclusively with the inch-pound system of units, the numeric constants defined in Part 1 have been converted to reflect these units.

The numeric constants for the basic flow equations, unit conversion values, density of water, and density of air are given in 3.5 and Appendix 3-G. The tables in this part that list solutions to these equations incorporate these constants and values. Other physical properties are given in 3.5. Key equation components are developed in 3.4.

3.3.2 EQUATIONS FOR MASS FLOW OF NATURAL GAS

The equations for the mass flow of natural gas, in pounds mass per hour, can be developed from the density of the flowing fluid (see Appendix 3-G), the ideal gas relative density (specific gravity), or the real gas relative density (specific gravity), using the following equations.

The mass flow developed from the density of the flowing fluid (ρ_{t,p_1}) is expressed as follows:

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \tag{3-1}$$

Mass flow developed from the ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \tag{3-2}$$

The mass flow equation developed from the real gas relative density (specific gravity), G_r, assumes a pressure of 14.73 pounds force per square inch absolute and a temperature of 519.67°R (60°F) as the reference base conditions for the determination of real gas relative density (specific gravity). This assumption allows the base compressibility of air at 14.73 pounds force per square inch absolute and 519.67°R (60°F) to be incorporated into the numeric constant of the flow rate equation. If the assumption about the base reference conditions is not valid, the results obtained from this flow rate equation will have an added increment of uncertainity. The mass flow equation developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_m = 590.006 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \tag{3-3}$$

Where:

$C_d(FT)$ = coefficient of discharge for flange-tapped orifice meter.
d = orifice plate bore diameter, in inches, calculated at flowing temperature (T_f).
E_v = velocity of approach factor.
G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_{f_1} = flowing pressure at upstream tap, in pounds force per square inch absolute.
Q_m = mass flow rate, in pounds mass per hour.
T_f = flowing temperature, in degrees Rankine.
Y_1 = expansion factor (upstream tap).
Z_s = compressibility at standard conditions (P_s, T_s).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
ρ_{t,p_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot.

3.3.3 EQUATIONS FOR VOLUME FLOW OF NATURAL GAS

The volume flow rate of natural gas, in cubic feet per hour at base conditions, can be developed from the densities of the fluid at flowing and base conditions and the ideal gas relative density (specific gravity) or real gas relative density (specific gravity) using the following equations.

The volume flow rate at base conditions, Q_b, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and base conditions (ρ_b) is expressed as follows:

$$Q_b = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \qquad (3\text{-}4a)$$

The volume flow rate at base conditions, developed from ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \qquad (3\text{-}5a)$$

To correctly apply the real gas relative density (specific gravity) to the flow calculation, the reference base conditions for the determination of real gas relative density (specific gravity) and the base conditions for the flow calculation must be the same. Therefore, the volume flow rate at base conditions, developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{P_{f_1} Z_b Z_{b_{air}} h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6a)$$

If standard conditions are substituted for base conditions in Equations 3-4a, 3-5a, and 3-6a, then

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ pounds force per square inch absolute} \\ T_b &= T_s \\ &= 519.67°R\ (60°F) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

The volume flow rate at standard conditions, Q_b, can then be determined using the following equations.

The volume flow rate at standard conditions, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and standard conditions (ρ_s), is expressed as follows:

$$Q_v = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_s} \qquad (3\text{-}4b)$$

The volume flow rate at standard conditions, developed from ideal gas relative density (specific gravity), G_i, is expressed as follows:

$$Q_v = 7711.19 C_d (FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \qquad (3\text{-}5b)$$

The volume flow rate equation at standard conditions, Q_v, developed from the real gas relative density (specific gravity), requires standard conditions as the reference base conditions for G_r and incorporates $Z_{b_{air}}$ at 14.73 pounds force per square inch absolute and 519.67°R (60°F) in its numeric constant. Therefore, the volume flow rate at standard conditions, developed from real gas relative density (specific gravity), G_r, is expressed as follows:

$$Q_v = 7709.61 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

Where:

$C_d(FT)$ = coefficient of discharge for flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature (T_f), in inches.
E_v = velocity of approach factor.
G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_b = base pressure, in pounds force per square inch absolute.
P_{f_1} = flowing pressure (upstream tap), in pounds force per square inch absolute.
P_s = standard pressure
= 14.73 pounds force per square inch absolute.
Q_b = volume flow rate per hour at base conditions, in cubic feet per hour.
Q_v = volume flow rate per hour at standard conditions, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_f = flowing temperature, in degrees Rankine.
T_s = standard temperature
= 519.67°R (60°F).
Y_1 = expansion factor (upstream tap).
Z_b = compressibility at base conditions (P_b, T_b).
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
Z_s = compressibility at standard conditions (P_s, T_s).
$Z_{s_{air}}$ = compressibility of air at standard conditions (P_s, T_s).
ρ_b = density of the flowing fluid at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_s = density of the flowing fluid at standard conditions (P_s, T_s), in pounds mass per cubic foot.
ρ_{t,p_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.

3.3.4 VOLUME CONVERSION FROM STANDARD TO BASE CONDITIONS

For the purposes of Part 3, standard and base conditions are assumed to be the same. However, if base conditions are different from standard conditions, the volume flow rate calculated at standard conditions can be converted to the volume flow rate at base conditions through the following relationship:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \quad (3\text{-}7)$$

Where:

P_b = base pressure, in pounds force per square inch absolute.
P_s = standard pressure, in pounds force per square inch absolute.
Q_b = base volume flow rate, in cubic feet per hour.
Q_v = standard volume flow rate, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_s = standard temperature, in degrees Rankine.
Z_b = compressibility at base conditions (P_b, T_b).
Z_s = compressibility at standard conditions (P_s, T_s).

3.4 Flow Equation Components Requiring Additional Computation

3.4.1 GENERAL

Some of the terms in Equations 3-1 through 3-6 require additional computation and are developed in this section.

3.4.2 DIAMETER RATIO (β)

The diameter ratio (β), which is used in determining (a) the orifice plate coefficient of discharge (C_d), (b) the velocity of approach factor (E_v), and (c) the expansion factor (Y), is the ratio of the orifice bore diameter (d) to the internal diameter of the meter tube (D). For the most precise results, the actual dimensions should be used, as determined in Parts 1 and 2.

$$\beta = d / D \tag{3-8}$$

Where

$$d = d_r[1 + \alpha_1(T_f - T_r)] \tag{3-9}$$

And

$$D = D_r[1 + \alpha_2(T_f - T_r)] \tag{3-10}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f.
d_r = reference orifice plate bore diameter calculated at reference temperature, T_r.
D = meter tube internal diameter calculated at flowing temperature, T_f.
D_r = reference meter tube internal diameter calculated at reference temperature, T_r.
T_f = temperature of the fluid at flowing conditions.
T_r = reference temperature for the orifice plate bore diameter and/or the meter tube internal diameter.
α_1 = linear coefficient of thermal expansion of the orifice plate material (see Table 3-1).
α_2 = linear coefficient of thermal expansion of the meter tube material (see Table 3-1).
β = diameter ratio.

Note: α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68°F.

The orifice plate bore diameter, d_r, and the meter tube internal diameter, D_r, calculated at T_r are the diameters determined in accordance with Part 2.

3.4.3 COEFFICIENT OF DISCHARGE FOR FLANGE–TAPPED ORIFICE METER, C_d(FT)

The coefficient of discharge for a flange-tapped orifice meter (C_d) has been determined from test data. It has been correlated as a function of diameter ratio (β), tube diameter, and pipe Reynolds number. In this part, the equation for the flange-tapped orifice meter coefficient of discharge developed in Part 1 has been adapted to the inch-pound system of units.

The equation for the concentric, square-edged flange-tapped orifice meter coefficient of discharge, C_d(FT), developed by Reader-Harris and Gallagher, is structured into distinct

Table 3-1—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion (α), in/in-°F
Type 304 and 316 stainless steel[a]	0.00000925
Monel[a]	0.00000795
Carbon steel[b]	0.00000620

Note: For flowing temperature conditions other than those stated in Footnotes a and b and for other materials, refer to the American Society for Metals *Metals Handbook* (Desk Edition, 1985).
[a]For flowing conditions between –100°F and +300°F, refer to the American Society of Mechanical Engineers data in PTC 19.5, *Application, Part II of Fluid Meters · Supplement on Instruments and Apparatus*.
[b]For flowing conditions between –7°F and +154°F, refer to Chapter 12, Section 2.

linkage terms and is considered to best represent the current regression data base. The equation is applicable to nominal pipe sizes of 2 inches and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d_r, is greater than 0.45 inches; and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For orifice diameters, diameter ratios, and pipe Reynolds numbers outside the stated limits, the uncertainty statement increases. For guidance, refer to Part 1, 1.12.4.1.

The Reader-Harris/Gallagher equation is defined as follows:

$$C_d(\text{FT}) = C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \quad (3\text{-}11)$$

$$C_i(\text{FT}) = C_i(\text{CT}) + \mathit{Tap\ Term} \quad (3\text{-}12)$$

$$C_i(\text{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \quad (3\text{-}13)$$

$$\mathit{Tap\ Term} = \mathit{Upstrm} + \mathit{Dnstrm} \quad (3\text{-}14)$$

$$\mathit{Upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \quad (3\text{-}15)$$

$$\mathit{Dnstrm} = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \quad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \quad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \quad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1 - \beta} \quad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \quad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \quad (3\text{-}21)$$

Where:

C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter.
C_i(CT) = coefficient of discharge at an infinite pipe Reynolds number for a corner-tapped orifice meter.
C_i(FT) = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant
= 2.71828.
$L_1 = L_2$
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Note: The equation for the coefficient of discharge for a flange-tapped orifice meter, C_d(FT), is different from those included in prior editions of this standard.

3.4.4 VELOCITY OF APPROACH FACTOR (E_v)

The velocity of approach factor (E_v) is a mathematical expression that relates the velocity of the flowing fluid in the orifice meter approach section (upstream meter tube) to the fluid velocity in the orifice plate bore.

The velocity of approach factor, E_v, is calculated as follows:

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \tag{3-22}$$

Where:

E_v = velocity of approach factor.
β = diameter ratio
= d/D.

3.4.5 REYNOLDS NUMBER (Re_D)

The pipe Reynolds number (Re_D) is used as a correlation parameter to represent the change in the orifice plate coefficient of discharge with reference to the meter tube diameter, the fluid flow rate, the fluid density, and the fluid viscosity. The use of the pipe Reynolds number is an additional change from prior editions of this standard. The Reynolds number is a dimensionless ratio when consistent units are used and is expressed as follows:

$$Re_D = \frac{U_{f_1} D \rho_{t,p_1}}{12\mu} \tag{3-23}$$

Or

$$Re_D = \frac{48 q_m}{\pi \mu D} \tag{3-24}$$

Note: The constant, 12, in the denominator of Equation 3-23 is required by the use of D in inches.

The fluid velocity can be obtained in terms of the volumetric flow rate at base conditions from the following relationship:

$$U_{f_1} = \frac{Q_b \rho_b}{D^2 \rho_{t,p_1}} \left[\frac{(4)(144)}{3600\pi}\right]$$

$$= 0.0509296 \frac{Q_b \rho_b}{D^2 \rho_{t,p_1}} \tag{3-25}$$

Substituting Equation 3-25 into Equation 3-23 results in the following relationship:

$$Re_D = \left(\frac{0.0509296}{12}\right)\left(\frac{Q_b \rho_b}{\mu D}\right)\left(\frac{D\rho_{t,p_1}}{D\rho_{t,p_1}}\right)$$

$$= (0.00424413)\left(\frac{Q_b \rho_b}{\mu D}\right) \tag{3-26}$$

The Reynolds number for natural gas can be approximated by substituting the following relationship for ρ_b (see 3.5.5.3 for equation development) into Equation 3-26:

$$\rho_b = \frac{2.69881 P_b}{T_b Z_{b_{air}}} \left(G_r \frac{Z_{b_{air}}}{Z_{b_{air}}}\right) \tag{3-27}$$

$$Re_D = 0.0114541 \left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \tag{3-28}$$

By using an average value of 0.0000069 pounds mass per foot-second for μ and substituting the standard conditions of 519.67°R, 14.73 pounds force per square inch, and 0.999590 for T_b, P_b, and $Z_{b_{air}}$, Equation 3-28 reduces to the following:

$$Re_D = 47.0723 \frac{Q_v G_r}{D} \tag{3-29}$$

Where:

D = meter tube internal diameter calculated at the flowing temperature (T_f), in inches.
G_r = real gas relative density (specific gravity).
P_b = base pressure.
Q_b = volume flow rate at base conditions, in cubic feet per hour.
q_m = mass flow rate, in pounds mass per second.
Q_v = volume flow rate at standard conditions, in cubic feet per hour.
Re_D = pipe Reynolds number.
T_b = base temperature, in degrees Rankine.
U_{f_1} = velocity of the flowing fluid at the upstream tap location, in feet per second.
$Z_{b_{air}}$ = compressibility of air at 14.73 pounds force per square inch absolute and 60°F.
$Z_{b_{gas}}$ = compressibility of the gas at base conditions (P_b, T_b).
μ = absolute (dynamic) viscosity, in pounds mass per foot-second.
π = 3.14159.
ρ_b = density of the flowing fluid at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_{t,p_1} = density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.

If the fluid being metered has a viscosity, temperature, or real gas relative density (specific gravity) quite different from those shown above, the assumptions are not applicable. For variations in viscosity from 0.0000059 to 0.0000079 pounds mass per foot-second, variations in temperature from 30°F to 90°F, or variations in real gas relative density (specific gravity) from 0.55 to 0.75, the variation should not be significant in terms of its effect on the orifice plate coefficient of discharge at higher Reynolds numbers.

When the flow rate is not known, the Reynolds number can be developed through iteration, assuming an initial value of 0.60 for the coefficient of discharge for a flange-tapped orifice meter, C_d(FT), and using the volume computed to estimate the Reynolds number.

3.4.6 EXPANSION FACTOR (Y)

3.4.6.1 General

When a gas flows through an orifice, the change in fluid velocity and static pressure is accompanied by a change in the density, and a factor must be applied to the coefficient to adjust for this change. The factor is known as the expansion factor (Y) and can be calculated from the following equations taken from the report to the A.G.A. Committee by the National Bureau of Standards dated May 26, 1934, and prepared by Howard S. Bean. The expansion factor (Y) is a function of diameter ratio (β), the ratio of differential pressure to static pressure at the designated tap, and the isentropic exponent (k).

The real compressible fluid isentropic exponent, k_r, is a function of the fluid and the pressure and temperature. For an ideal gas, the isentropic exponent, k_i, is equal to the ratio of the specific heats (c_p/c_v) of the gas at constant pressure (c_p) and constant volume (c_v) and is independent of pressure. A perfect gas is an ideal gas that has constant specific heats. The perfect gas isentropic exponent, k_p, is equal to k_i evaluated at base conditions.

It has been found that for many applications, the value of k_r is nearly identical to the value of k_i, which is nearly identical to k_p. From a practical standpoint, the flow equation is not particularly sensitive to small variations in the isentropic exponent. Therefore, the perfect gas isentropic exponent, k_p, is often used in the flow equation. Accepted practice for natural gas applications is to use $k_p = k = 1.3$. This greatly simplifies the calculations and is used in the tables. This approach was adopted by Buckingham in his correlation for the expansion factor.

The application of the expansion factor is valid as long as the following dimensionless criterion for pressure ratio is followed:

$$0 < \frac{h_w}{27.707 P_f} \leq 0.20 \tag{3-30}$$

Or

$$0.8 \leq \frac{P_{f_2}}{P_{f_1}} < 1.0 \tag{3-31}$$

Where:

h_w = flange tap differential pressure across the orifice plate, in inches of water at 60°F.
P_f = flowing pressure, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure at the upstream pressure tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream pressure tap, in pounds force per square inch absolute.

The expansion factor equation for flange taps may be used for a range of diameter ratios from 0.10 to 0.75. For diameter ratios (β) outside the stated limits, increased uncertainty will occur.

3.4.6.2 Expansion Factor Referenced to Upstream Pressure

If the absolute static pressure is taken at the upstream differential pressure tap, the value of the expansion factor, Y_1, can be calculated using the following equation:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \tag{3-32}$$

When the upstream static pressure is measured,

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707 P_{f_1}} \tag{3-33}$$

When the downstream static pressure is measured,

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_2} + (P_{f_1} - P_{f_2})} = \frac{h_w}{27.707 P_{f_2} + h_w} \tag{3-34}$$

Where:

h_w = differential pressure, in inches of water at 60°F.
k = isentropic exponent (see 3.4.6.1).
P_{f_1} = absolute static pressure at the upstream tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream tap, in pounds force per square inch absolute.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
β = diameter ratio (d/D).

The quantity x_1/k is known as the *acoustic ratio.*

3.4.6.3 Expansion Factor Referenced to Downstream Pressure

If the absolute static pressure is taken at the downstream differential tap, the value of the expansion factor, Y_2, can be calculated using the following equation:

$$Y_2 = Y_1 \sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{3-35}$$

And

$$Y_2 = Y_1 \frac{1}{\sqrt{1 - x_1}} \sqrt{\frac{Z_{f_2}}{Z_{f_1}}} \tag{3-36}$$

Or

$$Y_2 = \left[\sqrt{1 + x_2} - (0.41 + 0.35\beta^4)\frac{x_2}{k\sqrt{1 + x_2}}\right]\sqrt{\frac{Z_{f_2}}{Z_{f_1}}} \tag{3-37}$$

And

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_2}} = \frac{h_w}{27.707\, P_{f_2}} \tag{3-38}$$

Where:

h_w = differential pressure, in inches of water at 60°F.
k = isentropic exponent (see 3.4.5.1).
P_{f_1} = absolute static pressure at the upstream tap, in pounds force per square inch absolute.
P_{f_2} = absolute static pressure at the downstream tap, in pounds force per square inch absolute.
x_1 = ratio of differential pressure to absolute static pressure at the upstream tap.
x_2 = ratio of differential pressure to absolute static pressure at the downstream tap.
Y_1 = expansion factor based on the absolute static pressure measured at the upstream tap.
Y_2 = expansion factor based on the absolute static pressure measured at the downstream tap.
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).
Z_{f_2} = compressibility at downstream flowing conditions (P_{f_2}, T_f).
β = diameter ratio (d/D).

Note: x_2 equals the ratio of the differential pressure to the static pressure at the downstream tap (P_{f_2}).

3.5 Gas Properties

3.5.1 GENERAL

The measurement of gaseous flow rate in volume units under other than standard or base conditions requires conversion for pressure, temperature, and the deviation of the measured volume from the ideal gas laws (compressibility). Energy measurement also requires adjustment for heat content. The standard conditions used in Part 3 are a base pressure of 14.73 pounds force per square inch absolute and a base temperature of 519.67°R (60°F).

As a mixture of compounds, natural gas complicates the calculation of some of these conversion factors. The factors that cannot be determined by simple calculations can be derived from gas composition and/or other measurements. Certain factors can be measured in the field, using instruments calibrated against standard gas samples. Either approach will produce equivalent results when rigorous methods are applied.

3.5.2 PHYSICAL PROPERTIES

Table 3-F-1 in Appendix 3-F lists physical properties taken from GPA 2145-91. The data for ideal density and ideal heating value per cubic foot from GPA 2145-91 have, where nec-

essary, been corrected in Table 3-F-1 for the base pressure of 14.73 pounds force per square inch absolute through the following relationship:

$$\text{Table 3-F-1 value} = \frac{14.73}{14.696} \times \text{GPA 2145-91 table value} \qquad (3\text{-}39)$$

Table 3-F-1 provides the best currently available data on physical properties. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values from the most recent edition of GPA 2145 should be used, and the values for density and British thermal units per cubic foot should be corrected through the use of Equation 3-39.

In addition, GPA Publication 2172 and Publication 181 are incorporated in this standard as the method of calculating heating values of natural gas mixtures from compositional analysis. An abbreviated form of that methodology is included in Appendix 3-F as a reference.

In this edition, the compressibility of air at standard conditions ($Z_{s,air}$) has been updated to the value of 0.999590.

3.5.3 COMPRESSIBILITY

3.5.3.1 Ideal and Real Gas

The terms *ideal gas* and *real gas* are used to define calculation or interpretation methods. An ideal gas is one that conforms to the thermodynamic laws of Boyle and Charles (ideal gas laws), such that the following is true:

$$144PV = nRT \qquad (3\text{-}40)$$

If Subscript 1 represents a gas volume measured at one set of temperature–pressure conditions and Subscript 2 represents the same volume measured at a second set of temperature–pressure conditions, then

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \qquad (3\text{-}41)$$

The numerical constant in Equation 3-40 is required to convert P, in pounds force per square inch absolute, to units that are consistent with the value of R given in Part 2.

All gases deviate from the ideal gas laws to some extent. This deviation is known as *compressibility* and is denoted by the symbol Z. Additional discussion of compressibility and the method for determining the value of Z for natural gas are developed in detail in A.G.A. Transmission Measurement Committee Report No. 8. The method used in that report is included as a part of this standard.

The application of Z changes the ideal relationship in Equation 3-40 to the following real relationship:

$$144PV = nZRT \qquad (3\text{-}42)$$

As modified by Z, Equation 3-41 allows the volume at the upstream flowing conditions to be converted to the volume at base conditions by use of the following equation:

$$V_b = V_{f_1}\left(\frac{P_{f_1}}{P_b}\right)\left(\frac{Z_b}{Z_{f_1}}\right)\left(\frac{T_b}{T_f}\right) \qquad (3\text{-}43)$$

Where:

n = number of pound-moles of a gas.
P = absolute static pressure of a gas, in pounds force per square inch absolute.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.

P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute temperature of a gas, in degrees Rankine.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
V = volume of a gas, in cubic feet.
V_b = volume of a gas at base conditions (P_b, T_b), in cubic feet.
V_{f_1} = volume of a gas at flowing conditions (P_{f_1}, T_f), in cubic feet.
Z = compressibility of a gas at P and T.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).

3.5.3.2 Compressibility at Base Conditions

The value of Z at base conditions (Z_b) is required and is calculated from the procedures in A.G.A. Transmission Measurement Committee Report No. 8.

3.5.3.3 Supercompressibility

In orifice measurement, Z_b and Z_{f_1} appear as a ratio to the 0.5 power. This relationship is termed the *supercompressibility factor* and may be calculated from the following equation:

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \qquad (3\text{-}44)$$

Or

$$Z_{f_1} = \frac{Z_b}{F_{pv}^{\,2}} \qquad (3\text{-}45)$$

Where:

F_{pv} = supercompressibility factor.
Z_b = compressibility of the gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of the gas at flowing conditions (P_{f_1}, T_f).

3.5.4 RELATIVE DENSITY (SPECIFIC GRAVITY)

3.5.4.1 General

Relative density (specific gravity), G, is a component in several of the flow equations. The relative density (specific gravity) is defined as a dimensionless number that expresses the ratio of the density of the flowing fluid to the density of a reference gas at the same reference conditions of temperature and pressure. The gas industry has historically referred to the relative density (specific gravity) as either ideal or real and has designated the reference gas as air and the standard reference conditions as a pressure of 14.73 pounds force per square inch absolute and a temperature of 519.67°R (60°F). The value for relative density (specific gravity) may be determined by measurement or by calculation from the gas composition.

3.5.4.2 Ideal Gas Relative Density (Specific Gravity)

The ideal gas relative density (specific gravity), G_i, is defined as the ratio of the ideal density of the gas to the ideal density of dry air at the same reference conditions of pressure and temperature. Since the ideal densities are defined at the same reference conditions of pressure and temperature, the ratio reduces to a ratio of molar masses (molecular weights).

Therefore, the ideal gas relative density (specific gravity) is set forth in the following equation:

$$G_i = \frac{Mr_{gas}}{Mr_{air}} = \frac{Mr_{gas}}{28.9625} \tag{3-46}$$

Where:

G_i = ideal gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of a flowing gas, in pounds mass per pound-mole.

3.5.4.3 Real Gas Relative Density (Real Specific Gravity)

Real gas relative density (specific gravity), G_r, is defined as the ratio of the real density of the gas to the real density of dry air at the same reference conditions of pressure and temperature. To correctly apply the real gas relative density (specific gravity) to the flow calculation, the reference conditions for the determination of the real gas relative density (specific gravity) must be the same as the base conditions for the flow calculation. At reference (base) conditions (P_b, T_b), real gas relative density (specific gravity) is expressed as follows:

$$G_r = \frac{144\dfrac{P_{b_{gas}} Mr_{gas}}{Z_{b_{gas}} R T_{b_{gas}}}}{144\dfrac{P_{b_{air}} Mr_{air}}{Z_{b_{air}} R T_{b_{air}}}}$$

Since the pressures and temperatures are defined to be at the same designated base conditions,

$$P_{b_{gas}} = P_{b_{air}}$$

$$T_{b_{gas}} = T_{b_{air}}$$

And the real gas relative density (specific gravity) is expressed as follows:

$$G_r = \left(\frac{Mr_{gas}}{Mr_{air}}\right)\left(\frac{Z_{b_{air}}}{Z_{b_{gas}}}\right) \tag{3-47}$$

The use of real gas relative density (specific gravity) in the flow calculations has a historic basis but may add an increment of uncertainty to the calculation as a result of the limitations of field gravitometer devices. When real gas relative densities (specific gravities) are directly determined by relative density measurement equipment, the observed values must be adjusted so that both air and gas measurements reflect the same pressure and temperature. The fact that the temperature and/or pressure are not always at base conditions results in small variations in determinations of relative density (specific gravity). Another source of variation is the use of atmospheric air. The composition of atmospheric air—and its molecular weight and density—varies with time and geographical location.

When recording gravitometers are used and calibration is performed with reference gases, either ideal or real gas relative density (specific gravity) can be obtained as a recorded relative density (specific gravity) by proper certification of the reference gas. The relationship between ideal gas relative density (specific gravity) and real gas relative density (specific gravity) is expressed as follows:

$$G_r = G_i \frac{Z_{b_{air}}}{Z_{b_{gas}}} \tag{3-48}$$

Where:

G_i = ideal gas relative density (specific gravity).
G_r = real gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of the flowing gas, in pounds mass per pound-mole.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.
$P_{b_{air}}$ = base pressure of air, in pounds force per square inch absolute.
$P_{b_{gas}}$ = base pressure of a gas, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
$T_{b_{air}}$ = base temperature of air, in degrees Rankine.
$T_{b_{gas}}$ = base temperature of a gas, in degrees Rankine.
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
$Z_{b_{gas}}$ = compressibility of a gas at base conditions (P_b, T_b).

3.5.5 DENSITY OF FLUID AT FLOWING CONDITIONS

3.5.5.1 General

The flowing density ($\rho_{t,p}$) is a key component of certain flow equations. It is defined as the mass per unit volume at flowing pressure and temperature and is measured at the selected static pressure tap location. The value for flowing density can be calculated from equations of state or from the relative density (specific gravity) at the selected static pressure tap. The fluid density at flowing conditions can also be measured using commercial densitometers. Most densitometers, because of their physical installation requirements and design, cannot accurately measure the density at the selected pressure tap location. Therefore, the fluid density difference between the density measured and that existing at the defined pressure tap location must be checked to determine whether changes in pressure or temperature have an impact on the flow measurement uncertainty.

An approximation for field calculation is the direct application of tables from the equation of state. Such density tables have considerable bulk if they cover a wide range of conditions in small increments. Tables have a further deficiency in that they do not readily lend themselves to interpolation or extrapolation with fluctuating temperature and/or pressure.

At the time of publication, it was anticipated that a computer program for IBM and compatible personal computers that generates density and/or compressibility tables for user-defined gas and pressure–temperature ranges would be available through A.G.A. This program uses the equations in A.G.A. Transmission Measurement Committee Report No.8.

3.5.5.2 Density Based on Gas Composition

When the composition of a gas mixture is known, the gas densities $\rho_{t,p}$ and ρ_b may be calculated from the gas law equations. The molecular weight of the gas may be determined from composition data, using mole fractions of the components and their respective molecular weights.

$$Mr_{gas} = \phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_w Mr_w$$

$$= \sum_{i=1}^{w} \phi_i Mr_i \quad (3\text{-}49)$$

In the following, the gas law equation, Equation 3-42, is rearranged to obtain density values:

$$144PV = nZRT$$

$$n = \frac{m}{Mr_{gas}} \quad (3\text{-}50)$$

Therefore:

$$144PV = \left(\frac{m}{Mr_{gas}}\right)ZRT \quad (3\text{-}51)$$

And

$$\rho_{t,p_1} = \frac{m}{V_{f_1}} = \frac{144\,P_{f_1}\,Mr_{gas}}{Z_{f_1}RT_f} \quad (3\text{-}52)$$

Or

$$\rho_b = \frac{m}{V_b} = \frac{144\,P_b\,Mr_{gas}}{Z_bRT_b} \quad (3\text{-}53)$$

Where:

G_i = ideal gas relative density (specific gravity).
m = mass of a fluid, in pounds mass.
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of the flowing gas, in pounds mass per pound-mole.
Mr_i = molar mass (molecular weight) of a component, in pounds mass per pound-mole.
n = number of moles.
P = absolute static pressure of a gas, in pounds force per square inch absolute.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute temperature of a gas, in degrees Rankine.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
V = volume of a gas, in cubic feet.
Z = compressibility of a gas at P, T.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
ρ_b = density of a gas at base conditions (P_b, T_b), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f), in pounds mass per cubic foot.
ϕ_i = mole fraction of a component.

3.5.5.3 Density Based on Ideal Gas Relative Density (Specific Gravity)

The gas densities ρ_{t,p_1} and ρ_b may be calculated from the ideal gas relative density (specific gravity), as defined in 3.5.5.2. The following equations are applicable when a gas analysis is available:

$$G_i = \frac{Mr_{gas}}{Mr_{air}} = \frac{Mr_{gas}}{28.9625} \quad (3\text{-}46)$$

Note: The molecular weight of dry air, from GPA 2145-91, is given as 28 9625 pounds mass per pound-mole (exactly).

$$Mr_{gas} = G_i Mr_{air} = G_i(28.9625) \tag{3-54}$$

Substituting for Mr_{gas} in Equations 3-52 and 3-53, ρ_{t,p_1} and ρ_b are determined as follows:

$$\rho_{t,p_1} = \frac{P_{f_1} G_i (28.9625)(144)}{Z_{f_1} R T_f}$$

$$= 2.69881 \frac{P_{f_1} G_i}{Z_{f_1} T_f} \tag{3-55}$$

And

$$\rho_b = \frac{P_b G_i (28.9625)(144)}{Z_b R T_b}$$

$$= 2.69881 \frac{P_b G_i}{Z_b T_b} \tag{3-56}$$

Where:

G_i = ideal gas relative density (specific gravity).
Mr_{air} = molar mass (molecular weight) of air
= 28.9625 pounds mass per pound-mole.
Mr_{gas} = molar mass (molecular weight) of a flowing gas, in pounds mass per pound-mole.
P_b = absolute static pressure of the gas at base conditions, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
Z_b = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
ρ_b = density of a gas at base conditions (P_b, T_b, and Z_b), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot.

3.5.5.4 Density Based on Real Gas Relative Density (Specific Gravity)

The relationship of real gas relative density (specific gravity) to ideal gas relative density (specific gravity) is given by the following equation:

$$G_r = G_i \frac{Z_{b_{air}}}{Z_{b_{gas}}} \tag{3-48}$$

Or

$$G_i = G_r \frac{Z_{b_{gas}}}{Z_{b_{air}}}$$

Note: The real gas relative density (specific gravity) of dry air at base conditions is defined as exactly 1.00000.

Substituting for G_i in Equations 3-55 and 3-56 results in the following:

$$\rho_{t,p_1} = \frac{2.69881 P_{f_1} G_r Z_{b_{gas}}}{Z_{f_1} T_f Z_{b_{air}}} \quad (3\text{-}57)$$

$$\rho_b = \frac{2.69881 P_b G_i}{T_b Z_{b_{air}}} \quad (3\text{-}58)$$

To correctly apply the density equations, Equations 3-57 and 3-58, which were developed from the real gas relative density (specific gravity), to the flow calculation, the reference base conditions for the determination of real gas relative density (specific gravity) and the base conditions for the flow calculation must be the same. When standard conditions are substituted for base conditions,

$P_b = P_s$
$= 14.73$ pounds force per square inch absolute
$T_b = T_s$
$= 519.67°R\ (60°F)$
$Z_{b_{air}} = Z_{s_{air}}$
$= 0.999590$

The gas density based on real gas relative density (specific gravity) is given by the following equations:

$$\rho_{t,p_1} = \frac{2.69881 P_{f_1} G_r Z_{s_{gas}}}{0.999590\, Z_{f_1} T_f}$$

$$= 2.69992 \frac{P_{f_1} Z_{s_{gas}} G_r}{Z_{f_1} T_f} \quad (3\text{-}59)$$

And

$$\rho_s = \frac{(2.69881)(14.73) G_r}{(0.999590)(519.67)}$$

$$= 0.0765289\, G_r \quad (3\text{-}60)$$

Where:

G_i = ideal gas relative density.
G_r = real gas relative density.
P_b = absolute static pressure of a gas at base conditions, in pounds force per square inch absolute.
P_{f_1} = absolute static pressure of a gas at the upstream tap, in pounds force per square inch absolute.
T_b = absolute temperature of a gas at base conditions, in degrees Rankine.
T_f = absolute temperature of a flowing gas, in degrees Rankine.
$Z_{b_{air}}$ = compressibility of air at base conditions (P_b, T_b).
$Z_{b_{gas}}$ = compressibility of a gas at base conditions (P_b, T_b).
Z_{f_1} = compressibility of a gas at flowing conditions (P_{f_1}, T_f).
$Z_{s_{air}}$ = compressibility of air at standard conditions (P_s, T_s).
$Z_{s_{gas}}$ = compressibility of a gas at standard conditions (P_s, T_s).
ρ_b = density of a gas at base conditions (P_b, T_b, and Z_b), in pounds mass per cubic foot.
ρ_s = density of a gas at standard conditions (P_s, T_s, and Z_s), in pounds mass per cubic foot.
ρ_{t,p_1} = density of a gas at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in pounds mass per cubic foot.

The density equations for standard conditions based on the real gas relative density (specific gravity) developed above require standard conditions as the designated reference base conditions for G_r and incorporate $Z_{b_{air}}$ at 14.73 pounds force per square inch absolute and 519.67°R in their numeric constants.

APPENDIX 3-A—ADJUSTMENTS FOR INSTRUMENT CALIBRATION

3-A.1 Scope

This appendix provides equations and procedures for adjusting and correcting field measurement calibrations of secondary instruments.

3-A.2 General

Field practices for secondary instrument calibrations and calibration standard applications contribute to the overall uncertainty of flow measurement.

Calibration standards for differential pressure and static pressure instruments are often used in the field without local gravitational force adjustment or correction of the values indicated by the calibrating standards. For example, it is common to use water column manometers to calibrate differential pressure instruments without making field corrections to the manometer readings for changes in water density. The manometer readings are affected by local gravitational effects, water temperatures, and the use of other than distilled water.

Pressure devices that employ weights are also used to calibrate differential pressure instruments without correction for the local gravitational force. Similarly, deadweight testers are used to calibrate static pressure measuring equipment without correction for the local gravitational force. It is usually more convenient and accurate to incorporate these adjustments in the flow computation than for the person calibrating the instrument to apply these small corrections during the calibration process. Therefore, additional factors are added to the flow equation for the purpose of including the appropriate calibration standard corrections in the flow computation either by the flow calculation procedure in the office or by the meter technician in the field.

Six factors are provided that may be used individually or in combination, depending on the calibration device and the calibration procedure used:

- F_{am} Correction for air over the water in the water manometer during the differential instrument calibration.
- F_{wl} Local gravitational correction for the water column calibration standard.
- F_{wt} Water density correction (temperature or composition) for the water column calibration standard.
- F_{pwl} Local gravitational correction for the deadweight tester static pressure standard.
- F_{hgm} Manometer factor (correction for the gas column in mercury manometers).
- F_{hgt} Mercury manometer temperature factor (span correction for instrument temperature change after calibration).

These factors expand the base volume flow equation to the following:

$$Q'_v = Q_v F_{am} F_{wt} F_{wl} F_{pwl} F_{hgm} F_{hg} \qquad (3\text{-A-}1)$$

All of the flow factors that are pertinent to gas flow and are defined in this standard are included in Equation 3-A-1. Some of the factors are not applicable to all measurement systems and may therefore be considered equal to 1 or ignored, as preferred by the user. For other applications, particularly those involving mass flow calculation, specific factors may be included in the selected equation as appropriate for the system, the calibration of the instrumentation, and particular operating procedures.

3-A.3 Symbols, Units, and Terminology

3-A.3.1 GENERAL

The symbols and units used are specific to this appendix and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–A.3.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	—
F_{aml}	Correction for air over the water in the water manometer	—
F_{hgm}	Manometer factor	—
F_{hgt}	Mercury manometer temperature factor	—
F_{pwl}	Local gravitational correction for deadweight tester	—
F_{wl}	Local gravitational correction for water column	—
F_{wt}	Water density correction	—
g_l	Local acceleration due to gravity	ft/sec^2
g_o	Acceleration of gravity used to calibrate weights or deadweight calibrator	ft/sec^2
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_{wa}	Differential pressure above atmospheric	inches of water column at 60°F
H	Elevation above sea level	ft
L	Latitude on earth's surface	degrees
Mr	Molar mass of gas	lbm/lb-mol
Mr_{air}	Molar mass of air	28.9625 lbm/lb-mol
P	Absolute gas pressure	lbf/in^2 (abs)
P_{atm}	Local atmospheric pressure	lbf/in^2 (abs)
P_b	Base pressure	lbf/in^2 (abs)
P_f	Absolute pressure of flowing gas	lbf/in^2 (abs)
Q_v'	Volume flow rate at standard conditions modified for instrument calibration adjustments	ft^3/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Absolute gas temperature	°R
T_b	Base temperature	°R
T_f	Absolute temperature of a flowing gas	°R
T_{hga}	Mercury ambient temperature	°R
T_{gas_a}	Gas ambient temperature	°R
Z	Compressibility of a gas at T and P	—
Z_b	Compressibility of a gas at standard conditions (G_r, P_b, and T_b)	—
Z_a	Compressibility of air at $P_{atm} + h_{wa}$ and 519.67°R	—
Z_{aatm}	Compressibility of air at P_{atm} and 519.67°R	—
Z_{bair}	Compressibility of air at 14.73 psia and 519.67°R	0.999590
Z_f	Compressibility of gas at flowing conditions (G_r, P_f, and T_f)	—
ρ_a	Density of air at pressure above atmospheric	lbm/ft^3
ρ_{atm}	Density of atmospheric air	lbm/ft^3
ρ_g	Density of gas or vapor in the differential pressure instrument	lbm/ft^3
ρ_{hg}	Density of mercury in the differential pressure instrument	lbm/ft^3

ρ_{hgc}	Density of mercury in the differential pressure instrument at the time of its calibration	lbm/ft³
ρ_{hgo}	Density of mercury in the differential pressure instrument at the mercury gauge operating conditions	lbm/ft³
ρ_w	Density of water in the manometer at other than 60°F	lbm/ft³

3–A.4 Water Manometer Gas Leg Correction Factor (F_{am})

The factor F_{am} corrects for the gas leg over water when a water manometer is used to calibrate a differential pressure instrument:

$$F_{am} = \sqrt{\frac{\rho_w - \rho_a}{\rho_w}} \qquad (3\text{-A-}2)$$

When atmospheric air is used as the medium to pressure both the differential pressure instrument and the water U-tube manometer during calibration, the density of air at atmospheric pressure and 60°F must be calculated using the following equation:

$$\rho = \frac{Mr\,G_i P}{RZT} \qquad (3\text{-A-}3)$$

Substituting local atmospheric pressure (P_{atm}) for absolute pressure (P), 519.67°R (60°F) for the absolute temperature (T), 28.9625 for Mr_{air}, 1.0 for the ideal relative density (specific gravity) of air (G_i), and 1545.35 for the universal gas constant (R) provides the following relationship:

$$\rho_{am} = \frac{(28.9625)(1.0)P_{atm}}{\frac{1545.35}{144} Z_{a_{atm}} (519.67)} = \frac{P_{atm}}{192.556\,Z_{a_{atm}}} \qquad (3\text{-A-}4)$$

The local atmospheric pressure may be calculated using an equation published in the *Smithsonian Meteorological Tables:*

$$P_{atm} = 14.54\left[\frac{55096 - (\text{Elevation, ft} - 361)}{55096 + (\text{Elevation, ft} - 361)}\right] \qquad (3\text{-A-}5)$$

The density of air at any given differential pressure (h_{wa}) above atmospheric pressure can then be represented by the following:

$$\rho_a = \frac{P_{atm} + \frac{h_{wa}}{27.707}}{192.477\,Z_a} \qquad (3\text{-A-}6)$$

The density of water can be obtained from Table 3-A-1 or calculated from the following Wegenbreth density equation:

$$\begin{aligned}\rho_w = {} & 0.0624280[999.8395639 + 0.067982999 89T_w - 0.0091060255 64T_w^2 \\ & + 0.0001005272999T_w^3 - 0.0000011267135 26T_w^4 \\ & + 0.0000000065917956 06T_w^5]\end{aligned} \qquad (3\text{-A-}7)$$

Where:

G_i = ideal gas relative density (specific gravity).
h_{wa} = differential pressure above atmospheric, in inches of water at 60°F.
Mr = molar mass of a gas, in pounds mass per pound-mole.

Table 3-A-1—Water Density Based on Wegenbreth Equation

Temperature (°F)	Density (lbm/ft³)	Temperature (°F)	Density (lbm/ft³)
45	62.4212	63	62.3490
46	62.4193	64	62.3427
47	62.4172	65	62.3363
48	62.4148	66	62.3297
49	62.4121	67	62.3228
50	62.4092	68	62.3157
51	62.4060	69	62.3085
52	62.4026	70	62.3010
53	62.3980	71	62.2934
54	62.3949	72	62.2855
55	62.3908	73	62.2775
56	62.3863	74	62.2692
57	62.3817	75	62.2608
58	62.3768	76	62.2522
59	62.3717	77	62.2434
60	62.3663	78	62.2344
61	62.3608	79	62.2252
62	62.3550	80	62.2159

P = absolute gas pressure, in pounds force per square inch absolute.
P_{atm} = local atmospheric pressure, in pounds force per square inch absolute.
R = universal gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T = absolute gas temperature, in degrees Rankine.
T_w = temperature of water, in degrees Celsius.
Z = compressibility of a gas at P and T.
Z_a = compressibility of air at $P_{atm} + h_{wa}$ and 519.67°R.
$Z_{a_{atm}}$ = compressibility of air at P_{atm} and 519.67°R.
ρ = density of a gas, in pounds mass per cubic foot.
ρ_a = density of air at pressure above atmospheric, in pounds mass per cubic foot.
ρ_{atm} = density of atmospheric air, in pounds mass per cubic foot.
ρ_w = density of water in a manometer at a temperature other than 60°F, in pounds mass per cubic foot.

3–A.5 Water Manometer Temperature Correction Factor (F_{wt})

The factor F_{wt} corrects for variations in the density of water used in the manometer when the water is at a temperature other than 60°F. The F_{wt} correction factor should be included in the flow measurement computation when a differential instrument is calibrated with a water manometer.

$$F_{wt} = \frac{\rho_w}{62.3663} \qquad (3\text{-A-}8)$$

Where:

ρ_w = density of water in a manometer at a temperature other than 60°F, in pounds mass per cubic foot.

3–A.6 Local Gravitational Correction Factor for Water Manometers (F_{wl})

The factor F_{wl} corrects the weight of the manometer fluid for the local gravitational force. The effect on the quantity is the square root of the ratio of the local gravitational force to the standard gravitational force used in the equation derivations. This relationship is expressed as follows:

$$F_{wl} = \sqrt{\frac{g_l}{32.1740}} \qquad (3\text{-A-9})$$

Where:

g_l = local acceleration due to gravity, in feet per second per second.

The local value of gravity at any location may be obtained from a U.S. Coast and Geodetic Survey reference to aeronautical data or from the *Smithsonian Meteorological Tables*. Using Equation E11 from the 1985 edition of ANSI/API 2530 and the 45°-latitude-at-sea-level reference value, approximate values of g_l may be obtained from the following curve-fit equation covering latitudes from 0° to 90°:

$$g_l = 0.0328095[978.01855 - 0.0028247L + 0.0020299L^2 - 0.000015058L^3 - 0.000094H] \qquad (3\text{-A-10})$$

Where:

L = latitude, in degrees.
H = elevation, in feet above sea level.

3–A.7 Local Gravitational Correction Factor for Deadweight Calibrators Used to Calibrate Differential and Static Pressure Instruments (F_{pwl})

The factor F_{pwl} is used to correct for the effect of local gravity on the weights of a deadweight calibrator. The calibrator weights are usually sized for use at a standard gravitational force or at some specified gravitational force. A correction factor must then be applied to correct the calibrations to the local gravitational force:

$$F_{pwl} = \frac{g_l}{g_o} \qquad (3\text{-A-11})$$

Where:

g_l = acceleration due to local gravitational force, in feet per second per second.
g_o = acceleration of gravity used to calibrate the weights of a deadweight calibrator, in feet per second per second.

When a deadweight calibrator is used for the differential pressure and the static pressure, both must be corrected for local gravity. This involves using F_{pwl} twice.

3–A.8 Correction for Gas Column in Mercury Manometer Instruments (F_{hgm})

The factor F_{hgm} corrects for the gas or vapor leg of fluid at static pressure and the temperature of the manometer or other instrument. Mercury U-tube manometers and mercury-manometer-type differential pressure instruments are sometimes used to measure h_w. The manometer factor F_{hgm} is added to the flow equation to correct for the effect of the gas column above the mercury during flow measurements:

$$F_{hgm} = \sqrt{\frac{\rho_{hg} - \rho_g}{\rho_{hg}}} \qquad (3\text{-A-12})$$

Where:

ρ_{hg} = density of mercury in the differential pressure instrument, in pounds mass per cubic foot. The effect of atmospheric air (usually defined as the weight *in vacuo* of the mercury sample at the base pressure and temperature defined for the flow measurement) is excluded.

ρ_g = density of the gas or vapor in the differential pressure instrument, in pounds mass per cubic foot. The effect of atmospheric air (usually defined as weight in vacuo of the fluid sample at the flowing pressure existing at the orifice meter during the flow measurement and at the temperature existing at the differential pressure instrument during the flow measurement) is excluded.

The density of mercury at ambient temperature T_{hga}, in degrees Rankine, may be calculated from the following equation:

$$\rho_{hg} = 846.324[1.0 - 0.000101(T_{hga} - 519.67)] \qquad (3\text{-A-}13)$$

The density of a gas at ambient temperature may be calculated using the following equation:

$$\rho_g = \frac{Mr_{air} Z_b G_r P_f}{Z_{b_{air}} R Z_f T_{gas_a}} \qquad (3\text{-A-}14)$$

For standard conditions of

$$P_b = P_s = 14.73 \text{ lbf/in}^2 \text{ (abs)}$$

$$T_b = T_s = 519.67°\text{R } (60°\text{F})$$

$$Z_{b_{air}} = Z_{s_{air}} = 0.999590$$

Then

$$\rho_g = 2.69992 \frac{P_f Z_b G_r}{Z_f T_{gas_a}} \qquad (3\text{-A-}15)$$

Where:

G_r = real gas relative density (specific gravity).
Mr_{air} = molar mass of air
= 28.9625 pounds mass per pound-mole.
P_f = absolute pressure of a flowing gas, in pounds force per square inch absolute.
R = univeral gas constant
= 1545.35 (lbf-ft)/(lbmol-°R).
T_f = absolute temperature of a flowing gas, in degrees Rankine.
T_{gas_a} = gas ambient temperature, in degrees Rankine.
T_{hga} = mercury ambient temperature, in degrees Rankine.
Z_b = compressibility of a gas at G_r, T_b, and P_b.
$Z_{b_{air}}$ = compressibility of air at 519.67°R and 14.73 pounds force per square inch absolute
= 0.999590.
Z_f = compressibility of a gas at flowing conditions (G_r, T_f, and P_f).
Z_s = compressibility of a gas at 519.67°R and 14.73 pounds force per square inch absolute.

Tabular data for F_{hgm} are given in Table 3-A-2.

Correction for a liquid leg over the mercury can also be made if the liquid density is substituted for ρ_g in Equation 3-A-12. If the mercury differential pressure instrument is calibrated using a water column or a weight calibrator, the F_{wl} and F_{wt} factors are also needed.

Table 3-A-2—Mercury Manometer Factors (F_{hgm})

Real Gas Relative Density	Ambient Temperature (°F)	Static Pressure (pounds force per square inch gauge)						
		0	500	1000	1500	2000	2500	3000
0.550	0	1.0030	1.0019	1.0006	0.9990	0.9973	0.9960	0.9951
0.600	0	1.0030	1.0018	1.0002	0.9982	0.9962	0.9949	0.9940
0.650	0	1.0030	1.0017	0.9997	0.9971	0.9950	0.9938	0.9930
0.700	0	1.0030	1.0015	0.9991	0.9957	0.9937	0.9926	0.9920
0.750	0	1.0030	1.0014	0.9984	0.9940	0.9923	0.9913	0.9910
0.550	20	1.0020	1.0010	0.9997	0.9983	0.9969	0.9956	0.9947
0.600	20	1.0020	1.0009	0.9994	0.9977	0.9959	0.9946	0.9937
0.650	20	1.0020	1.0008	0.9990	0.9968	0.9949	0.9936	0.9927
0.700	20	1.0020	1.0007	0.9985	0.9957	0.9936	0.9924	0.9917
0.750	20	1.0020	1.0005	0.9980	0.9944	0.9924	0.9912	0.9907
0.550	40	1.0010	1.0000	0.9989	0.9977	0.9964	0.9952	0.9942
0.600	40	1.0010	0.9999	0.9986	0.9972	0.9956	0.9943	0.9933
0.650	40	1.0010	0.9998	0.9983	0.9965	0.9947	0.9933	0.9923
0.700	40	1.0010	0.9997	0.9980	0.9957	0.9936	0.9922	0.9913
0.750	40	1.0010	0.9996	0.9975	0.9947	0.9925	0.9912	0.9903
0.550	60	1.0000	0.9991	0.9980	0.9969	0.9957	0.9946	0.9936
0.600	60	1.0000	0.9990	0.9978	0.9965	0.9951	0.9938	0.9928
0.650	60	1.0000	0.9989	0.9975	0.9959	0.9943	0.9929	0.9919
0.700	60	1.0000	0.9988	0.9972	0.9953	0.9933	0.9919	0.9909
0.750	60	1.0000	0.9987	0.9968	0.9944	0.9923	0.9909	0.9900
0.550	80	0.9990	0.9981	0.9971	0.9961	0.9950	0.9940	0.9931
0.600	80	0.9990	0.9980	0.9969	0.9957	0.9945	0.9933	0.9923
0.650	80	0.9990	0.9979	0.9967	0.9953	0.9938	0.9925	0.9915
0.700	80	0.9990	0.9978	0.9964	0.9948	0.9930	0.9916	0.9905
0.750	80	0.9990	0.9977	0.9961	0.9941	0.9921	0.9906	0.9896
0.550	100	0.9980	0.9972	0.9962	0.9953	0.9943	0.9933	0.9925
0.600	100	0.9980	0.9971	0.9960	0.9949	0.9938	0.9926	0.9917
0.650	100	0.9980	0.9970	0.9958	0.9945	0.9932	0.9919	0.9909
0.700	100	0.9980	0.9969	0.9956	0.9941	0.9925	0.9912	0.9901
0.750	100	0.9980	0.9968	0.9953	0.9935	0.9917	0.9903	0.9892
0.550	120	0.9970	0.9962	0.9953	0.9944	0.9935	0.9926	0.9918
0.600	120	0.9970	0.9961	0.9951	0.9941	0.9930	0.9920	0.9911
0.650	120	0.9970	0.9960	0.9949	0.9937	0.9925	0.9914	0.9904
0.700	120	0.9970	0.9959	0.9947	0.9933	0.9920	0.9907	0.9896
0.750	120	0.9970	0.9958	0.9945	0.9929	0.9913	0.9899	0.9888

Note: This table is for use with mercury-type recording gauges that have gas in contact with the mercury surface.

A.9 Mercury Manometer Instrument Temperature Factor (F_{hgt})

The factor F_{hgt} corrects for the change in mercury density in the mercury differential pressure instrument due to temperature change from the time of instrument calibration. The mercury manometer temperature factor is introduced to correct for the error in differential pressure reading caused by a change in mercury temperature and the associated change in the density of mercury after calibration of the instrument. The factor is defined by the following equation:

$$F_{hgt} = \sqrt{\frac{\rho_{hgo}}{\rho_{hgc}}} \qquad \text{(3-A-16)}$$

Where:

ρ_{hgo} = density of the mercury in the differential pressure instrument, in pounds mass per cubic foot, at the mercury gauge operating conditions. The effect of atmospheric air (usually defined as the weight *in vacuo* of the mercury sample at the pressure for the flow measurement and the temperature of the mercury gauge) is excluded.

ρ_{hgc} = density of the mercury in the differential pressure instrument, in pounds mass per cubic foot, at the time of its calibration. The effect of atmospheric air (usually defined as the weight *in vacuo* of the mercury sample at a pressure of 1 atmosphere and the temperature of the mercury gauge) is excluded.

The mercury manometer temperature factor applies only to mercury-manometer-type gauges without internal temperature compensation when such gauges are used at operating temperatures different from the temperature of calibration.

APPENDIX 3-B—FACTORS APPROACH

3-B.1 Introduction

The factors approach can provide answers identical to those developed in this part of Chapter 14, Section 3. *The user is cautioned that when the tables in this appendix are used, the values are only precise for the variables stated.* For different dimensions or other input parameters, the true value can only be developed from computation.

3-B.2 Symbols, Units, and Terminology

3-B.2.1 GENERAL

Some of the symbols and units listed below are specific to this appendix and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3-B.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Composite orifice flow factor	—
C_d(FT)	Orifice plate coefficient of discharge	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
e	Napierian constant	2.71828
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	°F
°R	Absolute temperature, in degrees Rankine	°R
F_c	Orifice calculation factor	—
F_c'	Orifice calculation factor for $D < 2.8$	—
F_{gr}	Real gas relative density factor	—
F_n	Numeric conversion factor (see Table 3-B-2)	—
F_{pb}	Base pressure factor	—
F_{pv}	Supercompressibility factor	—
F_{sl}	Orifice slope factor	—
F_{tb}	Base temperature factor	—
F_{tf}	Flowing temperature factor	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
P_b	Absolute base pressure	lbf/in² (abs)
P_{f_1}	Absolute flowing pressure (upstream tap)	lbf/in² (abs)
P_s	Standard pressure	14.73 lbf/in² (abs)
Re_D	Pipe Reynolds number	—
Q_b	Volume flow rate per hour at base conditions	ft³/hr
Q_v	Volume flow rate per hour at standard conditions of Z_b, T_b, and P_b	ft³/hr
T_b	Absolute base temperature	°R
T_f	Absolute flowing temperature	°R
T_s	Standard temperature	519.67°R
Y	Expansion factor	—
Y_1	Expansion factor (upstream tap)	—

Y_2	Expansion factor (downstream tap)	—
Z_b	Compressibility at base conditions (P_b, T_b)	—
Z_{f_1}	Compressibility at upstream flowing conditions (P_{f_1}, T_f)	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Diameter ratio (d/D)	—

3–B.3 Equations for Volume Flow Rate of Natural Gas

In the measurement of natural gas, the general practice is to state the flow in cubic feet per hour at some specified standard or base conditions of pressure and temperature using the real gas relative density. For the purpose of this appendix, the following standard or base conditions are assumed:

$$G_{r_{air}} = 1.00000 \text{ (exactly)}$$
$$P_b = P_s$$
$$= 14\ 73 \text{ pounds force per square inch absolute}$$
$$T_b = T_s$$
$$= 519.67°R$$
$$T_f = 519.67°R$$
$$Z_b = Z_s$$

The volumetric flow rate equation, Equation 3-6a, can be expressed in the historically more familiar format through the inclusion of calculation factors. These factors (ratios) are formed to allow the various terms in Equation 3-6a to be calculated individually.

The factors are derived from combining Equation 3-6a with four numeric ratios, each having a value of 1.00000 (exactly). These ratios are 14.73/14.73, 519.67/519.67, $(519.67/519.67)^{0.5}$, and 1/1. One half of each ratio is combined with P_b, T_b, T_f, and G_r, respectively, to form the F_{pb}, F_{tb}, F_{tf}, and F_{gr} factors. The other half of each ratio is combined with the numeric constant in Equation 3-6a to form the numeric conversion factor, F_n. Therefore, starting with Equation 3-6a,

$$Q_b = 218.573 C_d(\text{FT}) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{P_{f_1} Z_s Z_{b_{air}} h_w}{G_r Z_{f_1} T_f}} \qquad \text{(3-6a)}$$

Reformatting to incorporate the factor approach and standard conditions results in the following:

$$Q_v = 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}}\, C_d(\text{FT}) E_v Y_1 d^2 \left(\frac{T_b}{519.67}\right)\sqrt{0.999590}$$
$$\times \left(\frac{14.73}{P_b}\right)\sqrt{\left(\frac{519.67}{T_f}\right)\left(\frac{1}{G_r}\right)\left(\frac{Z_b}{Z_{f_1}}\right)}\sqrt{P_{f_1} h_w} \qquad \text{(3-B-1)}$$

Note: Variations in the base compressibility of dry air, $Z_{b_{air}}$, from the value given at 14.73 pounds force per square inch absolute and 519.67°R (60°F) for base pressures between 14.4 and 15.025 pounds force per square inch absolute at 519.67°R (60°F), are within the basic uncertainity statement of the compressibilty data determination. Therefore, the value 0.999590 can be used in the development of the numeric constant for the flow equation.

Thus, Equation 3-B-1 can be simplified to the following form:

$$Q_v = F_n(F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \qquad \text{(3-B-2)}$$

Or

$$Q_v = C' \sqrt{P_{f_1} h_w} \qquad \text{(3-B-3)}$$

Where

$$C' = F_n(F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \qquad \text{(3-B-4)}$$

Where:

C' = composite orifice flow factor.
$C_d(FT)$ = coefficient of discharge for a flange-tapped orifice plate.
d = orifice plate bore diameter calculated at flowing temperature (T_f), in inches.
E_v = velocity of approach factor.
F_c = orifice calculation factor.
F_c' = orifice calculation factor for $D < 2.8$.
F_{gr} = real gas relative density factor.
F_n = numeric conversion factor (see Table 3-B-2).
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor.
F_{sl} = orifice slope factor.
F_{tb} = base temperature factor.
F_{tf} = flowing temperature factor.
G_r = real gas relative density (specific gravity).
h_w = orifice differential pressure, in inches of water at 60°F.
P_b = base pressure, in pounds force per square inch absolute.
P_{f_1} = absolute flowing pressure (upstream tap), in pounds force per square inch absolute.
Q_v = volume flow rate at standard conditions of Z_b, T_b, and P_b, in cubic feet per hour.
T_b = base temperature, in degrees Rankine.
T_f = absloute flowing temperature, in degrees Rankine.
Y_1 = expansion factor (upstream tap).
Z_b = compressibility at base conditions (P_b, T_b).
Z_{f_1} = compressibility at upstream flowing conditions (P_{f_1}, T_f).

The content of the composite orifice flow factor C' is different from what has been used in the past. The $F_n(F_c + F_{sl})$ product is a replacement for the F_b and F_r factors previously used in C'. Because of the form of the new discharge coefficient equation, the numeric constant (F_n) has been separated, and F_c and F_{sl} are treated as combined additive terms. The composite orifice flow factor assumes that the measured values are absolute. Adjustment factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately in Appendix 3-A. When the instruments are not calibrated or read to absolute values, adjustment factors may be applied as a multiplier to C'.

3–B.4 Numeric Conversion Factor (F_n)

The numeric conversion factor F_n (see Table 3-B-2) combines the numeric element of Equation 3-B-1 with the orifice diameter (d) and the velocity of approach factor (E_v) to provide the following equation:

$$\begin{aligned} F_n &= (218.573)(1.54761)E_v d^2\sqrt{Z_{b_{air}}} \\ &= 338.265 E_v d^2\sqrt{Z_{b_{air}}} \\ &= 338.265 E_v D^2\beta^2\sqrt{Z_{b_{air}}} \end{aligned} \quad (3\text{-B-}5)$$

When standard conditions are substituted for base conditions,

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ pounds force per square inch absolute} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

The numeric conversion factor, F_n, reduces to the following:

$$F_n = 338.196E_v d^2 \qquad \text{(3-B-5a)}$$

Or

$$F_n = 338.196E_v D^2\beta^2 \qquad \text{(3-B-5b)}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
E_v = velocity of approach factor
= $1/(1 - \beta^4)^{0.5}$.
F_n = numeric conversion factor.
β = diameter ratio (d/D).

For the purpose of the tables in this appendix, the numeric conversion factor, F_n, is specified at standard conditions. The velocity of approach factor is more fully described in 3.4.4.

3–B.5 Orifice Calculation Factor (F_c)

A modification of the basic form of the equation for the orifice plate coefficient of discharge in 3.4.3 resulted in the equation being divided into two parts. The first part is the orifice calculation factor (F_c). The second part is the slope factor (F_{sl}). The orifice plate coefficient of discharge, C_d(FT), is the sum of F_c (see Table 3-B-3) and F_{sl} (see Table 3-B-4):

$$C_d(\text{FT}) = F_c + F_{sl} \qquad \text{(3-B-6)}$$

The sum of F_c and F_{sl} is applicable to nominal pipe sizes of 2 inches and larger; diameter ratios (β) of 0.1–0.75, provided the orifice plate bore diameter, d, is greater than 0.45 inch; and pipe Reynolds numbers (Re_D) greater than or equal to 4000. For diameter ratios and pipe Reynolds numbers outside the limits stated, refer to Part 1, 1.12.4.1, and Part 4.

The orifice calculation factor (F_c) for meter tubes whose internal diameter is greater than or equal to 2.8 inches is computed by the following equation:

$$F_c = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19,000\beta}{Re_n}\right)^{0.8}\right] \qquad \text{(3-B-7)}$$

For meter tubes whose internal diameter is less than than 2.8 inches, F_c is modified by an additional term such that

$$F_c' = F_c + 0.003(1 - \beta)(2.8 - D) \qquad \text{(3-B-8)}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches
e = Napierian constant
= 2.71828
F_c = orifice calculation factor.
F_c' = orifice calculation factor for $D < 2.8$.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Equation 3-B-8 is only valid for tubes whose internal diameter is less than 2.8 inches.

The inclusion of Reynolds number in the calculation term (F_c) makes this function three-dimensional, including β, D, and Re_D. The expression can be simplified by assuming Reynolds number values for various meter tubes from Table 3-B-1. These assumed values can introduce an error greater than 0.01 percent for meter tubes with nominal diameters of less than 3 inches and β ratios greater than 0.6. The most precise values are obtained by computing the orifice calculation factor (F_c) using the actual Reynolds number.

Table 3-B-3 was developed using the approximate values for Re_D from Table 3-B-1.

The assumed values for Reynolds number may not be used to compute the orifice slope factor (F_{sl}). The value of F_{sl} can only be obtained through iteration.

3–B.6 Slope Factor (F_{sl})

The slope factor, F_{sl} (see Table 3-B-4), is the slope term from the coefficient of discharge equation developed in 3.4.3. It is expressed as follows:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \quad \text{(3-B-9)}$$

Where:

d = orifice plate bore diameter calculated at flowing temperature, T_f, in inches.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
F_{sl} = slope factor for flange-tapped coefficient of discharge equation (see Table 3-B-4).
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Since Re_D is a function of the flow rate (Q_v), F_{sl} can only be obtained through iteration. The values of Re_D given in Table 3-B-1 will not provide precise results but can be used as the first approximation in an iterative solution. Typically, three iterations of Q_v and Re_D are required to provide an accurate solution for F_{sl}.

As covered in 3.4.5, for most natural gases Equation 3-29 can be used to estimate Re_D from Q_v and D:

$$Re_D = 47.0723\frac{Q_v G_r}{D} \quad \text{(3-29)}$$

Where:

Q_v = volume flow rate at standard conditions (Z_s, T_s, and P_s), in cubic feet per hour.
D = meter tube internal diameter calculated at flowing temperature, T_f, in inches.
G_r = real gas relative density (specific gravity).

Table 3-B-5 was developed using Equation 3-29. Table 3-B-4 provides values for F_{sl} based on a normalized pipe Reynolds number ($Re_D/1{,}000{,}000$) and diameter ratio (β).1j

3–B.7 Expansion Factor (Y)

The expansion factor, Y, is a function of β ratio, the ratio of differential pressure to static pressure, and the ratio of specific heats (also called the isentropic exponent, or the ratio of specific heat capacity). Equations for the determinations of Y_1 and Y_2 are found in 3.4.6. Tabular values for Y_1 are found in Table 3-B-6.

3–B.8 Pressure Base Factor (F_{pb})

The pressure base factor, F_{pb}, is applied to change the base pressure from 14.73 pounds force per square inch absolute and is calculated by dividing 14.73 by the required (contract) absolute base pressure (see Table 3-B-7). Using this factor is equivalent to substituting the contract absolute base pressure for P_b in Equation 3-6a:

$$F_{pb} = \frac{14.73}{P_b} \tag{3-B-10}$$

Where:

P_b = contract absolute base pressure (see Table 3-B-7), in pounds force per square inch absolute.

3–B.9 Temperature Base Factor (F_{tb})

The temperature base factor, F_{tb}, is applied where the base temperature is other than 60°F and is calculated by dividing the required (contract) base temperature in degrees Rankine by 519.67°R (see Table 3-B-8). The use of this factor is equivalent to substituting the contract absolute base temperature for T_b in Equation 3-6a:

$$F_{tb} = \frac{T_b}{519.67} \tag{3-B-11}$$

Where:

T_b = contract absolute base temperature, in degrees Rankine.

3–B.10 Flowing Temperature Factor (F_{tf})

The flowing temperature factor, F_{tf}, is required to change from the assumed flowing temperature of 60°F to the actual flowing temperature, T_f. F_{tf} is calculated by dividing 519.67°R by the flowing temperature in degrees Rankine and taking the square root of the result (see Table 3-B-9). The use of this factor is equivalent to substituting the actual absolute flowing temperature for T_f in Equation 3-6a:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \tag{3-B-12}$$

Where:

T_f = flowing temperature, in degrees Rankine.

3–B.11 Real Gas Relative Density (Specific Gravity) Factor (F_{gr})

The real gas relative density (specific gravity) factor, F_{gr}, is applied to change from a real gas relative density of 1.0 to the real gas relative density of the flowing gas and is obtained as shown in Equation 3-B-13 (see Table 3-B-10). The use of this factor is equivalent to substituting the real gas relative density for G_r in Equation 3-6a:

$$F_{gr} = \sqrt{\frac{1}{G_r}} \tag{3-B-13}$$

Where:

G_r = real gas relative density (specific gravity).

Real gas relative density (specific gravity) is defined in 3.5.4.3.

3–B.12 Supercompressibility Factor (F_{pv})

The supercompressibility factor, F_{pv}, may be calculated from the following equation:

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \qquad \text{(3-B-14)}$$

Where:

Z_b = gas compressibility at base conditions (P_b, T_b).
Z_{f_1} = gas compressibility at upstream flowing conditions (P_{f_1}, T_f).

The development of compressibility and supercompressibility is covered in 3.5.3.2 and 3.5.3.3.

Historically, the natural gas industry has used a tabular approach to compressibility for field applications where there is no ready access to a computer. Table 3-B-11 has been included as a typical supercompressibility factor (F_{pv}) table. It is only applicable to a hydrocarbon gas with a specific gravity of 0.6 and no nitrogen or carbon dioxide. The table is provided as an example only and may not be interpolated; neither may values from the table be adjusted for diluent content. It is typical of the tables that can be developed for the user's specific application (gas quality, temperature range, and pressure range). The alternative is the direct calculation of F_{pv} for the specific measurement conditions using A.G.A. Transmission Measurement Committee Report No. 8.

3–B.13 Tables

The values of all the factors of C' as defined in Equation 3-B-4 are obtained from Equations 3-B-5 through 3-B-14. Tabular data are included in this appendix as alternative means of determining all factor values except for F_{pv} values. The tables can also be used to check calculated values. The tables are only precise for the values listed.

Table 3-B-1—Assumed Reynolds Numbers for Various Meter Tube Sizes

Nominal Tube Diameter (inches)	Assumed Reynolds Number, Re_D
2	500,000
3	750,000
4	1,000,000
6	1,500,000
8	2,000,000
10	2,500,000
12	3,000,000
16	4,000,000
20	5,000,000
24	6,000,000
30	8,000,000

Table 3-B-2—Numeric Conversion Factor (F_n)

$$F_n = \frac{338.196 D^2 \beta^2}{\sqrt{1 - \beta^4}}$$

β Ratio	Nominal Pipe Diameter: 2 Inches			3 Inches				4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.200	38.531	50.902	57.844	71.620	93.219	113.86	127.43	134.51	160.03	198.18	219.44
0.220	46.639	61.614	70.017	86.692	112.84	137.82	154.25	162.82	193.70	239.89	265.63
0.240	55.532	73.362	83.367	103.22	134.35	164.10	183.66	193.86	230.63	285.63	316.27
0.260	65.214	86.152	97.902	121.22	157.77	192.71	215.69	227.66	270.85	335.43	371.41
0.280	75.693	99.995	113.63	140.70	183.13	223.68	250.34	264.24	314.37	389.33	431.09
0.300	86.978	114.90	130.57	161.67	210.43	257.02	287.67	303.63	361.23	447.37	495.36
0.320	99.080	130.89	148.74	184.17	239.71	292.79	327.69	345.88	411.50	509.62	564.29
0.340	112.02	147.98	168.16	208.21	271.00	331.01	370.47	391.04	465.22	576.15	637.96
0.360	125.80	166.19	188.86	233.83	304.35	371.75	416.07	439.16	522.47	647.06	716.47
0.380	140.46	185.55	210.86	261.08	339.81	415.06	464.54	490.32	583.34	722.44	799.94
0.400	156.01	206.10	234.21	289.99	377.44	461.02	515.98	544.62	647.94	802.44	888.52
0.420	172.49	227.87	258.95	320.62	417.31	509.72	570.48	602.15	716.38	887.20	982.38
0.440	189.93	250.91	285.13	353.04	459.51	561.26	628.17	663.04	788.83	976.92	1,081.7
0.460	208.38	275.29	312.83	387.34	504.15	615.78	689.20	727.45	865.45	1,071.8	1,186.8
0.480	227.89	301.06	342.12	423.60	551.34	673.43	753.71	795.55	946.47	1,172.2	1,297.9
0.500	248.52	328.31	373.08	461.93	601.24	734.38	821.93	867.55	1,032.1	1,278.2	1,415.4
0.520	270.33	357.12	405.83	502.48	654.02	798.84	894.07	943.70	1,122.7	1,390.4	1,539.6
0.540	293.42	387.62	440.49	545.39	709.87	867.06	970.43	1,024.3	1,218.6	1,509.2	1,671.1
0.560	317.87	419.93	477.21	590.85	769.05	939.33	1,051.3	1,109.7	1,320.2	1,635.0	1,810.4
0.580	343.82	454.21	516.16	639.09	831.82	1,016.0	1,137.1	1,200.3	1,428.0	1,768.5	1,958.2
0.600	371.40	490.64	557.56	690.35	898.54	1,097.5	1,228.4	1,296.5	1,542.5	1,910.3	2,115.2
0.620	400.78	529.45	601.66	744.95	969.62	1,184.3	1,325.5	1,399.1	1,664.5	2,061.4	2,282.5
0.640	432.15	570.90	648.77	803.27	1,045.5	1,277.0	1,429.3	1,508.6	1,794.8	2,222.8	2,461.2
0.660	465.78	615.32	699.24	865.77	1,126.9	1,376.4	1,540.5	1,626.0	1,934.5	2,395.7	2,652.7
0.680	501.94	663.10	753.54	932.99	1,214.4	1,483.3	1,660.1	1,752.2	2,084.7	2,581.7	2,858.7
0.700	541.02	714.73	812.21	1,005.6	1,308.9	1,598.8	1,789.4	1,888.7	2,247.0	2,782.8	3,081.3
0.720	583.48	770.82	875.95	1,084.6	1,411.6	1,724.2	1,929.8	2,036.9	2,423.3	3,001.1	3,323.1
0.740	629.90	832.14	945.63	1,170.8	1,523.9	1,861.4	2,083.3	2,198.9	2,616.1	3,239.9	3,587.5

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-2—(Continued)

$$F_n = \frac{338.196 D^2 \beta^2}{\sqrt{1 - \beta^4}}$$

	Nominal Pipe Diameter												
	6 Inches				8 Inches			10 Inches			12 Inches		
β Ratio	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036	11.374	11.938	12.090
0 200	324.67	364.26	449.34	498.01	787.15	862.36	881.92	1,237.9	1,359.3	1,363.6	1,751.5	1,929.5	1,978.9
0.220	392.99	440.92	543.90	602.82	952.80	1,043.8	1,067.5	1,498.4	1,645.4	1,650.6	2,120.1	2,335.5	2,395.4
0.240	467.92	524.98	647.60	717.75	1,134.5	1,242.9	1,271.1	1,784.1	1,959.1	1,965.3	2,524.3	2,780.8	2,852.1
0.260	549.50	616.51	760.51	842.89	1,332.3	1,459.6	1,492.7	2,095.1	2,300.6	2,308.0	2,964.4	3,265 7	3,349.4
0.280	637.80	715.58	882.71	978.33	1,546.3	1,694.1	1,732.5	2,431.8	2,670.3	2,678.8	3,440.7	3,790.4	3,887.6
0 300	732.89	822.26	1,014 3	1,124 2	1,776.9	1,946.7	1,990.8	2,794.3	3,068.4	3,078.2	3,953.7	4,355 5	4,467.1
0 320	834.87	936.68	1,155.5	1,280.6	2,024.1	2,217.5	2,267.8	3,183.1	3,495.4	3,506.5	4,503.8	4,961.6	5,088.7
0.340	943.86	1,059.0	1,306.3	1,447.8	2,288.4	2,507.0	2,563.9	3,598.7	3,951.7	3,964.3	5,091.8	5,609.3	5,753.1
0.360	1,060.0	1,189.3	1,467.1	1,626.0	2,570.0	2,815.6	2,879.4	4,041.6	4,438.0	4,452.2	5,718.4	6,299.6	6,461.1
0.380	1,183.5	1,327.8	1,638.0	1,815.4	2,869.4	3,143.6	3,214.9	4,512.4	4,955.0	4,970.9	6,384.7	7,033.6	7,213.8
0 400	1,314.6	1,474.9	1,819.3	2,016.4	3,187.1	3,491.7	3,570.9	5,012.1	5,503.7	5,521.3	7,091.6	7,812 4	8,012.6
0.420	1,453.4	1,630.7	2,011.5	2,229.4	3,523.8	3,860.5	3,948.1	5,541.5	6,085.1	6,104.5	7,840.8	8,637.6	8,859.0
0.440	1,600.4	1,795.6	2,215.0	2,454.9	3,880.2	4,250.9	4,347.3	6,101.9	6,700.5	6,721.9	8,633.7	9,511.1	9,754.9
0.460	1,755.9	1,970.0	2,430.1	2,693.4	4,257.1	4,663.9	4,769.6	6,694.7	7,351.3	7,374.8	9,472.4	10,435 0	10,702.5
0.480	1,920.2	2,154.4	2,657.6	2,945.5	4,655.6	5,100.5	5,216.2	7,321.4	8,039.5	8,065.2	10,359.1	11,411.9	11,704.4
0.500	2,094.0	2,349.4	2,898.1	3,212.1	5,076.9	5,562.1	5,688.2	7,984.0	8,767.2	8,795.2	11,296.6	12,444.8	12,763.7
0.520	2,277.8	2,555.6	3,152.5	3,494.0	5,522.6	6,050.3	6,187.5	8,684.8	9,536.7	9,567.2	12,288.2	13,537.1	13,884.0
0.540	2,472.4	2,773.9	3,421.8	3,792.4	5,994.2	6,567.0	6,716.0	9,426.5	10,351.1	10,384.2	13,337.6	14,693.2	15,069.7
0.560	2,678.5	3,005.1	3,707.0	4,108.5	6,493.9	7,114.4	7,275.8	10,212.3	11,214.0	11,249.8	14,449.4	15,918.0	16,325.9
0.580	2,897.1	3,250.4	4,009.6	4,443.9	7,024.0	7,695.2	7,869.7	11,045.9	12,129.4	12,168.1	15,628.9	17,217.3	17,658.6
0.600	3,129.5	3,511.1	4,331.2	4,800.4	7,587.4	8,312.4	8,500.9	11,931.9	13.102.3	13,144.2	16,882.5	18,598.4	19,075.0
0.620	3,377.0	3,788.8	4,673.8	5,180.0	8,187.5	8,969.9	9,173.3	12,875.7	14,138.6	14,183.8	18,217.9	20,069.4	20,583.7
0.640	3,641.4	4,085.4	5,039.7	5,585.6	8,828.5	9,672.1	9,891.5	13,883.7	15,245.5	15,294.3	19,644.2	21,640.7	22,195.2
0.660	3,924.7	4,403.3	5,431.8	6,020.2	9,515.4	10,424.6	10,661.1	14,963.9	16,431.7	16,484.2	21,172.5	23,324.3	23,922.1
0 680	4,229.4	4,745.2	5,853.5	6,487.6	10,254.2	11,234.1	11,488.9	16,125.8	17,707.6	17,764.2	22,816.5	25,135.4	25,779.6
0 700	4,558.8	5,114.7	6,309.3	6,992.7	11,052.6	12,108.8	12,383.4	17,381.4	19,086.3	19,147.3	24,593.1	27,092.5	27,786 8
0.720	4,916.5	5,516.1	6,804.4	7,541.5	11,920.0	13,059.1	13,355.2	18,745.4	20.584.1	20.649.9	26,523.0	29,218.6	29,967.4
0.740	5,307.6	5,954.9	7,345.8	8,141.5	12,868.3	14,097.9	14,417.7	20,236.6	22,221.7	22,292.7	28,633.0	31,543.1	32,351.4

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-2—(Continued)

$$F_s = \frac{338.196 D^4 \beta^2}{\sqrt{1 - \beta^4}}$$

β Ratio	Nominal Pipe Diameter: 16 Inches			20 Inches			24 Inches			30 Inches		
	14.688	15.000	15.250	18 812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
0.200	2,920.8	3,046.2	3,148.6	4,791.2	4,887.5	5,016 9	6,929.7	7,162.0	7,318.5	11,190.6	11,386.0	11,583.2
0.220	3,535.5	3,687.3	3,811.2	5,799.5	5,916.0	6,072.7	8,388.1	8,669.2	8,858.7	13,545.6	13,782 2	14,020.9
0.240	4,209.6	4,390.3	4,537.9	6,905.3	7,044.0	7,230.6	9,987.4	10,322.1	10,547.7	16,128 3	16,410.0	16,694.2
0.260	4,943.5	5,155.8	5,329.0	8,109.2	8,272.1	8,491.2	11,728.7	12,121.8	12,386.7	18,940 2	19,271.1	19,604.8
0.280	5,737.8	5,984.2	6,185.3	9,412.2	9,601.3	9,855.6	13,613.3	14,069.5	14,377.0	21,983.6	22,367.6	22,754.9
0.300	6,593.3	6,876.4	7,107.5	10,815 5	11,032.8	11,325 0	15,642.9	16,167 1	16,520.5	25,261.1	25,702.4	26,147.4
0.320	7,510.7	7,833.2	8,096.5	12,320 5	12,568.0	12,900.9	17,819.5	18,416.8	18,819.3	28,776 2	29,278.8	29,785.8
0.340	8,491.3	8,855.9	9,153.5	13,928.9	14,208.7	14,585.1	20,145 9	20,821.1	21,276.2	32,533 0	33,101.2	33,674.4
0.360	9,536.2	9,945.7	10,280.0	15,643.1	15,957.3	16,380.0	22,625.1	23,383.4	23,894.5	36,536.5	37,174.7	37,818.4
0.380	10,647.2	11,104.4	11,477.6	17,465 5	17,816.3	18,288.3	25,261.0	26,107.6	26,678.3	40,793.1	41,505.7	42,224.4
0.400	11,826.2	12,334.0	12,748.5	19,399.5	19,789.2	20,313.3	28,058.1	28,998.5	29,632.3	45,310.2	46,101.6	46,899.9
0.420	13,075.5	13,636.9	14,095.2	21 448 7	21,879.6	22,459.1	31,022.0	32,061.8	32,762.5	50,096.5	50,971.5	51,854.1
0.440	14,397.8	15,015.9	15,520.6	23,617 8	24,092.2	24,730.4	34,159.2	35,304.1	36,075.7	55,162.6	56,126.2	57,098.0
0.460	15,796.3	16,474.6	17,028.3	25,912 0	26,432.5	27,132.7	37,477.5	38,733.5	39,580.1	60,521.1	61,578.3	62,644.5
0.480	17,275.1	18,016.8	18,622.4	28,337.8	28,907.0	29,672.7	40,985.9	42,359.5	43,285.4	66,186.8	67,342.8	68,508 9
0.500	18,838.6	19,647.4	20,307.8	30,902.5	31,523.2	32,358.2	44,695.3	46,193.3	47,202.9	72,177.0	73,437.7	74,709.3
0.520	20,492.2	21,372.0	22,090.3	33,615.0	34,290.2	35,198.5	48,618.5	50,248.0	51,346.2	78,512.4	79,883.8	81,267.0
0.540	22,242.2	23,197.2	23,976.9	36,485.7	37,218.6	38,204.5	52,770.6	54,539.2	55,731.2	85,217.5	86,705.9	88,207.3
0.560	24,096.3	25,130.8	25,975.5	39,527.1	40,321.0	41,389 1	57,169.3	59,085.4	60,376.8	92,320.9	93,933.5	95,560.0
0.580	26,063.2	27,182.3	28,095.9	42,753 6	43,612.4	44,767 7	61,836.1	63,908.5	65,305.4	99,857.1	101,601.3	103,360.6
0.600	28,153.8	29,362.6	30,349.5	46,182.9	47,110.6	48,358.5	66,796.0	69,034.7	70,543.6	107,866 7	109,750.8	111,651.2
0.620	30,380.7	31,685.0	32,750.0	49,835.8	50,836.9	52,183.5	72,079.3	74,495.1	76,123.3	116,398.5	118,431.6	120,482.4
0.640	32,759.1	34,165.7	35,314.0	53,737.5	54,816.9	56,268.9	77,722.4	80,327.3	82,083.0	125,511.3	127,703.6	129,914.9
0.660	35,307.9	36,823.8	38,061.5	57,918.3	59,081.7	60,646.8	83,769.3	86,576.8	88,469.2	135,276.3	137,639.2	140,022.5
0.680	38,049.5	39,683.1	41,016.9	62,415 6	63,669.4	65,355 9	90,273.9	93,299.5	95,338.7	145,780.4	148,326.8	150,895.1
0.700	41,012.1	42,772.9	44,210.6	67,275.4	68,626.8	70,444 6	97,302 7	100,563.9	102,761.9	157,131 0	159,875.6	162,644.0
0.720	44,230.5	46,129.6	47,680.0	72,554.9	74,012.4	75,972.9	104,938.7	108,455.8	110,826.3	169,462.1	172,422.1	175,407.7
0.740	47,749.2	49,799.3	51,473.2	78,326.9	79,900.3	82,016.8	113,287.0	117,083.8	119,642.9	182,943 4	186,138.9	189,362.0

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-3—Orifice Calculation Factor: F_c From Equations in 3-B.5

	Nominal Pipe Diameter											
	2 Inches (Re_D = 500,000)			3 Inches (Re_D = 750,000)				4 Inches (Re_D = 1,000,000)				
β Ratio	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.200	0.59879	0.59828	0.59801	0.59752	0.59683	0.59646	0.59649	0.59651	0.59655	0.59661	0.59663
0.220	0.59884	0.59836	0.59810	0.59763	0.59697	0.59662	0.59665	0.59667	0.59672	0.59678	0.59681
0.240	0.59892	0.59846	0.59822	0.59777	0.59713	0.59680	0.59684	0.59686	0.59691	0.59698	0.59701
0.260	0.59903	0.59860	0.59837	0.59794	0.59733	0.59701	0.59705	0.59707	0.59713	0.59720	0.59723
0.280	0.59918	0.59876	0.59855	0.59814	0.59755	0.59725	0.59730	0.59732	0.59738	0.59745	0.59749
0.300	0.59935	0.59896	0.59875	0.59836	0.59780	0.59752	0.59757	0.59759	0.59766	0.59773	0.59777
0.320	0.59956	0.59919	0.59899	0.59862	0.59809	0.59782	0.59787	0.59789	0.59796	0.59804	0.59808
0.340	0.59980	0.59946	0.59927	0.59892	0.59841	0.59815	0.59820	0.59823	0.59830	0.59839	0.59842
0.360	0.60009	0.59976	0.59959	0.59925	0.59877	0.59852	0.59857	0.59860	0.59867	0.59876	0.59880
0.380	0.60041	0.60011	0.59994	0.59962	0.59916	0.59893	0.59898	0.59900	0.59908	0.59917	0.59920
0.400	0.60079	0.60050	0.60034	0.60004	0.59959	0.59937	0.59943	0.59945	0.59952	0.59961	0.59965
0.420	0.60121	0.60093	0.60078	0.60050	0.60007	0.59986	0.59991	0.59993	0.60001	0.60009	0.60012
0.440	0.60168	0.60142	0.60128	0.60100	0.60059	0.60039	0.60044	0.60046	0.60053	0.60061	0.60064
0.460	0.60221	0.60196	0.60182	0.60156	0.60116	0.60097	0.60101	0.60103	0.60110	0.60117	0.60120
0.480	0.60281	0.60256	0.60243	0.60217	0.60179	0.60159	0.60163	0.60165	0.60171	0.60177	0.60180
0.500	0.60347	0.60323	0.60309	0.60284	0.60246	0.60227	0.60231	0.60232	0.60237	0.60242	0.60244
0.520	0.60420	0.60396	0.60383	0.60358	0.60320	0.60301	0.60303	0.60305	0.60308	0.60312	0.60313
0.540	0.60502	0.60477	0.60463	0.60438	0.60400	0.60380	0.60382	0.60383	0.60385	0.60386	0.60387
0.560	0.60592	0.60566	0.60552	0.60526	0.60488	0.60466	0.60467	0.60467	0.60467	0.60467	0.60466
0.580	0.60693	0.60664	0.60650	0.60623	0.60583	0.60560	0.60559	0.60559	0.60556	0.60553	0.60551
0.600	0.60805	0.60773	0.60757	0.60729	0.60686	0.60661	0.60658	0.60657	0.60652	0.60645	0.60641
0.620	0.60929	0.60894	0.60876	0.60845	0.60800	0.60772	0.60767	0.60764	0.60756	0.60744	0.60739
0.640	0.61069	0.61028	0.61008	0.60974	0.60924	0.60892	0.60884	0.60881	0.60868	0.60852	0.60844
0.660	0.61226	0.61178	0.61155	0.61116	0.61060	0.61024	0.61013	0.61008	0.60990	0.60968	0.60957
0.680	0.61404	0.61347	0.61320	0.61275	0.61212	0.61169	0.61154	0.61147	0.61123	0.61093	0.61079
0.700	0.61608	0.61538	0.61506	0.61454	0.61380	0.61330	0.61310	0.61302	0.61270	0.61231	0.61213
0.720	0.61842	0.61758	0.61719	0.61657	0.61571	0.61511	0.61485	0.61474	0.61433	0.61384	0.61360
0.740	0.62117	0.62012	0.61965	0.61890	0.61788	0.61716	0.61683	0.61668	0.61617	0.61554	0.61524

Note: Assumed values of Re_D are used in this table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-3—Continued

β Ratio	Nominal Pipe Diameter: 6 Inches (Re_D = 1,500,000)				8 Inches (Re_D = 2,000,000)			10 Inches (Re_D = 2,500,000)			12 Inches (Re_D = 3,000,000)		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036	11.374	11.938	12.090
0.200	0.59672	0.59674	0.59679	0.59680	0.59688	0.59689	0.59690	0.59695	0.59696	0.59696	0.59699	0.59700	0.59700
0.220	0.59690	0.59693	0.59698	0.59700	0.59708	0.59710	0.59710	0.59715	0.59717	0.59717	0.59720	0.59721	0.59722
0.240	0.59711	0.59714	0.59719	0.59721	0.59731	0.59732	0.59733	0.59738	0.59740	0.59740	0.59744	0.59745	0.59745
0.260	0.59735	0.59738	0.59743	0.59746	0.59756	0.59757	0.59758	0.59764	0.59766	0.59766	0.59770	0.59771	0.59771
0.280	0.59761	0.59764	0.59770	0.59772	0.59783	0.59785	0.59785	0.59792	0.59794	0.59794	0.59798	0.59799	0.59800
0.300	0.59790	0.59793	0.59799	0.59802	0.59813	0.59815	0.59815	0.59822	0.59824	0.59824	0.59829	0.59830	0.59831
0.320	0.59821	0.59825	0.59831	0.59834	0.59845	0.59847	0.59848	0.59855	0.59857	0.59857	0.59862	0.59864	0.59864
0.340	0.59856	0.59859	0.59866	0.59869	0.59880	0.59883	0.59883	0.59891	0.59893	0.59893	0.59897	0.59899	0.59900
0.360	0.59893	0.59897	0.59903	0.59906	0.59918	0.59921	0.59921	0.59929	0.59931	0.59931	0.59936	0.59937	0.59938
0.380	0.59934	0.59938	0.59944	0.59947	0.59959	0.59961	0.59962	0.59969	0.59971	0.59971	0.59976	0.59978	0.59979
0.400	0.59978	0.59982	0.59988	0.59991	0.60002	0.60005	0.60005	0.60013	0.60015	0.60015	0.60020	0.60021	0.60022
0.420	0.60025	0.60029	0.60035	0.60037	0.60049	0.60051	0.60051	0.60058	0.60060	0.60060	0.60065	0.60067	0.60068
0.440	0.60076	0.60079	0.60085	0.60087	0.60098	0.60100	0.60100	0.60107	0.60109	0.60109	0.60114	0.60115	0.60116
0.460	0.60131	0.60133	0.60138	0.60141	0.60150	0.60152	0.60152	0.60158	0.60160	0.60160	0.60164	0.60166	0.60167
0.480	0.60189	0.60191	0.60195	0.60197	0.60205	0.60207	0.60207	0.60212	0.60214	0.60214	0.60218	0.60219	0.60220
0.500	0.60251	0.60253	0.60256	0.60257	0.60263	0.60264	0.60265	0.60269	0.60270	0.60270	0.60274	0.60275	0.60275
0.520	0.60317	0.60318	0.60320	0.60321	0.60324	0.60325	0.60325	0.60328	0.60329	0.60329	0.60332	0.60333	0.60333
0.540	0.60388	0.60388	0.60388	0.60388	0.60389	0.60389	0.60389	0.60390	0.60391	0.60391	0.60392	0.60393	0.60393
0.560	0.60463	0.60462	0.60460	0.60459	0.60456	0.60456	0.60456	0.60455	0.60455	0.60455	0.60455	0.60456	0.60456
0.580	0.60543	0.60540	0.60536	0.60534	0.60527	0.60525	0.60525	0.60522	0.60521	0.60521	0.60520	0.60520	0.60520
0.600	0.60627	0.60623	0.60616	0.60613	0.60600	0.60598	0.60598	0.60591	0.60590	0.60590	0.60587	0.60587	0.60586
0.620	0.60718	0.60712	0.60701	0.60696	0.60677	0.60674	0.60673	0.60663	0.60661	0.60661	0.60656	0.60655	0.60654
0.640	0.60814	0.60805	0.60791	0.60784	0.60757	0.60753	0.60752	0.60737	0.60734	0.60734	0.60727	0.60724	0.60724
0.660	0.60917	0.60905	0.60885	0.60876	0.60841	0.60835	0.60833	0.60814	0.60809	0.60809	0.60799	0.60795	0.60794
0.680	0.61027	0.61012	0.60986	0.60974	0.60928	0.60920	0.60918	0.60892	0.60886	0.60886	0.60872	0.60867	0.60866
0.700	0.61146	0.61127	0.61094	0.61078	0.61019	0.61009	0.61006	0.60973	0.60965	0.60965	0.60947	0.60940	0.60939
0.720	0.61275	0.61251	0.61209	0.61190	0.61115	0.61102	0.61098	0.61056	0.61046	0.61046	0.61022	0.61014	0.61012
0.740	0.61417	0.61387	0.61334	0.61310	0.61216	0.61199	0.61196	0.61143	0.61130	0.61129	0.61099	0.61089	0.61086

Note: Assumed values of Re_D are used in this table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-3—Continued

	Nominal Pipe Diameter											
	16 Inches (Re_D = 4,000,000)			20 Inches (Re_D = 5,000,000)			24 Inches (Re_D = 6,000,000)			30 Inches (Re_D = 8,000,000)		
β Ratio	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28 750	29 000	29 250
0 200	0.59704	0.59705	0.59705	0.59708	0.59709	0.59709	0.59711	0.59711	0.59711	0.59714	0.59714	0.59714
0.220	0.59726	0.59726	0 59727	0.59731	0.59731	0.59731	0.59734	0.59734	0.59734	0.59737	0.59737	0.59737
0.240	0.59750	0.59751	0.59751	0.59755	0.59756	0.59756	0.59759	0.59759	0.59759	0.59762	0.59762	0.59762
0.260	0.59777	0.59777	0.59778	0.59782	0.59782	0.59783	0.59786	0.59786	0.59786	0.59790	0.59790	0.59790
0.280	0.59805	0.59806	0.59806	0 59812	0.59812	0.59812	0.59815	0.59816	0.59816	0.59820	0.59820	0.59820
0 300	0.59837	0.59837	0 59838	0.59843	0.59843	0.59844	0.59847	0.59848	0 59848	0.59852	0.59852	0.59852
0.320	0.59870	0.59871	0.59871	0.59877	0.59877	0.59878	0.59881	0.59882	0.59882	0.59886	0.59886	0.59887
0.340	0.59906	0.59907	0.59907	0.59913	0.59914	0.59914	0.59918	0.59918	0.59919	0.59923	0.59923	0.59923
0.360	0.59945	0.59945	0.59946	0.59952	0.59952	0.59953	0.59957	0.59957	0.59958	0.59962	0.59962	0.59963
0.380	0.59986	0.59986	0.59987	0.59993	0.59993	0.59994	0.59998	0.59998	0.59999	0.60004	0.60004	0.60004
0.400	0.60029	0.60029	0.60030	0.60036	0.60037	0.60037	0.60041	0.60042	0.60042	0.60047	0.60047	0.60048
0.420	0 60074	0.60075	0 60076	0.60082	0.60082	0.60083	0.60087	0 60088	0.60088	0.60093	0 60093	0.60093
0.440	0.60122	0.60123	0 60124	0.60130	0.60130	0.60131	0.60135	0.60136	0 60136	0.60141	0.60141	0.60141
0.460	0.60173	0.60174	0.60174	0.60180	0.60181	0.60181	0.60185	0.60186	0.60186	0.60191	0.60191	0.60192
0.480	0.60226	0.60226	0.60227	0.60233	0.60233	0.60233	0.60237	0.60238	0.60238	0.60243	0.60243	0.60244
0.500	0.60281	0.60281	0.60282	0.60287	0.60287	0.60288	0.60292	0.60292	0.60292	0.60297	0.60297	0.60298
0.520	0.60338	0.60338	0.60338	0.60343	0.60344	0.60344	0.60348	0.60348	0.60348	0.60353	0.60353	0.60353
0.540	0.60397	0.60397	0.60397	0.60402	0.60402	0.60402	0.60405	0.60406	0.60406	0.60410	0.60410	0.60411
0.560	0.60458	0.60458	0.60458	0 60461	0.60461	0.60462	0.60465	0.60465	0.60465	0 60469	0.60469	0.60469
0.580	0.60520	0.60521	0.60521	0.60523	0.60523	0.60523	0.60525	0.60525	0.60525	0.60529	0.60529	0.60529
0.600	0.60585	0.60585	0.60585	0.60585	0.60585	0.60585	0.60586	0.60587	0.60587	0.60589	0.60589	0.60590
0.620	0.60650	0.60650	0.60650	0.60648	0.60648	0.60648	0.60648	0.60649	0.60649	0.60650	0.60650	0.60650
0.640	0.60717	0.60716	0.60716	0.60712	0.60712	0.60712	0.60711	0.60711	0.60711	0.60711	0.60711	0.60711
0.660	0.60784	0.60783	0.60782	0.60776	0.60776	0.60775	0.60773	0.60773	0.60773	0.60772	0 60772	0.60772
0.680	0.60851	0.60850	0.60849	0 60839	0.60839	0.60838	0.60834	0.60834	0.60834	0.60831	0 60831	0.60831
0.700	0.60919	0.60917	0.60916	0.60902	0.60901	0.60901	0.60894	0.60894	0.60893	0.60889	0.60889	0.60888
0.720	0.60986	0.60984	0.60982	0.60963	0.60963	0.60962	0.60952	0.60952	0.60951	0.60944	0.60944	0.60943
0.740	0.61053	0.61049	0.61047	0.61023	0.61022	0.61021	0.61008	0.61007	0.61006	0.60996	0.60996	0.60995

Note: Assumed values of Re_D are used in this table. These may induce an error greater than 0.01 percent for line sizes less than 4 inches with β ratios greater than 0.60. This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-4—Orifice Slope Factor: F_{sl} From Equations in 3-B.6

	β Ratio													
$Re_D/10^5$	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46
0.020	0.00270	0.00294	0.00320	0.00348	0.00379	0.00413	0.00450	0.00492	0.00539	0.00591	0.00650	0.00716	0.00790	0.00873
0.030	0.00205	0.00224	0.00244	0.00266	0.00291	0.00318	0.00348	0.00382	0.00420	0.00463	0.00511	0.00565	0.00626	0.00694
0.040	0.00168	0.00184	0.00201	0.00220	0.00241	0.00264	0.00291	0.00320	0.00353	0.00390	0.00432	0.00480	0.00533	0.00593
0.050	0.00145	0.00159	0.00174	0.00190	0.00209	0.00230	0.00253	0.00279	0.00309	0.00342	0.00380	0.00423	0.00471	0.00525
0.060	0.00128	0.00140	0.00154	0.00169	0.00186	0.00205	0.00226	0.00250	0.00277	0.00308	0.00343	0.00383	0.00427	0.00477
0.070	0.00115	0.00127	0.00139	0.00153	0.00169	0.00186	0.00206	0.00228	0.00254	0.00282	0.00315	0.00352	0.00393	0.00440
0.080	0.00105	0.00116	0.00128	0.00140	0.00155	0.00171	0.00190	0.00211	0.00235	0.00262	0.00292	0.00327	0.00366	0.00410
0.090	0.00097	0.00107	0.00118	0.00130	0.00144	0.00159	0.00177	0.00197	0.00219	0.00245	0.00274	0.00307	0.00344	0.00386
0.100	0.00091	0.00100	0.00110	0.00122	0.00135	0.00149	0.00166	0.00185	0.00206	0.00231	0.00259	0.00290	0.00326	0.00366
0.150	0.00069	0.00076	0.00085	0.00094	0.00105	0.00117	0.00130	0.00146	0.00164	0.00185	0.00208	0.00235	0.00265	0.00299
0.200	0.00057	0.00063	0.00070	0.00078	0.00088	0.00098	0.00110	0.00124	0.00140	0.00158	0.00179	0.00203	0.00230	0.00260
0.250	0.00049	0.00055	0.00061	0.00068	0.00077	0.00086	0.00097	0.00110	0.00124	0.00141	0.00160	0.00181	0.00206	0.00233
0.300	0.00044	0.00049	0.00054	0.00061	0.00069	0.00077	0.00087	0.00099	0.00112	0.00128	0.00145	0.00166	0.00188	0.00214
0.350	0.00039	0.00044	0.00049	0.00055	0.00063	0.00071	0.00080	0.00091	0.00104	0.00118	0.00135	0.00153	0.00175	0.00199
0.400	0.00036	0.00040	0.00045	0.00051	0.00058	0.00065	0.00074	0.00085	0.00097	0.00110	0.00126	0.00144	0.00164	0.00187
0.450	0.00033	0.00038	0.00042	0.00048	0.00054	0.00061	0.00070	0.00079	0.00091	0.00104	0.00119	0.00136	0.00155	0.00177
0.500	0.00031	0.00035	0.00039	0.00045	0.00051	0.00058	0.00066	0.00075	0.00086	0.00098	0.00113	0.00129	0.00148	0.00169
0.600	0.00028	0.00031	0.00035	0.00040	0.00045	0.00052	0.00059	0.00068	0.00078	0.00090	0.00103	0.00119	0.00136	0.00156
0.700	0.00025	0.00028	0.00032	0.00036	0.00042	0.00048	0.00055	0.00063	0.00072	0.00083	0.00096	0.00110	0.00127	0.00145
0.800	0.00023	0.00026	0.00030	0.00034	0.00039	0.00044	0.00051	0.00059	0.00068	0.00078	0.00090	0.00104	0.00119	0.00137
0.900	0.00021	0.00024	0.00028	0.00031	0.00036	0.00041	0.00048	0.00055	0.00064	0.00074	0.00085	0.00098	0.00113	0.00130
1.000	0.00020	0.00023	0.00026	0.00030	0.00034	0.00039	0.00045	0.00052	0.00060	0.00070	0.00081	0.00094	0.00108	0.00124
1.500	0.00015	0.00018	0.00020	0.00023	0.00027	0.00031	0.00036	0.00043	0.00050	0.00058	0.00067	0.00078	0.00090	0.00104
2.000	0.00013	0.00015	0.00017	0.00020	0.00023	0.00027	0.00031	0.00037	0.00043	0.00050	0.00059	0.00069	0.00080	0.00092
2.500	0.00011	0.00013	0.00015	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00053	0.00062	0.00072	0.00084
3.000	0.00010	0.00012	0.00013	0.00016	0.00019	0.00022	0.00026	0.00030	0.00036	0.00042	0.00049	0.00057	0.00067	0.00078
3.500	0.00009	0.00011	0.00012	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054	0.00063	0.00073
4.000	0.00008	0.00010	0.00011	0.00013	0.00016	0.00019	0.00022	0.00026	0.00031	0.00037	0.00043	0.00051	0.00059	0.00069
4.500	0.00008	0.00009	0.00011	0.00013	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00041	0.00048	0.00057	0.00066
5.000	0.00007	0.00009	0.00010	0.00012	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054	0.00063
5.500	0.00007	0.00008	0.00010	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00044	0.00052	0.00061
6.000	0.00007	0.00008	0.00009	0.00011	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036	0.00043	0.00050	0.00059
6.500	0.00006	0.00007	0.00009	0.00010	0.00012	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00041	0.00049	0.00057
7.000	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00020	0.00024	0.00029	0.00034	0.00040	0.00047	0.00055
7.500	0.00006	0.00007	0.00008	0.00010	0.00011	0.00014	0.00017	0.00020	0.00024	0.00028	0.00033	0.00039	0.00046	0.00054
8.000	0.00005	0.00007	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00045	0.00052
8.500	0.00005	0.00006	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00022	0.00027	0.00031	0.00037	0.00044	0.00051
9.000	0.00005	0.00006	0.00007	0.00009	0.00010	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036	0.00043	0.00050
9.500	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00015	0.00018	0.00021	0.00025	0.00030	0.00035	0.00042	0.00049
10.000	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00029	0.00035	0.00041	0.00048
12.000	0.00004	0.00005	0.00006	0.00008	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038	0.00045
15.000	0.00004	0.00005	0.00006	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00030	0.00035	0.00041
18.000	0.00003	0.00004	0.00005	0.00006	0.00007	0.00009	0.00011	0.00013	0.00016	0.00019	0.00023	0.00027	0.00032	0.00038
21.000	0.00003	0.00004	0.00005	0.00006	0.00007	0.00008	0.00010	0.00013	0.00015	0.00018	0.00022	0.00026	0.00031	0.00036
24.000	0.00003	0.00004	0.00004	0.00005	0.00007	0.00008	0.00010	0.00012	0.00014	0.00017	0.00021	0.00025	0.00029	0.00034
27.000	0.00003	0.00003	0.00004	0.00005	0.00006	0.00008	0.00009	0.00011	0.00014	0.00016	0.00020	0.00023	0.00028	0.00033
30.000	0.00003	0.00003	0.00004	0.00005	0.00006	0.00007	0.00009	0.00011	0.00013	0.00016	0.00019	0.00022	0.00027	0.00031

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-4—(Continued)

	β Ratio													
$Re_D/10^6$	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70	0.72	0.74
0.020	0.00966	0.01069	0.01184	0.01312	0.01453	0.01609	0.01782	0.01972	0.02181	0.02409	0.02659	0.02932	0.03229	0.03552
0.030	0.00770	0.00856	0.00951	0.01056	0.01173	0.01302	0.01445	0.01601	0.01774	0.01962	0.02168	0.02393	0.02638	0.02904
0.040	0.00659	0.00734	0.00818	0.00910	0.01013	0.01126	0.01252	0.01389	0.01541	0.01706	0.01887	0.02085	0.02300	0.02533
0.050	0.00586	0.00654	0.00729	0.00813	0.00906	0.01009	0.01123	0.01248	0.01385	0.01536	0.01700	0.01879	0.02074	0.02286
0.060	0.00533	0.00596	0.00665	0.00743	0.00829	0.00925	0.01030	0.01145	0.01272	0.01412	0.01564	0.01729	0.01910	0.02106
0.070	0.00492	0.00551	0.00616	0.00689	0.00770	0.00859	0.00958	0.01066	0.01186	0.01316	0.01459	0.01614	0.01783	0.01967
0.080	0.00460	0.00515	0.00577	0.00646	0.00723	0.00807	0.00901	0.01003	0.01116	0.01239	0.01374	0.01522	0.01682	0.01855
0.090	0.00434	0.00486	0.00545	0.00611	0.00684	0.00764	0.00853	0.00951	0.01059	0.01176	0.01305	0.01445	0.01598	0.01763
0.100	0.00411	0.00462	0.00518	0.00581	0.00651	0.00728	0.00813	0.00907	0.01010	0.01123	0.01246	0.01381	0.01527	0.01686
0.150	0.00337	0.00380	0.00428	0.00482	0.00541	0.00607	0.00679	0.00759	0.00847	0.00943	0.01048	0.01163	0.01287	0.01422
0.200	0.00294	0.00332	0.00375	0.00423	0.00476	0.00535	0.00600	0.00671	0.00750	0.00836	0.00930	0.01032	0.01144	0.01265
0.250	0.00265	0.00300	0.00339	0.00383	0.00432	0.00486	0.00545	0.00611	0.00683	0.00762	0.00848	0.00942	0.01045	0.01156
0.300	0.00243	0.00276	0.00313	0.00354	0.00399	0.00449	0.00505	0.00566	0.00633	0.00707	0.00788	0.00876	0.00971	0.01075
0.350	0.00227	0.00258	0.00292	0.00331	0.00373	0.00421	0.00473	0.00531	0.00595	0.00664	0.00741	0.00824	0.00914	0.01012
0.400	0.00213	0.00243	0.00276	0.00312	0.00353	0.00398	0.00448	0.00503	0.00563	0.00630	0.00702	0.00781	0.00867	0.00960
0.450	0.00202	0.00230	0.00262	0.00297	0.00336	0.00379	0.00427	0.00480	0.00537	0.00601	0.00670	0.00746	0.00828	0.00917
0.500	0.00193	0.00220	0.00250	0.00284	0.00321	0.00363	0.00409	0.00460	0.00515	0.00576	0.00643	0.00716	0.00795	0.00881
0.600	0.00178	0.00203	0.00231	0.00263	0.00298	0.00337	0.00380	0.00427	0.00479	0.00536	0.00599	0.00667	0.00741	0.00821
0.700	0.00166	0.00190	0.00217	0.00247	0.00280	0.00316	0.00357	0.00402	0.00451	0.00505	0.00564	0.00628	0.00698	0.00774
0.800	0.00157	0.00180	0.00205	0.00233	0.00265	0.00300	0.00338	0.00381	0.00428	0.00479	0.00535	0.00597	0.00663	0.00736
0.900	0.00149	0.00171	0.00195	0.00222	0.00252	0.00286	0.00323	0.00364	0.00409	0.00458	0.00512	0.00570	0.00634	0.00703
1.000	0.00143	0.00163	0.00187	0.00213	0.00242	0.00274	0.00310	0.00349	0.00392	0.00439	0.00491	0.00548	0.00609	0.00676
1.500	0.00120	0.00138	0.00158	0.00181	0.00206	0.00233	0.00264	0.00298	0.00335	0.00376	0.00421	0.00470	0.00523	0.00581
2.000	0.00107	0.00123	0.00141	0.00161	0.00184	0.00209	0.00236	0.00267	0.00301	0.00337	0.00378	0.00422	0.00470	0.00522
2.500	0.00097	0.00112	0.00129	0.00147	0.00168	0.00191	0.00217	0.00245	0.00276	0.00310	0.00347	0.00388	0.00432	0.00480
3.000	0.00090	0.00104	0.00120	0.00137	0.00157	0.00178	0.00202	0.00229	0.00258	0.00290	0.00325	0.00363	0.00404	0.00449
3.500	0.00085	0.00098	0.00113	0.00129	0.00148	0.00168	0.00191	0.00216	0.00243	0.00274	0.00307	0.00343	0.00382	0.00425
4.000	0.00080	0.00093	0.00107	0.00123	0.00140	0.00160	0.00181	0.00205	0.00232	0.00260	0.00292	0.00326	0.00364	0.00404
4.500	0.00077	0.00089	0.00102	0.00117	0.00134	0.00153	0.00174	0.00196	0.00222	0.00249	0.00279	0.00312	0.00348	0.00387
5.000	0.00073	0.00085	0.00098	0.00113	0.00129	0.00147	0.00167	0.00189	0.00213	0.00240	0.00269	0.00301	0.00335	0.00373
5.500	0.00071	0.00082	0.00094	0.00109	0.00124	0.00142	0.00161	0.00182	0.00206	0.00231	0.00260	0.00290	0.00324	0.00360
6.000	0.00068	0.00079	0.00091	0.00105	0.00120	0.00137	0.00156	0.00176	0.00199	0.00224	0.00251	0.00281	0.00314	0.00349
6.500	0.00066	0.00077	0.00089	0.00102	0.00117	0.00133	0.00151	0.00171	0.00193	0.00218	0.00244	0.00273	0.00305	0.00339
7.000	0.00064	0.00075	0.00086	0.00099	0.00113	0.00129	0.00147	0.00167	0.00188	0.00212	0.00238	0.00266	0.00296	0.00330
7.500	0.00063	0.00073	0.00084	0.00096	0.00110	0.00126	0.00143	0.00162	0.00183	0.00206	0.00232	0.00259	0.00289	0.00322
8.000	0.00061	0.00071	0.00082	0.00094	0.00108	0.00123	0.00140	0.00159	0.00179	0.00202	0.00226	0.00253	0.00282	0.00314
8.500	0.00060	0.00069	0.00080	0.00092	0.00105	0.00120	0.00137	0.00155	0.00175	0.00197	0.00221	0.00248	0.00276	0.00307
9.000	0.00058	0.00068	0.00078	0.00090	0.00103	0.00118	0.00134	0.00152	0.00172	0.00193	0.00217	0.00243	0.00271	0.00301
9.500	0.00057	0.00066	0.00077	0.00088	0.00101	0.00115	0.00131	0.00149	0.00168	0.00189	0.00213	0.00238	0.00265	0.00295
10.000	0.00056	0.00065	0.00075	0.00086	0.00099	0.00113	0.00129	0.00146	0.00165	0.00186	0.00209	0.00233	0.00260	0.00290
12.000	0.00052	0.00061	0.00070	0.00081	0.00093	0.00106	0.00120	0.00137	0.00154	0.00174	0.00195	0.00219	0.00244	0.00271
15.000	0.00048	0.00056	0.00064	0.00074	0.00085	0.00097	0.00111	0.00126	0.00142	0.00160	0.00180	0.00202	0.00225	0.00251
18.000	0.00045	0.00052	0.00060	0.00069	0.00080	0.00091	0.00104	0.00118	0.00133	0.00150	0.00169	0.00189	0.00211	0.00235
21.000	0.00042	0.00049	0.00057	0.00065	0.00075	0.00086	0.00098	0.00111	0.00126	0.00142	0.00159	0.00179	0.00199	0.00222
24.000	0.00040	0.00047	0.00054	0.00062	0.00072	0.00082	0.00093	0.00106	0.00120	0.00135	0.00152	0.00170	0.00190	0.00212
27.000	0.00038	0.00045	0.00052	0.00060	0.00069	0.00078	0.00089	0.00102	0.00115	0.00130	0.00146	0.00163	0.00182	0.00203
30.000	0.00037	0.00043	0.00050	0.00057	0.00066	0.00076	0.00086	0.00098	0.00111	0.00125	0.00140	0.00157	0.00175	0.00195

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-5—Conversion of $Re_D/10^6$ to $Q_v/1000$ (Q_v in Thousands of Cubic Feet per Hour): $Q_v/1000 = Re_D/1000D/28.2435$

	Nominal Pipe Diameter										
	2 Inches			3 Inches				4 Inches			
$Re_D/10^5$	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.020	1.2	1.4	1.5	1.6	1.9	2.1	2.2	2.2	2.4	2.7	2.9
0.030	1.8	2.1	2.2	2.4	2.8	3.1	3.3	3.3	3.7	4.1	4.3
0.040	2.4	2.7	2.9	3.3	3.7	4.1	4.3	4.5	4.9	5.4	5.7
0.050	3.0	3.4	3.7	4.1	4.6	5.1	5.4	5.6	6.1	6.8	7.1
0.060	3.6	4.1	4.4	4.9	5.6	6.2	6.5	6.7	7.3	8.1	8.6
0.070	4.2	4.8	5.1	5.7	6.5	7.2	7.6	7.8	8.5	9.5	10.0
0.080	4.8	5.5	5.9	6.5	7.4	8.2	8.7	8.9	9.7	10.8	11.4
0.090	5.4	6.2	6.6	7.3	8.4	9.2	9.8	10.0	11.0	12.2	12.8
0.100	6.0	6.9	7.3	8.1	9.3	10.3	10.9	11.2	12.2	13.5	14.3
0.150	9.0	10.3	11.0	12.2	13.9	15.4	16.3	16.7	18.3	20.3	21.4
0.200	11.9	13.7	14.6	16.3	18.6	20.5	21.7	22.3	24.3	27.1	28.5
0.250	14.9	17.2	18.3	20.4	23.2	25.7	27.2	27.9	30.4	33.9	35.6
0.300	17.9	20.6	22.0	24.4	27.9	30.8	32.6	33.5	36.5	40.6	42.8
0.350	20.9	24.0	25.6	28.5	32.5	35.9	38.0	39.1	42.6	47.4	49.9
0.400	23.9	27.5	29.3	32.6	37.2	41.1	43.5	44.6	48.7	54.2	57.0
0.450	26.9	30.9	32.9	36.6	41.8	46.2	48.9	50.2	54.8	61.0	64.1
0.500	29.9	34.3	36.6	40.7	46.5	51.3	54.3	55.8	60.9	67.7	71.3
0.600	35.8	41.2	43.9	48.9	55.7	61.6	65.2	67.0	73.0	81.3	85.5
0.700	41.8	48.1	51.2	57.0	65.0	71.9	76.0	78.1	85.2	94.8	99.8
0.800	47.8	54.9	58.5	65.1	74.3	82.1	86.9	89.3	97.4	108	114
0.900	53.8	61.8	65.9	73.3	83.6	92.4	97.8	100	110	122	128
1.000	59.7	68.7	73.2	81.4	92.9	103	109	112	122	135	143
1.500	89.6	103	110	122	139	154	163	167	183	203	214
2.000	119	137	146	163	186	205	217	223	243	271	285
2.500	149	172	183	204	232	257	272	279	304	339	356
3.000	179	206	220	244	279	308	326	335	365	406	428
3.500	209	240	256	285	325	359	380	391	426	474	499
4.000	239	275	293	326	372	411	435	446	487	542	570
4.500	269	309	329	366	418	462	489	502	548	610	641
5.000	299	343	366	407	465	513	543	558	609	677	713
5.500	329	378	403	448	511	565	597	614	670	745	784
6.000	358	412	439	489	557	616	652	670	730	813	855
6.500	388	446	476	529	604	667	706	725	791	881	927
7.000	418	481	512	570	650	719	760	781	852	948	998
7.500	448	515	549	611	697	770	815	837	913	1,016	1,069
8.000	478	549	585	651	743	821	869	893	974	1,084	1,140
8.500	508	584	622	692	790	873	923	949	1,035	1,151	1,212
9.000	538	618	659	733	836	924	978	1,004	1,096	1,219	1,283
9.500	567	652	695	774	883	975	1,032	1,060	1,156	1,287	1,354
10.000	597	687	732	814	929	1,027	1,086	1,116	1,217	1,355	1,425

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-5—Continued

	Nominal Pipe Diameter									
	6 Inches				8 Inches			10 Inches		
$Re_D/10^6$	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.036
0.020	3.5	3.7	4.1	4.3	5.4	5.7	5.7	6.8	7.1	7.1
0.030	5.2	5.5	6.1	6.4	8.1	8.5	8.6	10.2	10.6	10.7
0.040	6.9	7.3	8.2	8.6	10.8	11.3	11.4	13.5	14.2	14.2
0.050	8.7	9.2	10.2	10.7	13.5	14.1	14.3	16.9	17.7	17.8
0.060	10.4	11.0	12.2	12.9	16.2	17.0	17.1	20.3	21.3	21.3
0.070	12.1	12.9	14.3	15.0	18.9	19.8	20.0	23.7	24.8	24.9
0.080	13.9	14.7	16.3	17.2	21.6	22.6	22.9	27.1	28.4	28.4
0.090	15.6	16.5	18.4	19.3	24.3	25.4	25.7	30.5	31.9	32.0
0.100	17.3	18.4	20.4	21.5	27.0	28.3	28.6	33.9	35.5	35.5
0.150	26.0	27.5	30.6	32.2	40.5	42.4	42.9	50.8	53.2	53.3
0.200	34.7	36.7	40.8	42.9	54.0	56.5	57.2	67.7	71.0	71.1
0.250	43.3	45.9	51.0	53.7	67.5	70.6	71.4	84.6	88.7	88.8
0.300	52.0	55.1	61.2	64.4	81.0	84.8	85.7	102	106	107
0.350	60.7	64.3	71.4	75.2	94.5	98.9	100	118	124	124
0.400	69.4	73.5	81.6	85.9	108	113	114	135	142	142
0.450	78.0	82.6	91.8	96.6	121	127	129	152	160	160
0.500	86.7	91.8	102	107	135	141	143	169	177	178
0.600	104	110	122	129	162	170	171	203	213	213
0.700	121	129	143	150	189	198	200	237	248	249
0.800	139	147	163	172	216	226	229	271	284	284
0.900	156	165	184	193	243	254	257	305	319	320
1.000	173	184	204	215	270	283	286	339	355	355
1.500	260	275	306	322	405	424	429	508	532	533
2.000	347	367	408	429	540	565	572	677	710	711
2.500	433	459	510	537	675	706	714	846	887	888
3.000	520	551	612	644	810	848	857	1,016	1,064	1,066
3.500	607	643	714	752	945	989	1,000	1,185	1,242	1,244
4.000	694	735	816	859	1,080	1,130	1,143	1,354	1,419	1,421
4.500	780	826	918	966	1,215	1,272	1,286	1,524	1,596	1,599
5.000	867	918	1,020	1,074	1,350	1,413	1,429	1,693	1,774	1,777
5.500	954	1,010	1,122	1,181	1,485	1,554	1,572	1,862	1,951	1,954
6.000	1,040	1,102	1,224	1,288	1,620	1,695	1,715	2,031	2,129	2,132
6.500	1,127	1,194	1,326	1,396	1,755	1,837	1,857	2,201	2,306	2,310
7.000	1,214	1,286	1,428	1,503	1,890	1,978	2,000	2,370	2,483	2,487
7.500	1,300	1,377	1,530	1,611	2,025	2,119	2,143	2,539	2,661	2,665
8.000	1,387	1,469	1,632	1,718	2,160	2,261	2,286	2,708	2,838	2,843
8.500	1,474	1,561	1,734	1,825	2,295	2,402	2,429	2,878	3,016	3,020
9.000	1,560	1,653	1,836	1,933	2,430	2,543	2,572	3,047	3,193	3,198
9.500	1,647	1,745	1,938	2,040	2,565	2,685	2,715	3,216	3,370	3,376
10.000	1,734	1,837	2,040	2,147	2,700	2,826	2,858	3,386	3,548	3,553

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-5—Continued

	Nominal Pipe Diameter														
	12 Inches			16 Inches			20 Inches			24 Inches			30 Inches		
$Re_D/10^6$	11.374	11.938	12.090	14 688	15.000	15.250	18.812	19 000	19.250	22.624	23 000	23.250	28.750	29 000	29.250
0.150	60.4	63.4	64.2	78.0	79.7	81.0	99.9	101	102	120	122	123	153	154	155
0.200	80.5	84.5	85.6	104	106	108	133	135	136	160	163	165	204	205	207
0.250	101	106	107	130	133	135	167	168	170	200	204	206	254	257	259
0.300	121	127	128	156	159	162	200	202	204	240	244	247	305	308	311
0.350	141	148	150	182	186	189	233	235	239	280	285	288	356	359	362
0.400	161	169	171	208	212	216	266	269	273	320	326	329	407	411	414
0.450	181	190	193	234	239	243	300	303	307	360	366	370	458	462	466
0.500	201	211	214	260	266	270	333	336	341	401	407	412	509	513	518
0.600	242	254	257	312	319	324	400	404	409	481	489	494	611	616	621
0.700	282	296	300	364	372	378	466	471	477	561	570	576	713	719	725
0.800	322	338	342	416	425	432	533	538	545	641	651	659	814	821	829
0.900	362	380	385	468	478	486	599	605	613	721	733	741	916	924	932
1.000	403	423	428	520	531	540	666	673	682	801	814	823	1,018	1,027	1,036
1.500	604	634	642	780	797	810	999	1,009	1,022	1,202	1,222	1,235	1,527	1,540	1,553
2.000	805	845	856	1,040	1,062	1,080	1,332	1,345	1,363	1,602	1,629	1,646	2,036	2,054	2,071
2.500	1,007	1,057	1,070	1,300	1,328	1,350	1,665	1,682	1,704	2,003	2,036	2,058	2,545	2,567	2,589
3.000	1,208	1,268	1,284	1,560	1,593	1,620	1,998	2,018	2,045	2,403	2,443	2,470	3,054	3,080	3,107
3.500	1,409	1,479	1,498	1,820	1,859	1,890	2,331	2,355	2,386	2,804	2,850	2,881	3,563	3,594	3,625
4.000	1,611	1,691	1,712	2,080	2,124	2,160	2,664	2,691	2,726	3,204	3,257	3,293	4,072	4,107	4,143
4.500	1,812	1,902	1,926	2,340	2,390	2,430	2,997	3,027	3,067	3,605	3,665	3,704	4,581	4,621	4,660
5.000	2,014	2,113	2,140	2,600	2,655	2,700	3,330	3,364	3,408	4,005	4,072	4,116	5,090	5,134	5,178
5.500	2,215	2,325	2,354	2,860	2,921	2,970	3,663	3,700	3,749	4,406	4,479	4,528	5,599	5,647	5,696
6.000	2,416	2,536	2,568	3,120	3,187	3,240	3,996	4,036	4,089	4,806	4,886	4,939	6,108	6,161	6,214
6.500	2,618	2,747	2,782	3,380	3,452	3,510	4,329	4,373	4,430	5,207	5,293	5.351	6,617	6,674	6,732
7.000	2,819	2,959	2,996	3,640	3,718	3,780	4,662	4,709	4,771	5,607	5,700	5,762	7,126	7,188	7,249
7.500	3,020	3,170	3,210	3,900	3,983	4,050	4,996	5,045	5,112	6,008	6,108	6,174	7,635	7,701	7,767
8.000	3,222	3,381	3,425	4,160	4,249	4,320	5,329	5,382	5,453	6,408	6,515	6,586	8,143	8,214	8,285
8.500	3,423	3,593	3,639	4,420	4,514	4,590	5,662	5,718	5,793	6,809	6,922	6.997	8,652	8,728	8,803
9.000	3,624	3,804	3,853	4,680	4,780	4,860	5,995	6,055	6.134	7,209	7,329	7.409	9,161	9,241	9,321
9.500	3,826	4,015	4,067	4,940	5,045	5,130	6,328	6,391	6.475	7,610	7,736	7,820	9,670	9.754	9,839
10.000	4,027	4,227	4,281	5,201	5,311	5,399	6,661	6,727	6,816	8,010	8,143	8,232	10,179	10,268	10,356
12.000	4,833	5,072	5,137	6,241	6,373	6,479	7,993	8,073	8,179	9,612	9,772	9,878	12,215	12,321	12,428
15.000	6,041	6,340	6,421	7,801	7,966	8,099	9,991	10,091	10,224	12,016	12,215	12,348	15,269	15,402	15,535
18.000	7,249	7,608	7,705	9,361	9,560	9,719	11,989	12,109	12,268	14,419	14,658	14,818	18,323	18,482	18,642
21.000	8,457	8,876	8,989	10,921	11,153	11,339	13,987	14,127	14,313	16,822	17,101	17,287	21,377	21,563	21,748
24 000	9,665	10,144	10,274	12,481	12,746	12,959	15,986	16,145	16,358	19,225	19,544	19,757	24,430	24,643	24,855
27.000	10,873	11,412	11,558	14,041	14,340	14,579	17,984	18,164	18,403	21,628	21,987	22,226	27,484	27,723	27,962
30.000	12,081	12,680	12,842	15,602	15,933	16,198	19,982	20,182	20.447	24,031	24,430	24,696	30,538	30,804	31,069

Note: This table was developed for informational purposes only and is specific to the following conditions: T_f = 68°F; G_r = 0.6; μ = 0.000069; k = 1.3; P_b = 14.73; and T_b = 519.67°R.

Table 3-B-6—Expansion Factors for Flange Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$												
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60	0.61	0.62
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9989	0.9989	0.9989	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9988	0.9987	0.9987	0.9987
0.2	0.9977	0.9977	0.9977	0.9977	0.9976	0.9976	0.9976	0.9976	0.9975	0.9975	0.9975	0.9975	0.9974
0.3	0.9966	0.9966	0.9966	0.9965	0.9965	0.9964	0.9964	0.9963	0.9963	0.9963	0.9962	0.9962	0.9962
0.4	0.9954	0.9954	0.9954	0.9953	0.9953	0.9952	0.9952	0.9951	0.9951	0.9950	0.9949	0.9949	0.9949
0.5	0.9943	0.9943	0.9943	0.9942	0.9941	0.9940	0.9940	0.9939	0.9938	0.9938	0.9937	0.9936	0.9936
0.6	0.9932	0.9932	0.9931	0.9930	0.9929	0.9928	0.9927	0.9927	0.9926	0.9925	0.9924	0.9924	0.9923
0.7	0.9920	0.9920	0.9920	0.9919	0.9918	0.9916	0.9915	0.9915	0.9914	0.9913	0.9912	0.9911	0.9910
0.8	0.9909	0.9909	0.9908	0.9907	0.9906	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899	0.9898	0.9897
0.9	0.9898	0.9897	0.9897	0.9895	0.9894	0.9892	0.9891	0.9890	0.9889	0.9888	0.9886	0.9885	0.9885
1.0	0.9886	0.9886	0.9885	0.9884	0.9882	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9872
1.1	0.9875	0.9875	0.9874	0.9872	0.9870	0.9868	0.9867	0.9866	0.9864	0.9863	0.9861	0.9860	0.9859
1.2	0.9863	0.9863	0.9862	0.9860	0.9859	0.9856	0.9855	0.9853	0.9852	0.9850	0.9848	0.9847	0.9846
1.3	0.9852	0.9852	0.9851	0.9849	0.9847	0.9844	0.9843	0.9841	0.9840	0.9838	0.9836	0.9835	0.9833
1.4	0.9841	0.9840	0.9840	0.9837	0.9835	0.9832	0.9831	0.9829	0.9827	0.9825	0.9823	0.9822	0.9821
1.5	0.9829	0.9829	0.9828	0.9826	0.9823	0.9820	0.9819	0.9817	0.9815	0.9813	0.9810	0.9809	0.9808
1.6	0.9818	0.9818	0.9817	0.9814	0.9811	0.9808	0.9806	0.9805	0.9803	0.9800	0.9798	0.9796	0.9795
1.7	0.9806	0.9806	0.9805	0.9802	0.9800	0.9796	0.9794	0.9792	0.9790	0.9788	0.9785	0.9784	0.9782
1.8	0.9795	0.9795	0.9794	0.9791	0.9788	0.9784	0.9782	0.9780	0.9778	0.9775	0.9772	0.9771	0.9769
1.9	0.9784	0.9783	0.9782	0.9779	0.9776	0.9772	0.9770	0.9768	0.9766	0.9763	0.9760	0.9758	0.9756
2.0	0.9772	0.9772	0.9771	0.9767	0.9764	0.9760	0.9758	0.9756	0.9753	0.9750	0.9747	0.9745	0.9744
2.1	0.9761	0.9761	0.9759	0.9756	0.9753	0.9748	0.9746	0.9744	0.9741	0.9738	0.9734	0.9733	0.9731
2.2	0.9750	0.9749	0.9748	0.9744	0.9741	0.9736	0.9734	0.9731	0.9729	0.9725	0.9722	0.9720	0.9718
2.3	0.9738	0.9738	0.9736	0.9732	0.9729	0.9724	0.9722	0.9719	0.9716	0.9713	0.9709	0.9707	0.9705
2.4	0.9727	0.9726	0.9725	0.9721	0.9717	0.9712	0.9710	0.9707	0.9704	0.9700	0.9697	0.9694	0.9692
2.5	0.9715	0.9715	0.9713	0.9709	0.9705	0.9700	0.9698	0.9695	0.9692	0.9688	0.9684	0.9682	0.9680
2.6	0.9704	0.9704	0.9702	0.9698	0.9694	0.9688	0.9686	0.9683	0.9679	0.9675	0.9671	0.9669	0.9667
2.7	0.9693	0.9692	0.9691	0.9686	0.9682	0.9676	0.9673	0.9670	0.9667	0.9663	0.9659	0.9656	0.9654
2.8	0.9681	0.9681	0.9679	0.9674	0.9670	0.9664	0.9661	0.9658	0.9654	0.9650	0.9646	0.9644	0.9641
2.9	0.9670	0.9669	0.9668	0.9663	0.9658	0.9652	0.9649	0.9646	0.9642	0.9638	0.9633	0.9631	0.9628
3.0	0.9658	0.9658	0.9656	0.9651	0.9647	0.9640	0.9637	0.9634	0.9630	0.9626	0.9621	0.9618	0.9615
3.1	0.9647	0.9647	0.9645	0.9639	0.9635	0.9628	0.9625	0.9622	0.9617	0.9613	0.9608	0.9605	0.9603
3.2	0.9636	0.9635	0.9633	0.9628	0.9623	0.9616	0.9613	0.9609	0.9605	0.9601	0.9595	0.9593	0.9590
3.3	0.9624	0.9624	0.9622	0.9616	0.9611	0.9604	0.9601	0.9597	0.9593	0.9588	0.9583	0.9580	0.9577
3.4	0.9613	0.9612	0.9610	0.9604	0.9599	0.9592	0.9589	0.9585	0.9580	0.9576	0.9570	0.9567	0.9564
3.5	0.9602	0.9601	0.9599	0.9593	0.9588	0.9580	0.9577	0.9573	0.9568	0.9563	0.9558	0.9554	0.9551
3.6	0.9590	0.9590	0.9587	0.9581	0.9576	0.9568	0.9565	0.9560	0.9556	0.9551	0.9545	0.9542	0.9538
3.7	0.9579	0.9578	0.9576	0.9570	0.9564	0.9556	0.9553	0.9548	0.9543	0.9538	0.9532	0.9529	0.9526
3.8	0.9567	0.9567	0.9564	0.9558	0.9552	0.9544	0.9540	0.9536	0.9531	0.9526	0.9520	0.9516	0.9513
3.9	0.9556	0.9555	0.9553	0.9546	0.9540	0.9532	0.9528	0.9524	0.9519	0.9513	0.9507	0.9504	0.9500
4.0	0.9545	0.9544	0.9542	0.9536	0.9529	0.9520	0.9516	0.9512	0.9506	0.9501	0.9494	0.9491	0.9487

Table 3-B-6—Continued

	$\beta = d/D$												
h_w/P_{f_1}	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70	0.71	0.72	0.73	0.74	0.75
0.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.1	0.9987	0.9987	0.9987	0.9987	0.9987	0.9987	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986	0.9986
0.2	0.9974	0.9974	0.9974	0.9974	0.9973	0.9973	0.9973	0.9973	0.9972	0.9972	0.9972	0.9971	0.9971
0.3	0.9961	0.9961	0.9961	0.9960	0.9960	0.9960	0.9959	0.9959	0.9958	0.9958	0.9958	0.9957	0.9957
0.4	0.9948	0.9948	0.9948	0.9947	0.9947	0.9946	0.9946	0.9945	0.9945	0.9944	0.9943	0.9943	0.9942
0.5	0.9935	0.9935	0.9934	0.9934	0.9933	0.9933	0.9932	0.9931	0.9931	0.9930	0.9929	0.9929	0.9928
0.6	0.9923	0.9922	0.9921	0.9921	0.9920	0.9919	0.9918	0.9918	0.9917	0.9916	0.9915	0.9914	0.9913
0.7	0.9910	0.9909	0.9908	0.9907	0.9907	0.9906	0.9905	0.9904	0.9903	0.9902	0.9901	0.9900	0.9899
0.8	0.9897	0.9896	0.9895	0.9894	0.9893	0.9892	0.9891	0.9890	0.9889	0.9888	0.9887	0.9886	0.9884
0.9	0.9884	0.9883	0.9882	0.9881	0.9880	0.9879	0.9878	0.9877	0.9875	0.9874	0.9873	0.9871	0.9870
1.0	0.9871	0.9870	0.9869	0.9868	0.9867	0.9865	0.9864	0.9863	0.9861	0.9860	0.9859	0.9857	0.9855
1.1	0.9858	0.9857	0.9856	0.9854	0.9853	0.9852	0.9851	0.9849	0.9848	0.9846	0.9844	0.9843	0.9841
1.2	0.9845	0.9844	0.9843	0.9841	0.9840	0.9838	0.9837	0.9835	0.9834	0.9832	0.9830	0.9828	0.9826
1.3	0.9832	0.9831	0.9829	0.9828	0.9827	0.9825	0.9823	0.9822	0.9820	0.9818	0.9816	0.9814	0.9812
1.4	0.9819	0.9818	0.9816	0.9815	0.9813	0.9812	0.9810	0.9808	0.9806	0.9804	0.9802	0.9800	0.9798
1.5	0.9806	0.9805	0.9803	0.9802	0.9800	0.9798	0.9796	0.9794	0.9792	0.9790	0.9788	0.9786	0.9783
1.6	0.9793	0.9792	0.9790	0.9788	0.9787	0.9785	0.9783	0.9781	0.9778	0.9776	0.9774	0.9771	0.9769
1.7	0.9780	0.9779	0.9777	0.9775	0.9773	0.9771	0.9769	0.9767	0.9764	0.9762	0.9760	0.9757	0.9754
1.8	0.9768	0.9766	0.9764	0.9762	0.9760	0.9758	0.9755	0.9753	0.9751	0.9748	0.9745	0.9743	0.9740
1.9	0.9755	0.9753	0.9751	0.9749	0.9747	0.9744	0.9742	0.9739	0.9737	0.9734	0.9731	0.9728	0.9725
2.0	0.9742	0.9740	0.9738	0.9735	0.9733	0.9731	0.9728	0.9726	0.9723	0.9720	0.9717	0.9714	0.9711
2.1	0.9729	0.9727	0.9725	0.9722	0.9720	0.9717	0.9715	0.9712	0.9709	0.9706	0.9703	0.9700	0.9696
2.2	0.9716	0.9714	0.9711	0.9709	0.9706	0.9704	0.9701	0.9698	0.9695	0.9692	0.9689	0.9685	0.9682
2.3	0.9703	0.9701	0.9698	0.9696	0.9693	0.9690	0.9688	0.9685	0.9681	0.9678	0.9675	0.9671	0.9667
2.4	0.9690	0.9688	0.9685	0.9683	0.9680	0.9677	0.9674	0.9671	0.9668	0.9664	0.9661	0.9657	0.9653
2.5	0.9677	0.9675	0.9672	0.9669	0.9666	0.9663	0.9660	0.9657	0.9654	0.9650	0.9646	0.9643	0.9639
2.6	0.9664	0.9662	0.9659	0.9656	0.9653	0.9650	0.9647	0.9643	0.9640	0.9636	0.9632	0.9628	0.9624
2.7	0.9651	0.9649	0.9646	0.9643	0.9640	0.9637	0.9633	0.9630	0.9626	0.9622	0.9618	0.9614	0.9610
2.8	0.9638	0.9636	0.9633	0.9630	0.9626	0.9623	0.9620	0.9616	0.9612	0.9608	0.9604	0.9600	0.9595
2.9	0.9625	0.9623	0.9620	0.9616	0.9613	0.9610	0.9606	0.9602	0.9598	0.9594	0.9590	0.9585	0.9581
3.0	0.9613	0.9610	0.9606	0.9603	0.9600	0.9596	0.9592	0.9588	0.9584	0.9580	0.9576	0.9571	0.9566
3.1	0.9600	0.9597	0.9593	0.9590	0.9586	0.9583	0.9579	0.9575	0.9571	0.9566	0.9562	0.9557	0.9552
3.2	0.9587	0.9584	0.9580	0.9577	0.9573	0.9569	0.9567	0.9561	0.9557	0.9552	0.9547	0.9542	0.9537
3.3	0.9574	0.9571	0.9567	0.9564	0.9560	0.9556	0.9552	0.9547	0.9543	0.9538	0.9533	0.9528	0.9525
3.4	0.9561	0.9558	0.9554	0.9550	0.9546	0.9542	0.9538	0.9534	0.9529	0.9524	0.9519	0.9514	0.9508
3.5	0.9548	0.9545	0.9541	0.9537	0.9533	0.9529	0.9524	0.9520	0.9515	0.9510	0.9505	0.9500	0.9494
3.6	0.9535	0.9532	0.9528	0.9524	0.9520	0.9515	0.9511	0.9506	0.9501	0.9496	0.9491	0.9485	0.9480
3.7	0.9552	0.9518	0.9515	0.9511	0.9506	0.9502	0.9497	0.9492	0.9487	0.9482	0.9477	0.9471	0.9465
3.8	0.9509	0.9505	0.9502	0.9497	0.9493	0.9488	0.9484	0.9479	0.9474	0.9468	0.9463	0.9457	0.9451
3.9	0.9496	0.9492	0.9488	0.9484	0.9480	0.9475	0.9470	0.9465	0.9460	0.9454	0.9448	0.9442	0.9436
4.0	0.9483	0.9479	0.9475	0.9471	0.9465	0.9462	0.9457	0.9451	0.9446	0.9440	0.9434	0.9428	0.9422

Table 3-B-7—F_{pb} Factors Used to Change From a Pressure Base of 14.73 Pounds Force per Square Inch Absolute to Other Pressure Bases

$$F_{pb} = \frac{14.73}{\text{Contract pressure base, psia}}$$

Pressure Base (pounds force per square inch absolute)	F_{pb}
14.4	1.0229
14.525	1.0141
14.65	1.0055
14.696	1 0023
14.70	1.0020
14.725	1.0003
14.73	1.0000
14.735	0.9997
14.775	0.9970
14.90	0.9886
15.025	0.9804
15.15	0.9723
15.225	0.9675
15.275	0.9643
15 325	0.9612
15.40	0.9565
15.525	0.9488
15.65	0.9412
15.775	0.9338
15.90	0.9264
16.025	0.9192
16.15	0.9121
16.275	0.9051
16.40	0.8982
16.70	0.8820

Table 3-B-8—F_{tb} Factors Used to Change From a Temperature Base of 60°F to Other Temperature Bases

$$F_{tb} = \frac{\text{Base °F} + 459.67}{60 + 459.67}$$

Temperature (°F)	F_{tb}	Temperature (°F)	F_{tb}
40	0.9615	65	1.0096
41	0.9634	66	1.0115
42	0.9654	67	1.0135
43	0 9673	68	1.0154
44	0.9692	69	1 0173
45	0.9711	70	1.0192
46	0.9731	71	1.0212
47	0.9750	72	1.0231
48	0.9769	73	1.0250
49	0.9788	74	1.0269
50	0.9808	75	1.0289
51	0.9827	76	1 0308
52	0.9846	77	1.0327
53	0.9865	78	1.0346
54	0.9885	79	1.0366
55	0.9904	80	1.0385
56	0.9923	81	1 0404
57	0.9942	82	1.0423
58	0.9962	83	1.0443
59	0.9981	84	1.0462
60	1.0000	85	1.0481
61	1.0019	86	1.0500
62	1.0038	87	1.0520
63	1.0058	88	1.0539
64	1.0077	89	1.0558
		90	1.0577

Table 3-B-9—F_{tf} Factors Used to Change From a Flowing Temperature of 60°F to Actual Flowing Temperature

$$F_{tf} = \sqrt{\frac{60 + 459.67}{T_f + 459.67}}$$

Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}	Temperature (°F)	F_{tf}
−20	1.0872	37	1.0229	94	0.9688
−19	1.0859	38	1.0219	95	0.9679
−18	1.0847	39	1.0208	96	0.9671
−17	1.0835	40	1.0198	97	0.9662
−16	1.0823	41	1.0188	98	0.9653
−15	1.0810	42	1.0178	99	0.9645
−14	1.0798	43	1.0168	100	0.9636
−13	1.0786	44	1.0158	101	0.9627
−12	1.0774	45	1.0148	102	0.9619
−11	1.0762	46	1.0137	103	0.9610
−10	1.0750	47	1.0127	104	0.9602
−9	1.0738	48	1.0117	105	0.9593
−8	1.0726	49	1.0108	106	0.9585
−7	1.0715	50	1.0098	107	0.9576
−6	1.0703	51	1.0088	108	0.9568
−5	1.0691	52	1.0078	109	0.9559
−4	1.0679	53	1.0068	110	0.9551
−3	1.0668	54	1.0058	111	0.9543
−2	1.0656	55	1.0048	112	0.9534
−1	1.0644	56	1.0039	113	0.9526
0	1.0633	57	1.0029	114	0.9518
1	1.0621	58	1.0019	115	0.9509
2	1.0610	59	1.0010	116	0.9501
3	1.0598	60	1.0000	117	0.9493
4	1.0587	61	0.9990	118	0.9485
5	1.0575	62	0.9981	119	0.9477
6	1.0564	63	0.9971	120	0.9468
7	1.0553	64	0.9962	121	0.9460
8	1.0541	65	0.9952	122	0.9452
9	1.0530	66	0.9943	123	0.9444
10	1.0519	67	0.9933	124	0.9436
11	1.0508	68	0.9924	125	0.9428
12	1.0497	69	0.9915	126	0.9420
13	1.0485	70	0.9905	127	0.9412
14	1.0474	71	0.9896	128	0.9404
15	1.0463	72	0.9887	129	0.9396
16	1.0452	73	0.9877	130	0.9388
17	1.0441	74	0.9868	131	0.9380
18	1.0430	75	0.9859	132	0.9372
19	1.0419	76	0.9850	133	0.9364
20	1.0409	77	0.9840	134	0.9356
21	1.0398	78	0.9831	135	0.9348
22	1.0387	79	0.9822	136	0.9340
23	1.0376	80	0.9813	137	0.9332
24	1.0365	81	0.9804	138	0.9325
25	1.0355	82	0.9795	139	0.9317
26	1.0344	83	0.9786	140	0.9309
27	1.0333	84	0.9777	141	0.9301
28	1.0323	85	0.9768	142	0.9294
29	1.0312	86	0.9759	143	0.9286
30	1.0302	87	0.9750	144	0.9278
31	1.0291	88	0.9741	145	0.9271
32	1.0281	89	0.9732	146	0.9263
33	1.0270	90	0.9723	147	0.9255
34	1.0260	91	0.9714	148	0.9248
35	1.0250	92	0.9706	149	0.9240
36	1.0239	93	0.9697	150	0.9232

Table 3-B-10—F_{gr} Factors Used to Adjust for Real Gas Relative Density (G_r): Base Conditions of 60°F and 14.73 Pounds Force per Square Inch Absolute

$$F_{gr} = \sqrt{\frac{1}{G_r}}$$

G_r	F_{gr} 0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.550	1.3484	1.3472	0.3460	1.3447	1.3435	1.3423	1.3411	1.3399	1.3387	1.3375
0.560	1.3363	1.3351	1.3339	1.3327	1.3316	1.3304	1.3292	1.3280	1.3269	1.3257
0.570	1.3245	1.3234	1.3222	1.3211	1.3199	1.3188	1.3176	1.3165	1.3153	1.3142
0.580	1.3131	1.3119	1.3108	1.3097	1.3086	1.3074	1.3063	1.3052	1.3041	1.3030
0.590	1.3019	1.3008	1.2997	1.2986	1.2975	1.2964	1.2953	1.2942	1.2932	1.2921
0.600	1.2910	1.2899	1.2888	1.2878	1.2867	1.2856	1.2846	1.2835	1.2825	1.2814
0.610	1.2804	1.2793	1.2783	1.2772	1.2762	1.2752	1.2741	1.2731	1.2720	1.2710
0.620	1.2700	1.2690	1.2680	1.2669	1.2659	1.2649	1.2639	1.2629	1.2619	1.2609
0.630	1.2599	1.2589	1.2579	1.2569	1.2559	1.2549	1.2539	1.2529	1.2520	1.2510
0.640	1.2500	1.2490	1.2480	1.2471	1.2461	1.2451	1.2442	1.2432	1.2423	1.2413
0.650	1.2403	1.2394	1.2384	1.2375	1.2365	1.2356	1.2347	1.2337	1.2328	1.2318
0.660	1.2309	1.2300	1.2290	1.2281	1.2272	1.2263	1.2254	1.2244	1.2235	1.2226
0.670	1.2217	1.2208	1.2199	1.2190	1.2181	1.2172	1.2163	1.2154	1.2145	1.2136
0.680	1.2127	1.2118	1.2109	1.2100	1.2091	1.2082	1.2074	1.2065	1.2056	1.2047
0.690	1.2039	1.2030	1.2021	1.2012	1.2004	1.1995	1.1986	1.1978	1.1969	1.1961
0.700	1.1952	1.1944	1.1935	1.1927	1.1918	1.1910	1.1901	1.1893	1.1884	1.1876
0.710	1.1868	1.1859	1.1851	1.1843	1.1834	1.1826	1.1818	1.1810	1.1802	1.1793
0.720	1.1785	1.1777	1.1769	1.1761	1.1752	1.1744	1.1736	1.1728	1.1720	1.1712
0.730	1.1704	1.1696	1.1688	1.1680	1.1672	1.1664	1.1656	1.1648	1.1640	1.1633
0.740	1.1625	1.1617	1.1609	1.1601	1.1593	1.1586	1.1578	1.1570	1.1562	1.1555
0.750	1.1547	1.1539	1.1532	1.1524	1.1516	1.1509	1.1501	1.1493	1.1486	1.1478
0.760	1.1471	1.1463	1.1456	1.1448	1.1441	1.1433	1.1426	1.1418	1.1411	1.1403
0.770	1.1396	1.1389	1.1381	1.1374	1.1366	1.1359	1.1352	1.1345	1.1337	1.1330
0.780	1.1323	1.1316	1.1308	1.1301	1.1294	1.1287	1.1279	1.1272	1.1265	1.1258
0.790	1.1251	1.1244	1.1237	1.1230	1.1222	1.1215	1.1208	1.1201	1.1194	1.1187
0.800	1.1180	1.1173	1.1166	1.1159	1.1152	1.1146	1.1139	1.1132	1.1125	1.1118
0.810	1.1111	1.1104	1.1097	1.1090	1.1084	1.1077	1.1070	1.1063	1.1057	1.1050
0.820	1.1043	1.1036	1.1030	1.1023	1.1016	1.1010	1.1003	1.0996	1.0990	1.0983
0.830	1.0976	1.0970	1.0963	1.0957	1.0950	1.0944	1.0937	1.0930	1.0924	1.0917
0.840	1.0911	1.0904	1.0898	1.0891	1.0885	1.0878	1.0872	1.0866	1.0859	1.0853
0.850	1.0846	1.0840	1.0834	1.0827	1.0821	1.0815	1.0808	1.0802	1.0796	1.0790
0.860	1.0783	1.0777	1.0771	1.0764	1.0758	1.0752	1.0746	1.0740	1.0733	1.0727
0.870	1.0721	1.0715	1.0709	1.0703	1.0696	1.0690	1.0684	1.0678	1.0672	1.0666
0.880	1.0660	1.0654	1.0648	1.0642	1.0636	1.0630	1.0624	1.0618	1.0612	1.0606
0.890	1.0600	1.0594	1.0588	1.0582	1.0576	1.0570	1.0564	1.0558	1.0553	1.0547
0.900	1.0541	1.0535	1.0529	1.0523	1.0518	1.0512	1.0506	1.0500	1.0494	1.0489
0.910	1.0483	1.0477	1.0471	1.0466	1.0460	1.0454	1.0448	1.0443	1.0437	1.0431
0.920	1.0426	1.0420	1.0414	1.0409	1.0403	1.0398	1.0392	1.0386	1.0381	1.0375
0.930	1.0370	1.0364	1.0358	1.0353	1.0347	1.0342	1.0336	1.0331	1.0325	1.0320
0.940	1.0314	1.0309	1.0303	1.0298	1.0292	1.0287	1.0281	1.0276	1.0270	1.0265
0.950	1.0260	1.0254	1.0249	1.0244	1.0238	1.0233	1.0228	1.0222	1.0217	1.0212
0.960	1.0206	1.0201	1.0196	1.0190	1.0185	1.0180	1.0174	1.0169	1.0164	1.0159
0.970	1.0153	1.0148	1.0143	1.0138	1.0132	1.0127	1.0122	1.0117	1.0112	1.0107
0.980	1.0102	1.0096	1.0091	1.0086	1.0081	1.0076	1.0071	1.0066	1.0060	1.0055
0.990	1.0050	1.0045	1.0040	1.0035	1.0030	1.0025	1.0020	1.0015	1.0010	1.0005
1.000	1.0000									

Table 3-B-11—Supercompressibility Factors (F_{pv}) for G_r = 0.6 Without Nitrogen or Carbon Dioxide

Pressure (psia)	Temperature (°F)					
	20	40	60	80	100	120
100	1.00947	1.00807	1.00687	1.00504	1.00496	1.00419
200	1.02058	1.01762	1.01512	1.01294	1.01116	1.00958
300	1.03218	1.02748	1.02355	1.02022	1.01740	1.01497
400	1.04427	1.03764	1.03216	1.02756	1.02367	1.02035
500	1.05688	1.04810	1.04093	1.03497	1.02996	1.02572
600	1.06999	1.05884	1.04983	1.04243	1.03625	1.03104
700	1.08360	1.06983	1.05885	1.04990	1.04251	1.03631
800	1.09766	1.08103	1.06793	1.05737	1.04871	1.04149
900	1.11209	1.09237	1.07703	1.06479	1.05482	1.04656
1000	1.12679	1.10375	1.08608	1.07211	1.06081	1.05150
1100	1.14156	1.11508	1.09501	1.07927	1.06663	1.05628
1200	1.15616	1.12621	1.10372	1.08622	1.07225	1.06087
1300	1.17029	1.13696	1.11211	1.09289	1.07763	1.06524
1400	1.18358	1.14715	1.12007	1.09922	1.08271	1.06935
1500	1.19565	1.15657	1.12749	1.10512	1.08745	1.07318
1600	1.20615	1.16504	1.13425	1.11054	1.09180	1.07669
1700	1.21481	1.17237	1.14025	1.11540	1.09573	1.07986
1800	1.22146	1.17845	1.14541	1.11965	1.09919	1.08267
1900	1.22606	1.18318	1.14965	1.12324	1.10216	1.08509
2000	1.22868	1.18655	1.15294	1.12615	1.10462	1.08710

Note: The data in this table were generated using the A.G.A Gas Measurement Program. Copyright © 1988 American Gas Association. All rights reserved. Gas input data are as follows: % CO_2 = 0; % N_2 = 0; specific gravity = 0.6. This table was developed for informational purposes only and is specific to the gas quality listed. The data in this table are *not* subject to adjustment for nitrogen or carbon dioxide content and, because of their broad range, should not be interpolated. With the A.G.A Program, the user establishes the gas composition parameters and specifies the table range that is consistent with field or measurement conditions.

APPENDIX 3-C—FLOW CALCULATION EXAMPLES

3-C.1 General

This appendix presents two methods for calculating the volume flow rate of natural gas through an orifice meter equipped with flange taps. The first method uses the equations presented in 3.3 through 3.5. The second method is based on the more traditional calculation format, which involves the computation of various factors. The equations used for the factor approach are presented in Appendix 3-B.

To assist the user in interpreting the calculation methodology, the data set given below, which is for a single orifice meter, is used consistently throughout the flow calculation examples. The volume flow rate is computed under the assumption that the measurements are absolute and without error. It should be noted that depending on the type of instrumentation used and the calibration methods employed, calibration and correction factors may need to be applied. *For simplicity in using hand calculations and for ease of interpretation in the following examples, intermediate values are rounded to six significant digits. Part 4 should be used for any implementation of the equations.*

3-C.2 Given Data

The orifice meter consists of a carbon steel meter tube equipped with flange taps and a Type 304 stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

d_r = mean orifice bore diameter at T_r of 68°F, in inches
= 4.000.

D_r = mean meter tube internal diameter at T_r of 68°F, in inches
= 8.071.

G_r = real gas relative density (specific gravity)
= 0.570.

h_w = average differential pressure, in inches of water at 60°F
= 50.0.

P_b = contract base pressure, in pounds force per square inch absolute
= 14.65.

P_{f_1} = average upstream absolute static pressure, in pounds force per square inch absolute
= 370.0.

T_b = contract base temperature of 50°F, in degrees Rankine (50°F + 459.67)
= 509.67.

T_f = flowing temperature of 65°F, in degrees Rankine (65°F + 459.67)
= 524.67.

xc = carbon dioxide content, in mole percent
= 0.00.

xn = nitrogen content, in mole percent
= 1.10.

k = isentropic exponent (c_p/c_v)
= 1.3.

α_1 = linear coefficient of thermal expansion for a stainless steel orifice plate, in inches per inch-°F
= 0.00000925.

α_2 = linear coefficient of thermal expansion for a carbon steel meter tube, in inches per inch-°F
= 0.00000620.

μ = dynamic viscosity, in pounds mass per foot-second
= 0.0000069.

3-C.3 Calculation Examples

3-C.3.1 METHOD 1: VOLUME FLOW RATE CALCULATION BASED ON 3.3 THROUGH 3.5

3-C.3.1.1 General

Using the given data set, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-6b:

$$Q_v = 7709.61 C_d(\text{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

Note: Since the given data contain values for the contract base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate at standard conditions will require conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 50°F.

The systematic approach to solving the volume flow rate equation above involves the calculation of the intermediate values described 3-C.3.1.2 through 3-C.3.1.7.

3-C.3.1.2 Flange-Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equations are used to calculate the coefficient of discharge, C_d(FT):

$$C_d(\text{FT}) = C_i(\text{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \qquad (3\text{-}11)$$

$$C_i(\text{FT}) = C_i(\text{CT}) + \textit{Tap Term} \qquad (3\text{-}12)$$

$$C_i(\text{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \qquad (3\text{-}13)$$

$$\textit{Tap Term} = \textit{Upstrm} + \textit{Dnstrm} \qquad (3\text{-}14)$$

$$\textit{Upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)$$

$$\textit{Dnstrm} = -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)$$

Also,

$$B = \frac{\beta^4}{1 - \beta^4} \qquad (3\text{-}17)$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\ 0.0\right) \qquad (3\text{-}18)$$

$$M_2 = \frac{2L_2}{1 - \beta} \qquad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \qquad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \qquad (3\text{-}21)$$

Where:

C_d(FT) = coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter.
C_i(CT) = coefficient of discharge at an infinite pipe Reynolds number for corner-tapped orifice meter.
C_i(FT) = coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter.

d = orifice plate bore diameter calculated at T_f, in inches.
D = meter tube internal diameter calculated at T_f, in inches.
e = Napierian constant
= 2.71828.
$L_1 = L_2$
= dimensionless correction for tap location
= N_4/D for flange taps.
N_4 = 1.0 when D is in inches.
Re_D = pipe Reynolds number.
β = diameter ratio
= d/D.

Note: For this example, M_1 is equal to 0.0, since the given meter tube diameter (D) is greater than or equal to 2.8 inches. For meter tube diameters (D) less than 2.8 inches, $M_1 = 2.8 - D$. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

3–C.3.1.3 Meter Tube Diameter, Orifice Plate Bore Diameter, and Diameter Ratio (D, d, and β)

Calculate the values of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$d = d_r[1 + \alpha_1(T_f - T_r)] \quad (3\text{-}9)$$
$$= 4.000[1 + 0.00000925(524.67 - 527.67)]$$
$$= 3.99989$$

And

$$D = D_r[1 + \alpha_2(T_f - T_r)] \quad (3\text{-}10)$$
$$= 8.071[1 + 0.00000620(524.67 - 527.67)]$$
$$= 8.07085$$

Substitute the given values of d and D at 65°F into Equation 3-8:

$$\beta = d/D \quad (3\text{-}8)$$
$$= 3.99989/8.07085$$
$$= 0.495597$$

3–C.3.1.4 Velocity of Approach Factor (E_v)

The following equation is used to calculate the velocity of approach factor:

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \quad (3\text{-}22)$$
$$= \frac{1}{\sqrt{1 - 0.495597^4}}$$
$$= 1.03160$$

3–C.3.1.5 Expansion Factor (Y)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \quad (3\text{-}32)$$

The intermediate value, x_1, is calculated as follows:

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\, P_{f_1}} \quad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-32:

$$x_1 = \frac{50.0}{(27.707)(370.0)}$$
$$= 0.00487729$$

Substitute the values for k, x_1, and β into Equation 3-32:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \quad (3\text{-}32)$$
$$= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right)$$
$$= 0.998383$$

3–C.3.1.6 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the calculation procedures necessary for determining the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the conditions given in the data set were obtained from the A.G.A. computer program that uses the calculation given in A.G.A. Transmission Measurement Committee Report No. 8. At G_r = 0.57,

Z_b = 0.997839 at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
Z_s = 0.997971 at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
Z_{f_1} = 0.951308 at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.1.7 Reynolds Number (Re_D)

The following equation is used to calculate the pipe Reynolds number:

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \quad (3\text{-}28)$$

Substituting the calculated value for D, standard conditions for P_b and T_b, a value of 0.999590 for $Z_{b_{air}}$, and the data set values for G_r and μ in Equation 3-28 produce the following:

$$Re_D = (0.0114541)\left(\frac{Q_v(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right)$$
$$= 3.32449Q_v$$

When the flow rate is not known, the Reynolds number can be developed by assuming an initial value for the flange-tapped orifice meter coefficient of discharge, C_d(FT), and iterating for the correct values, as stated in 3.4.5. The following flow rate calculation provides the initial iteration of the Reynolds number. This initial iteration is based on an assumed value for C_d(FT) of 0.60. Based on experience, from three to five iterations should provide results consistent with the requirements of Part 4.

3–C.3.1.8 Volume Flow Rate (Q_v and Q_b)

The volume flow rate can be calculated by substituting the given parameters, the intermediate calculated values, and an assumed value of 0.60 for C_d(FT) in Equation 3-6b and iterating for the final solution:

$$Q_v = 7709.61 C_d(\text{FT}) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \quad (3\text{-}6b)$$

$$= 7709.61(0.60)(1.03160)(0.998383)(3.99989)^2$$

$$\times \sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.951308)(0.570)(524.67)}}$$

$$= 614{,}033 \text{ cubic feet per hour at standard conditions}$$

[This is an estimate of the initial flow rate based on an assumed C_d(FT) of 0.60.]

Substitute the estimate of initial flow rate into the Reynolds number equation and calculate the estimated initial Reynolds number:

$$Re_D = 3.32449 Q_v$$

$$= 3.32449(614{,}033)$$

$$= 2{,}041{,}347 \text{ (initial estimate of Reynolds number)}$$

Substitute the calculated value of β into Equation 3-17:

$$B = \frac{\beta^4}{1 - \beta^4} \quad (3\text{-}17)$$

$$= \frac{0.495597^4}{1 - 0.495597^4}$$

$$= 0.0642005$$

Substitute the calculated values of β and D into Equation 3-19:

$$M_2 = \frac{2L_2}{1 - \beta} \quad (3\text{-}19)$$

$$= \frac{2}{8.07085(1 - 0.495597)}$$

$$= 0.491284$$

Substitute the calculated values of Re_D and β into Equation 3-20:

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \quad (3\text{-}20)$$

$$= \left[\frac{19{,}000(0.495597)}{2{,}041{,}347}\right]^{0.8}$$

$$= 0.0135261$$

Substitute the calculated value of Re_D into Equation 3-21:

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \quad (3\text{-}21)$$

$$= \left(\frac{10^6}{2{,}041{,}347}\right)^{0.35}$$

$$= 0.778985$$

Substitute the appropriate calculated values into Equation 3-13 to determine the C_i(CT) term of the coefficient of discharge, C_d(FT):

$$C_i(\text{CT}) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1 - \beta)M_1 \quad (3\text{-}13)$$

$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$

$$+ 0.003(1 - 0.495597)(0.0)$$

$$= 0.602414$$

Substitute the applicable calculated values into Equation 3-15 to compute the *Upstrm* term of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
Upstrm &= [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \qquad (3\text{-}15)\\
&= [0.0433 + 0.0712e^{-8.5/[illegible]} - 0.1145e^{-6.0/[illegible]}]\\
&\quad \times [1 - 0.23(0.0135269)](0.0642005)\\
&= 0.000851774
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-16 to compute the *Dnstrm* term of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
Dnstrm &= -0.0116[M_2 - 0.52M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \qquad (3\text{-}16)\\
&= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1}\\
&\quad \times [1 - 0.14(0.0134223)]\\
&= -0.00149777
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-14 to compute the *Tap Term* of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
Tap\ Term &= Upstrm + Dnstrm \qquad (3\text{-}14)\\
&= 0.000851774 + (-0.00149777)\\
&= -0.000645999
\end{aligned}
$$

Substitute the applicable calculated values into Equation 3-13 to compute the C_i(FT) term of the coefficient of discharge, C_d(FT):

$$
\begin{aligned}
C_i(\mathrm{FT}) &= C_i(\mathrm{CT}) + Tap\ Term \qquad (3\text{-}12)\\
&= 0.602414 - 0.000645999\\
&= 0.601768
\end{aligned}
$$

Substitute the value for C_i(FT) and the intermediate values into Equation 3-11 to calculate the discharge coefficient, C_d(FT):

$$
\begin{aligned}
C_d(\mathrm{FT}) &= C_i(\mathrm{FT}) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C \qquad (3\text{-}11)\\
&= 0.601768 + 0.000511\left[\frac{10^6(0.495597)}{2{,}041{,}347}\right]^{0.7}\\
&\quad + [0.0210 + 0.0049(0.0135261)](0.495597)^4(0.778985)\\
&= 0.602947 \text{ (second estimate of the coefficient of discharge)}
\end{aligned}
$$

By substituting the value of C_d(FT) into the applicable equations, the volume flow rate can be recalculated following the same process outlined in this example. The resulting volume flow rate value is as follows:

$$
\begin{aligned}
Q_v &= 617{,}049 \text{ cubic feet per hour at standard conditions}\\
&\quad [\text{based on } C_d(\mathrm{FT}) = 0.602947]
\end{aligned}
$$

And

$$
\begin{aligned}
Re_D &= 3.32449Q_v = 3.32449(617{,}049)\\
&= 2{,}051{,}373 \text{ (second estimate of Reynolds number)}
\end{aligned}
$$

Resulting in

$$
C_d(\mathrm{FT}) = 0.602944 \text{ (third estimate of coefficient of discharge)}
$$

Following the same calculation procedure for iteration of flow rate, the resulting volumetric flow rate is as follows:

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

And

$$Re_D = 3.32449Q_v = 3.32449(617{,}046)$$
$$= 2{,}051{,}363 \text{ (third estimate of Reynolds number)}$$

Resulting in

$$C_d(FT) = 0.602944 \text{ (fourth estimate of coefficient of discharge)}$$

The volume flow rate calculation based on the fourth estimate of C_d(FT) follows. As stated above, three estimates of C_d(FT) should normally provide volume flow rate calculation results that are consistent with the requirements of Part 4.

$$Q_v = 617{,}046 \text{ cubic feet per hour at standard conditions}$$
$$[\text{based on } C_d(FT) = 0.602944]$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at the given base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \quad (3\text{-}7)$$

$$= 617{,}046\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}396 \text{ cubic feet per hour at base conditions}$$

3-C.3.2 METHOD 2: VOLUME FLOW RATE CALCULATION BASED ON THE FACTOR APPROACH PRESENTED IN APPENDIX 3-B

3-C.3.2.1 General

Using the given data, the volume flow rate of natural gas, in cubic feet per hour at standard conditions, can be calculated using Equation 3-B-2, as stated in Appendix 3-B:

$$Q_v = F_n(F_c + F_{sl})Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}\sqrt{P_{f_1}h_w} \quad (3\text{-B-}2)$$

Since the given data contain values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differ from the values established in Part 3 as standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate requires conversion to the flow rate at base conditions of 14.65 pounds force per square inch absolute and 60°F.

The systematic approach to solving Equation 3-B-2 involves calculation of the individual factors as shown in 3-C.3.2.2 through 3-C.3.2.10.

3-C.3.2.2 Numeric Conversion Factor (F_n)

Equation 3-B-5b is used to calculate the numeric conversion factor:

$$F_n = 338.196E_vD^2\beta^2 \quad (3\text{-B-}5b)$$

Where

$$E_v = \frac{1}{\sqrt{1 - \beta^4}} \qquad (3\text{-}22)$$

Calculate the value of d, D, and β at a flowing temperature of 65°F from the given diameters d_r and D_r:

$$\begin{aligned} d &= d_r[1 + \alpha_1(T_f - T_r)] && (3\text{-}9) \\ &= 4.000[1 + 0.00000925(524.67 - 527.67)] \\ &= 3.99989 \end{aligned}$$

And

$$\begin{aligned} D &= D_r[1 + \alpha_2(T_f - T_r)] && (3\text{-}10) \\ &= 8.071[1 + 0.00000620(524.67 - 527.67)] \\ &= 8.07085 \end{aligned}$$

$$\begin{aligned} \beta &= d / D && (3\text{-}8) \\ &= 3.99989 / 8.07085 \\ &= 0.495597 \end{aligned}$$

Substitute the values for β and D into Equation 3-B-5:

$$\begin{aligned} F_n &= 338.196 E_v D^2 \beta^2 && (3\text{-B-}5) \\ &= 338.196 \frac{1}{\sqrt{1 - \beta^4}} D^2 \beta^2 \\ &= 338.196 \frac{1}{\sqrt{1 - (0.495597)^4}} (8.07085)^2 (0.495597)^2 \\ &= 5581.82 \end{aligned}$$

3–C.3.2.3 Flange–Tapped Orifice Meter Coefficient of Discharge [C_d(FT)]

The following equation is used to calculate the coefficient of discharge:

$$C_d(\mathrm{FT}) = F_c + F_{sl} \qquad (3\text{-B-}6)$$

Where:

$$\begin{aligned} F_c = {} & 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\ & + \left(0.0433 + 0.0712 e^{-8.5/D} - 0.1145 e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1 - \beta^4} \\ & - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right] \qquad (3\text{-B-}7) \end{aligned}$$

$$\begin{aligned} F_{sl} = {} & 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} \\ & + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \qquad (3\text{-B-}9) \end{aligned}$$

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{air}}}\right) \qquad (3\text{-}28)$$

$$B = \frac{\beta^4}{1 - \beta^4} \quad (3\text{-}17)$$

$$M_2 = \frac{2L_2}{1 - \beta} \quad (3\text{-}19)$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \quad (3\text{-}20)$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \quad (3\text{-}21)$$

Note: In this example, since the given meter tube diameter (D) is greater than 2.8 inches, Equation 3-B-7 is used to calculate the F_c term. For meter tube diameters (D) less than 2.8 inches, Equation 3-B-8 must be used to calculate the F_c term. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

Substituting the calculated values of β and D gives the following:

$$\frac{\beta^4}{1 - \beta^4} = \frac{(0.495597)^4}{1 - (0.495597)^4} = 0.0642005$$

$$\frac{2}{D(1 - \beta)} = \frac{2}{8.07085(1 - 0.495597)} = 0.491284$$

As discussed in 3.4.5, the Reynolds number (Re_D) for natural gas can be approximated using Equation 3-28. Note that the parameters of this example are within the recommended tolerances for viscosity, temperature, and specific gravity. Furthermore, 3.4.5 states that when the flow rate is not known, a more precise value for the Reynolds number can be determined through iteration of Equation 3-28 and that three to five iterations will provide results that are consistent with the requirements of Part 4. The initial assumption needed for the first iteration can come from assuming a value for $C_d(FT)$ as in the previous example or from assuming an initial Reynolds number for the pipe Reynolds number. Table 3-B-1, Appendix 3-B, provides values for pipe Reynolds numbers versus nominal pipe diameters for the purpose of initiating the iteration process. This example uses Table 3-B-1 for the initial estimate of pipe Reynolds number.

$$Re_D = 2{,}000{,}000 \quad \text{(initial assumption from Table 3-B-1)}$$

Substituting the values of Re_D and β gives the following:

$$\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} = \left[\frac{19{,}000(0.495597)}{2{,}000{,}000}\right]^{0.8} = 0.0137493$$

$$\left(\frac{10^6}{Re_D}\right)^{0.35} = \left(\frac{10^6}{2{,}000{,}000}\right)^{0.35} = 0.784584$$

Substitute the appropriate calculated values into Equation 3-B-7 to determine the orifice calculation factor, F_c:

$$F_c = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8$$
$$+ \left(0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D}\right)\left[1 - 0.23\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4}$$
$$- 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]$$
$$= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8$$
$$+ \left(0.0433 + 0.0712e^{-8.5/[illegible]} - 0.1145e^{-6.0/[illegible]}\right)[1 - 0.23(0.0137493)](0.0642005)$$
$$- 0.0116[0.491284 - 0.52(0.491284)]^{1.3}(0.495597)^{1.1}[1 - 0.14(0.0137493)]$$
$$= 0.601767$$

Substitute the applicable calculated values into Equation 3-B-9 to compute the orifice slope factor, F_{sl}:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7}$$
$$+ \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.35} \quad (3\text{-B-}9)$$
$$= 0.000511\left(\frac{1{,}000{,}000(0.4955972)}{2{,}000{,}000}\right)^{0.7}$$
$$+ [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584)$$
$$= 0.00118960$$

Substitute the values for F_c and F_{sl} in Equation 3-B-6 to calculate the discharge coefficient, C_d(FT):

$$C_d(\text{FT}) = F_c + F_{sl}$$
$$= 0.601767 + 0.00118960$$
$$= 0.602957$$

3–C.3.2.4 Expansion Factor (Y_1)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \quad (3\text{-}32)$$

The intermediate value, x_1, is calculated as follows:

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\,P_{f_1}} \quad (3\text{-}33)$$

Substitute the given values of h_w and P_{f_1} into Equation 3-33:

$$x_1 = \frac{50.0}{27.707(370.0)}$$
$$= 0.00487729$$

Substitute the values for k, x_1, and β into Equation 3-32:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\left(\frac{x_1}{k}\right) \quad (3\text{-}32)$$

$$= 1 - [0.41 + 0.35(0.495597)^4]\left(\frac{0.00487729}{1.3}\right)$$

$$= 0.998383$$

3–C.3.2.5 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the compressibility equation is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at base conditions (Z_b), standard conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the given conditions were obtained from the A.G.A. computer program, using the A.G.A. Transmission Measurement Committee Report No. 8 calculation.

At $G_r = 0.57$,

Z_b = 0.997839 at 14.65 pounds force per square inch absolute and 509.67°R (50°F)
Z_s = 0.997971 at 14.73 pounds force per square inch absolute and 519.67°R (60°F)
Z_{f_1} = 0.951308 at 370 pounds force per square inch absolute and 524.67°R (65°F)

3–C.3.2.6 Base Pressure Factor (F_{pb})

The base pressure factor is calculated using Equation 3-B-10 as follows:

$$F_{pb} = \frac{14.73}{P_b} \quad (3\text{-B-}10)$$

$$= \frac{14.73}{14.73}$$

$$= 1.00000$$

In this example, F_{pb} has been calculated for a base pressure of 14.73 pounds force per square inch absolute, instead of 14.65 pounds force per square inch absolute as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.7 Base Temperature Factor (F_{tb})

Equation 3-B-11 is used to calculate the base temperature factor:

$$F_{tb} = \frac{T_b}{519.67} \quad (3\text{-B-}11)$$

$$= \frac{519.67}{519.67}$$

$$= 1.00000$$

In this example, F_{tb} has been calculated for a base temperature of 519.67°R (60°F) instead of 509.67°R(50°F) as in the given data, and a base volume at the given base conditions has been calculated after the standard volume was determined. This procedure was necessary because of the use of the base compressibility of air ($Z_{b_{air}}$) of 0.999590 at 14.73 pounds force per square inch absolute and 60°F in the development of the numerical constant 338.196 in the F_n factor (see Appendix 3-G).

3–C.3.2.8 Flowing Temperature Factor (F_{tf})

The flowing temperature factor is calculated using Equation 3-B-12 as follows:

$$F_{tf} = \sqrt{\frac{519.67}{T_f}} \qquad (3\text{-B-12})$$

Substitute the given flowing temperature, T_f, into Equation 3-B-12:

$$\begin{aligned} F_{tf} &= \sqrt{\frac{519.67}{T_f}} \\ &= \sqrt{\frac{519.67}{524.67}} \\ &= 0.995224 \end{aligned}$$

3–C.3.2.9 Real Gas Relative Density Factor (F_{gr})

Equation 3-B-13 is used to calculate the real gas relative density factor.

$$F_{gr} = \sqrt{\frac{1}{G_r}} \qquad (3\text{-B-13})$$

Substitute the given specific gravity, G_r, into Equation 3-B-13:

$$\begin{aligned} F_{gr} &= \sqrt{\frac{1}{G_r}} \\ &= \sqrt{\frac{1}{0.570}} \\ &= 1.32453 \end{aligned}$$

3–C.3.2.10 Supercompressibility Factor (F_{pv})

As stated in the calculations in 3-C.3.1, the derivation of the equation for compressibility is presented in A.G.A. Transmission Measurement Committee Report No. 8. It is not within the scope of this example to present the procedures necessary for calculating the compressibility at standard conditions (Z_s) or at flowing conditions (Z_{f_1}).

$$\begin{aligned} Z_s &= 0.997971 \\ Z_{f_1} &= 0.951308 \end{aligned}$$

Equation 3-B-14 is used to calculate the supercompressibility factor:

$$\begin{aligned} F_{pv} &= \sqrt{\frac{Z_b}{Z_{f_1}}} \\ &= \sqrt{\frac{0.997971}{0.951308}} \\ &= 1.02423 \end{aligned}$$

3–C.3.2.11 Volume Flow Rate (Q_v)

The volume flow rate is calculated by substituting the given parameters and the intermediate calculated factors into Equation 3-B-2:

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f_1} h_w} \qquad (3\text{-B-2}) \\ &= 617{,}057 \end{aligned}$$

The calculated flow rate above is based on an initial assumed value for the Reynolds number (Re_D) of 2,000,000. For the second estimate, the value of Re_D is calculated as follows:

$$\begin{aligned} Re_D &= 0.0114588\left(\frac{Q_v P_s G_r}{\mu D T_s}\right) \\ &= 3.32449 Q_v \\ &= 3.32449(617{,}057) \\ &= 2{,}051{,}400 \text{ (second iteration)} \end{aligned}$$

By substituting the second estimate of Re_D into the applicable equations, the volume flow rate can be recalculated by following the process outlined in 3-C.3.1. The resulting volume flow rate is as follows:

$$Q_v = 617{,}013 \quad \text{(based on the second estimate of } Re_D\text{)}$$

The same calculation procedures are used to obtain the third estimate of Re_D:

$$\begin{aligned} Re_D &= 3.32449 Q_v \\ &= 3.32449(617{,}013) \\ &= 2{,}051{,}254 \text{ (third iteration)} \end{aligned}$$

The volume flow rate calculation based on the third estimate of Re_D follows. As stated above, three to five estimates of Re_D will provide calculation results that are consistent with the requirements of Part 4.

$$\begin{aligned} Q_v &= F_n (F_c + F_{sl}) Y_1 F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \sqrt{P_{f1} h_w} \\ &= (5581.82)(0.601767 + 0.00117736)(0.998383)(1.00000)(1.00000) \\ &\quad \times (0.995224)(1.32453)(1.02423)\sqrt{(370.0)(50.0)} \\ &= 617{,}044 \text{ cubic feet per hour} \end{aligned}$$

Note: The calculated volume flow rate is based on the third estimate of Re_D. The small discrepancy between the calculated volume flow rate, Q_v, in Methods 1 and 2 results from the rounding techniques used in the series of equations in the examples.

Since the given data included values for the base pressure (14.65 pounds force per square inch absolute) and temperature (50°F) that differed from the values established in Part 3 for standard conditions (14.73 pounds force per square inch absolute and 60°F), the initial calculated flow rate is the standard volume flow rate. To calculate the flow rate at base conditions (P_b = 14.65 pounds force per square inch absolute and T_b = 509.67°R), the standard volume flow rate and the appropriate values for P, T, and Z are substituted into Equation 3-7 as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{3-7}$$

$$\begin{aligned} &= 617{,}044\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right) \\ &= 608{,}394 \text{ cubic feet per hour at base conditions} \end{aligned}$$

APPENDIX 3-D—PIPE TAP ORIFICE METERING

CONTENTS

3–D.1 Symbols, Units, and Terminology

3–D.1.1 GENERAL

Some of the symbols listed in 3-D.1.2 are specific to this appendix. Unless otherwise noted, all of these symbols are dimensionless. Symbols that are used in this appendix but not listed in 3-D.1.2 are defined in 3 2.2.

3–D.1.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
C'	Orifice flow constant	—
F_b	Basic orifice factor	—
K_e	Coefficient of discharge when Reynolds number = (1,000,000d)/15	—
K_o	Coefficient of discharge for infinite Reynolds number	—
ρ	Specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F	lbm/ft^3

3–D.2 Scope

3–D.2.1 INTRODUCTION

Recent research work on orifice measurement has been restricted to flange, corner, and radius tap meters. It is recognized that a number of "pipe tap" meters continue in operation in natural gas measurement in the United States. The provisions of the second (1985) edition of Chapter 14, Section 3, that are applicable to pipe tap configurations are included in this appendix. The dimensional information, tolerances, and computation methods in this appendix are only applicable to pipe tap meters.

This appendix provides recommendations and specifications relating to the measurement of natural gas and other related hydrocarbon fluids by means of orifice meters equipped with pipe taps. It includes definitions, construction and installation specifications, and instructions for computing flow rate and volume. Also included are equations and tables that provide factors necessary to apply adjustments to the basic pipe tap orifice flow.

This appendix covers the measurement of natural gas by pipe tap orifice meters, including the primary element and the methods of calculation. It does not cover the equipment used to determine the pressure, temperature, specific gravity, and other variances that must be known for the accurate measurement of natural gas.

3–D.2.2 GENERAL

Unless specifically noted in this appendix, all information and data presented in the body of this standard—including recommendations, specifications, and symbols—are applicable to pipe tap orifice metering.

3–D.2.3 TYPE OF METER

This appendix is limited to orifice meters that have circular orifices located concentrically in the meter tube, having upstream and downstream pressure taps as specified for pipe taps.

3–D.2.4 DEFINITION OF *PIPE TAP PRESSURE MEASUREMENT*

The definition of *pipe tap pressure measurement* is based on the position of the pair of tap holes: The upstream tap center is located 2.5 times the inside pipe diameter upstream from the nearest plate face, and the downstream tap center is located 8 times the inside pipe diameter downstream from the nearest plate face (see 3-D.3.4.1).

3–D.3 Construction and Installation Specifications

3–D.3.1 BETA RATIO LIMITATIONS OF ORIFICE PLATES

The orifice-to-meter-tube (pipe) diameter ratio ($\beta = d/D$) should fall within the range from 0.20 to 0.67 inclusive. These limits, with an uncertainty as high as ±0.75 percent, may be exceeded when additional flow uncertainty is acceptable. Beta ratios that exceed the range from 0.20 to 0.67, with an uncertainty as high as ±1.5 percent, may be used; however, the flow constants for these extreme values of β are subject to higher tolerances, and the use of these extremes should be avoided.

3–D.3.2 METER TUBE SPECIFICATIONS

3–D.3.2.1 Definition

The term *meter tube* refers to the straight upstream pipe of length A or A' on the installation sketches in Part 2 (including the straightening vanes, if used), the orifice flanges or fittings, and the downstream pipe (length B on the installation sketches in Part 2) beyond the orifice. The length of upstream and downstream pipe is specified in Part 2. The tolerances for the diameter and the restrictions on the inside surface of the meter tube are specified in 3-D 3.2.4. There shall be no pipe connections within these distances other than straightening vanes, the thermometer wells specified in Part 2, and the pressure taps specified in 3-D.2.4 and Part 2.

3–D.3.2.2 Inside Surface

The sections of pipe to which the orifice flanges or fittings are attached and the adjacent pipe sections that constitute the meter tube, as defined in 3-D.3.2.1, shall comply with the following:

a. The roughness of the inside pipe walls shall not exceed 300 microinches. Carefully selected smooth commercial pipe may be used. Seamless pipe or cold drawn seamless pressure tubing may be used, provided its inside wall is smooth. Drawn-over-mandrel (DOM), electric-resistance-welded (ERW), straight-seam tubing manufactured to the requirements of ASTM A 513, T-5, may also be used. To improve smoothness inside the meter tube, the inside pipe walls may be machined, ground, or coated.
b. Grooves, scoring, pits, and ridges resulting from seams; distortion caused by welding; offsets; and other irregularities (regardless of their size) that affect the inside diameter at the points identified in Figure 3-D-1 by more than the tolerances shown are not permitted. When these tolerances are exceeded, the irregularities must be corrected.
c. The interior of the meter tube shall be kept clean and free from accumulations of contaminants, such as dirt and liquids, at all times.

3–D.3.2.3 Meter Tube Diameter

The mean inside diameter of the meter tube shall be determined as follows:

a. Measurements shall be made on at least four diameters equally spaced in a plane 1 inch upstream from the upstream face of the orifice plate. The mean (arithmetic average) of these measurements is defined as the mean meter tube diameter to be used in calculating the flow coefficient when minimum uncertainty of this variable is desired.
b. Check measurements of the upstream inside diameter of the meter tube shall be made at two or more additional cross-sections. The actual locations of the check measurements of the diameter, circumferentially and axially along the tube, are not specified. These checks should be taken at points that will indicate the maximum and minimum diameters that exist and should cover at least two pipe diameters from the face of the orifice plate or extend past the flange or fitting weld, whichever distance is greater. Check measurements are used to verify the uniformity of the upstream meter tube but do not become a part of the mean meter tube diameter.

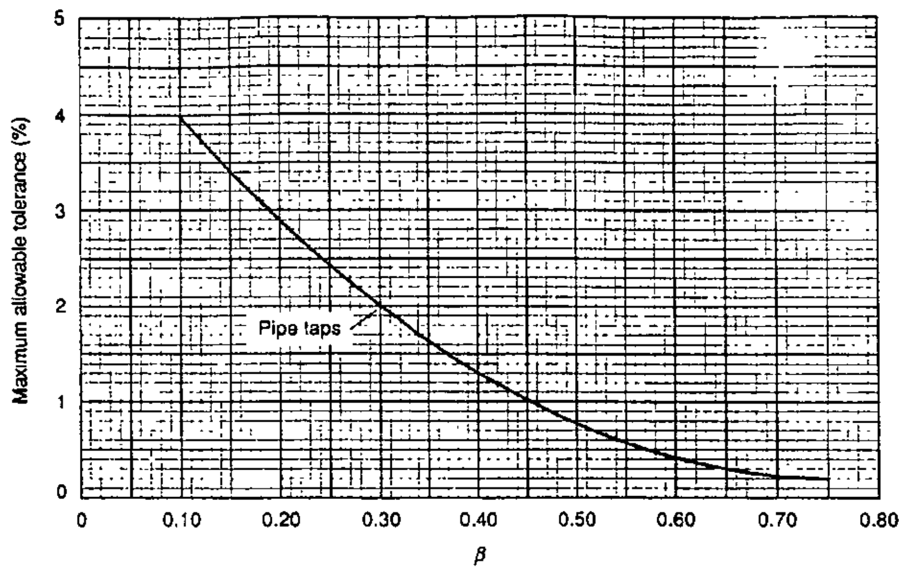


Figure 3-D-1—Maximum Percentage Allowable Meter Tube Tolerance Versus Beta Ratio

c. The inside diameter of the downstream section of the meter tube shall be measured in a plane 1 inch downstream from the downstream face of the orifice plate. Check measurements of the diameter of the downstream section of the meter tube, similar to those described in Item b above, shall be made at two additional cross-sections.

3-D.3.2.4 Tolerances and Restrictions

The tolerances for the diameter and the restrictions on the inside surface of the meter tube are as follows:

a. The difference between the maximum measured diameter and the minimum measured diameter on the inlet section shall not exceed the tolerance shown in Figure 3-D-1 as a percentage of the mean diameter defined in 3-D.3.2.3. The relationship below may be used to calculate the variance of the diameter of the upstream section of the meter tube:

$$\frac{\text{Maximum diameter} - \text{Minimum diameter}}{D} \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

b. Abrupt changes in diameter (shoulders, offsets, ridges, and so forth) shall not exist in the meter tube (see 3-D.3.2.3, Item b).

c. When Table 3-D-1 is used for flow measurement estimation, the meter tube diameter, as defined in 3-D.3.2.3, shall agree with the inside diameters listed in the tables within the tolerance shown in Figure 3-D-1.

d. Any diameter measurement in the downstream section shall not vary from the mean diameter of the meter tube, as defined in 3-D.3.2.3, by more than the tolerance shown in Figure 3-D-1. The following relationship may be used to calculate the variance of the diameter of the downstream section of the meter tube:

$$\left|\frac{\text{Any diameter} - D}{D}\right| \times 100 \leq \text{Percent tolerance in Figure 3-D-1}$$

Application of this equation doubles the tolerance for the downstream section of the meter tube.

e. The temperature at which the meter tube measurements are made should be recorded for correction to the operating conditions.

For new installations, in which the beta ratio is likely to be changed, the tolerance permitted for variations in pipe size, as shown in Figure 3-D-1, should be the same as that given for a maximum orifice plate diameter ratio (β) of 0.75.

3–D.3.2.5 Use of Table 3–D–1

If Table 3-D-1 is used for flow estimation, the mean inside diameter of the upstream section of the meter tube should be as nearly the same as the published inside diameter given in Table 3-D-1 as is possible. The inside diameters given in the table were used to calculate the constants in the table. If the mean meter tube diameter differs from the table inside diameter by an amount greater than the tolerance set forth in Figure 3-D-1 or if minimum uncertainty is desired, the mean meter tube diameter should be used to compute the orifice-to-meter-tube diameter ratio, β, as well as the flow coefficient. Other factors should be calculated for this exact value of β.

3–D.3.3 LENGTH OF PIPE PRECEDING AND FOLLOWING THE ORIFICE

The installation sketches and accompanying graphs are not duplicated in this appendix but are available in Part 2, Figures 2-5 through 2-9. The graphs show the minimum lengths of straight pipe required (expressed in nominal pipe diameters) versus beta ratio. It must be noted that when pipe taps are used, lengths A, A', and C shall be increased by two nominal pipe diameters and length B shall be increased by eight nominal pipe diameters. The lengths of straight pipe should be those required for the maximum beta ratio that may be used.

3–D.3.4 PRESSURE TAP HOLES

3–D.3.4.1 Location

Meter tubes that use pipe taps shall have the center of the upstream tap hole located 2 5 times the published or actual inside diameter from the upstream face of the orifice plate.

Table 3-D-1—Basic Orifice Factors (F_b) for Pipe Taps (All Dimensions in Inches)

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4.026
0.250	12.850	12.813	12.800	12.782	22.765	12.754	12.748	12.745	12.737	12.727	12.723
0.375	29.362	29.098	29.006	28.883	28.772	28.711	28.682	28.670	28.635	26.599	28 585
0.500	53.713	52.817	52.482	52.020	51.594	51.354	51.244	51.197	51.065	50.937	50.887
0.625	87.237	84.920	84.085	82.924	81.802	81.143	80.837	80.704	80.334	79.976	79.837
0.750	132.29	126.87	124.99	122.45	120.08	118.67	118.00	117.70	116.87	116.05	115.73
0.875	192.87	181.02	177.09	171.93	167.26	164.58	163.31	162.76	161.17	159.58	158.94
1.000	275.73	251.11	243.28	233.30	224.61	219.77	217.53	216.55	213.79	211.03	209.92
1.125	392 50	342.99	327.99	309.44	293.87	285.49	281 67	280.03	275.43	270.91	269.10
1.250		466.00	438.00	404.53	377.50	363.41	357.13	354.45	347.04	339.88	337.06
1.375			583.98	524.69	478.89	455.83	445.75	441.49	429.84	418.80	414.51
1.500				679.11	602.80	565.80	549.95	543.32	525.41	508.77	502.39
1.625					755.89	697.45	672.96	662.83	635.77	611.12	601.81
1.750					947.87	856.39	819.07	803.79	763.53	727.55	714.17
1.875						1,050.4	994.01	971.22	912.00	860.19	841.21
2.000						1,290.7	1,205.6	1,171.9	1,085.5	1,011.7	985.07
2.125							1,465.1	1,415.0	1,289.7	1,185.4	1,148.4
2.250									1,532.0	1,385.4	1,334.5
2.375									1,822.9	1,617.2	1,547.4
2.500										1,887.7	1,792.3
2.625										2,206.1	2,076.0
2.750											2,407.0

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
	4 897	5 187	5.761	6.065	7 625	7.981	8 071	9.562	10.020	10 136	11 374	11.938	12.090
0.500	50.740	50.707	50.653	50 629									
0.625	79.438	79.351	79 219	79 164									
0.750	114.81	114.62	114.32	114.20									
0 875	157.11	156.72	156.13	155 89	155.11	154.99	154.97						
1.000	206.63	205.92	204 85	204 41	203 01	202.80	202.76	202.16					
1 125	263.71	262.52	260.72	259.99	257.62	257.28	257.20	256.23	256.01	255.96			
1 250	328.73	326 87	324 03	322 87	319.10	318.57	318.44	316.90	316.57	316.49	315.82	315.57	315.51
1.375	402.07	399.32	395.09	393.34	387.63	386 81	386.63	384.30	383 80	383 68	382 67	382.31	382.22
1.500	484.21	480.26	474.21	471 70	463.40	462.20	461 93	458 53	457.80	457.64	456.17	455.65	455 53
1.625	575.75	570.19	561.74	558 25	546.62	544.93	544.54	539.73	538 70	538.47	536.40	535.67	535.49
1.750	677.39	669.69	658.09	653.34	637.52	635.20	634.67	628 05	626.63	626.30	623.46	622.46	622.22
1.875	790.00	779.49	763 79	757 41	736.36	733 25	732.53	723.63	721.72	721.28	717.45	716.12	715.79
2.000	914.59	900 39	879.40	870 95	843 36	839.31	838.37	826.66	824.14	823.56	818.51	816.75	816.32
2.125	1,052.3	1,033.4	1,005.6	994.54	958.80	953.61	952.40	937 31	934.04	933.29	926.74	924.46	923 90
2.250	1,204.7	1,179.6	1,143 2	1,128 9	1,083 0	1,076 4	1,074 9	1,055 8	1,051.6	1,050 7	1,042.3	1,039.4	1,038.7
2.375	1,373.4	1,340.5	1,293.2	1,274 6	1,216.3	1,208.0	1,206.1	1,182 3	1,177 0	1,175.8	1,165.3	1,161.7	1,160.8
2.500	1,560.5	1,517.5	1,456.5	1,432 8	1,359.2	1,348 9	1,346.5	1,316.9	1,310.5	1,309 0	1,296 0	1,291.4	1,290 3
2 625	1,768.3	1,712.6	1,634.4	1,604 3	1,512.1	1,499.3	1,496.4	1,460 1	1,452.2	1,450.4	1,434 4	1,428.8	1,427 4
2.750	1,999.9	1,928.1	1,828.3	1,790.4	1,675.4	1,659 7	1,656.1	1,611.8	1,602.3	1,600.1	1,580.7	1,573.9	1,572.2
2.875	2,258.6	2,166.5	2,040.0	1,992.3	1,849.9	1,830.7	1,826.3	1,771 6	1,761.1	1,758.4	1,735.2	1,727.0	1,725.0
3.000	2,548.6	2,431.0	2,271.2	2,211 6	2,036.1	2,012.7	2,007.4	1,942.6	1,928.8	1,925.6	1,897.9	1,888.2	1,885.8
3.125	2,875.3	2,725.3	2,524.3	2,450 2	2,234.7	2,206.4	2,200.0	2,122.2	2,105.8	2,102 0	2,069.1	2,057.6	2,054 7
3.250	3,244 9	3,054 0	2,801.9	2,710 0	2,446.6	2,412.5	2,404 8	2,311.8	2,292.3	2,287.8	2,249 0	2,235.4	2,232.1
3.375	3,665.7	3,422.4	3,106.9	2,993 4	2,672 6	2,631 7	2,622.4	2,511.7	2,488.7	2,483 4	2,437 8	2,421.9	2,418.0
3.500		3,837.6	3,443.1	3,303 1	2,913.7	2,864 8	2,853.7	2,722.5	2,695 4	2,689 2	2,635.8	2,617.2	2,612.7
3.625		4,308.1	3,814.5	3,642 4	3,171.2	3,112 8	3,099.6	2,944.5	2,912.8	2,905.5	2,843.2	2,821.6	2,816.4
3.750			4,226.4	4,014 9	3,446.1	3,376 7	3,361.1	3,178.4	3,141.3	3,132.8	3,060.3	3,035.4	3,029.3
3.875			4,685.0	4,425 2	3,739.9	3,657 7	3,639.3	3,424.6	3,381.4	3,371 5	3,287.5	3,258.8	3,251.8
4 000			5,197.9	4,878.5	4,054.3	3,957.1	3,935.3	3,683.9	3,633 6	3,622.2	3,525.2	3,492.1	3,484.0
4.250					4,751.6	4,616.7	4,586.7	4,244.2	4,176.9	4,161.7	4,033.1	3,989.6	3,979.1
4.500					5,554.8	5,369.1	5,328.1	4,865.6	4,776.3	4,756.2	4,587.4	4,530.9	4,517.3
4.750					6,485.5	6,231 3	6,175.4	5,555 6	5,438.0	5,411.6	5,191.9	5,119.1	5,101.6
5.000					7,571 6	7,224 5	7,148 8	6,323 1	6,169 4	6,135.0	5,851.1	5,757.9	5,735.6
5.250					8,850 5	8,376 6	8,274 2	7,178.8	6,979.1	6,934.6	6,570.1	6,451.7	6,423.4
5.500						9,724.0	9,585.4	8,135.5	7,877 4	7,820 2	7,354 9	7,205.3	7,169.7
5.750								9,208.8	8,876.6	8,803.3	8,212.4	8,024.4	7,979.8
6.000								10,418	9,991.5	9,898.0	9,150.7	8,915.6	8,860.0
6.250								11,786	11,240	11,121	10,179	9,886.4	9,817 5
6.500								13,344	12,644	12,493	11,309	10,946	10,860
6.750									14,231	14,038	12,552	12,103	11,998
7 000									16,035	15,790	13,925	13,371	13,242
7 250											15,446	14,763	14,605
7.500											17,135	16,295	16,102
7.750											19,021	17,986	17,750
8.000												19,861	19,572
8.250												21,948	21,594

The center of the downstream tap hole shall be located eight times the published or actual inside diameter from the downstream face of the orifice plate. Figure 3-D-2 shows the allowable tolerances. A maximum beta ratio of 0.75 should be used in the design of new installations.

3–D.3.4.2 Fabrication

Meter tubes that use pipe taps shall have a hole of the proper size drilled through the pipe wall. Proper hole sizes are listed in Table 3-D-2. The hole shall not be threaded. A fitting

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
1.500	453.93	453.79										
1.625	533.28	533.09	532.94									
1.750	619.20	618.94	618.74									
1.875	711.75	711.41	711.14									
2.000	811.01	810.55	810.21	806.73	806.59	806.42						
2.125	917.03	916.45	916.01	911.54	911.37	911.15						
2.250	1,029.9	1,029.2	1,028.6	1,022.9	1,022.7	1,022.5						
2.375	1,149.7	1,148.8	1,148.1	1,141.0	1,140.7	1,140.4	1,136.8	1,136.5	1,136.3			
2.500	1,276.6	1,275.4	1,274.5	1,265.7	1,265.4	1,265.0	1,260.6	1,260.2	1,260.0			
2.625	1,410.5	1,409.1	1,408.0	1,397.2	1,396.8	1,396.3	1,390.9	1,390.5	1,390.2			
2.750	1,551.7	1,550.0	1,548.6	1,535.5	1,535.0	1,534.4	1,527.9	1,527.4	1,527.0			
2.875	1,700.2	1,698.1	1,696.5	1,680.7	1,680.1	1,679.4	1,671.6	1,670.9	1,670.5	1,663.7		
3.000	1,856.1	1,853.6	1,851.7	1,832.8	1,832.1	1,831.2	1,821.9	1,821.1	1,820.6	1,821.6	1,812.3	1,812.1
3.125	2,019.6	2,016.6	2,014.4	1,991.9	1,991.1	1,990.0	1,979.0	1,978.1	1,977.5	1,968.0	1,967.7	1,967.4
3.250	2,190.7	2,187.2	2,184.6	2,158.1	2,157.1	2,155.8	2,142.9	2,141.8	2,141.1	2,130.0	2,129.7	2,129.3
3.375	2,369.7	2,365.6	2,362.5	2,331.4	2,330.3	2,328.8	2,313.6	2,312.3	2,311.5	2,298.6	2,298.2	2,297.8
3.500	2,556.5	2,551.7	2,548.1	2,512.0	2,510.6	2,508.9	2,491.2	2,489.8	2,488.8	2,473.9	2,473.4	2,472.9
3.625	2,751.5	2,745.9	2,741.7	2,699.8	2,698.3	2,696.3	2,675.8	2,674.1	2,673.0	2,655.8	2,655.2	2,654.7
3.750	2,954.6	2,948.2	2,943.4	2,895.1	2,893.3	2,891.0	2,867.4	2,865.5	2,864.2	2,844.4	2,843.7	2,843.1
3.875	3,166.0	3,158.7	3,153.2	3,097.8	3,095.7	3,093.1	3,066.1	3,063.8	3,062.4	3,039.7	3,039.0	3,038.3
4.000	3,385.8	3,377.5	3,371.3	3,308.1	3,305.7	3,302.7	3,271.9	3,269.3	3,267.7	3,241.8	3,241.0	3,240.2
4.250	3,851.7	3,841.0	3,832.9	3,751.8	3,748.8	3,744.9	3,705.1	3,701.8	3,699.7	3,666.5	3,665.4	3,664.4
4.500	4,353.5	4,339.9	4,329.7	4,226.9	4,223.1	4,218.2	4,167.7	4,163.5	4,160.8	4,118.7	4,117.4	4,116.1
4.750	4,893.0	4,875.9	4,863.0	4,734.3	4,729.5	4,723.4	4,660.2	4,654.9	4,651.5	4,598.9	4,597.2	4,595.5
5.000	5,472.1	5,450.6	5,434.5	5,274.7	5,268.8	5,261.3	5,183.1	5,176.6	5,172.4	5,107.3	5,105.2	5,103.1
5.250	6,092.7	6,066.0	6,046.0	5,849.2	5,842.0	5,832.8	5,737.2	5,729.2	5,724.1	5,644.3	5,641.8	5,639.3
5.500	6,757.2	6,724.3	6,699.6	6,458.8	6,450.1	6,438.8	6,323.1	6,313.4	6,307.2	6,210.4	6,207.3	6,204.3
5.750	7,468.2	7,427.8	7,397.6	7,104.7	7,094.2	7,080.6	6,941.5	6,929.8	6,922.4	6,806.0	6,802.3	6,798.7
6.000	8,228.7	8,179.4	8,142.5	7,778.2	7,775.5	7,759.3	7,593.1	7,579.2	7,570.3	7,431.5	7,427.1	7,422.8
6.250	9,041.9	8,981.9	8,937.2	8,510.8	8,495.6	8,476.2	8,278.6	8,262.2	8,251.7	8,087.5	8,082.2	8,077.1
6.500	9,911.4	9,838.9	9,784.9	9,273.8	9,255.8	9,232.7	8,999.1	8,979.7	8,967.3	8,774.3	8,768.1	8,762.1
6.750	10,842	10,754	10,689	10,079	10,058	10,031	9,755.4	9,732.6	9,718.1	9,492.6	9,485.4	9,478.4
7.000	11,837	11,732	11,654	10,929	10,903	10,871	10,548	10,522	10,505	10,243	10,234	10,226
7.250	12,902	12,777	12,684	11,824	11,795	11,757	11,380	11,349	11,329	11,026	11,016	11,007
7.500	14,044	13,894	13,784	12,768	12,733	12,689	12,250	12,214	12,191	11,841	11,830	11,819
7.750	15,269	15,091	14,959	13,763	13,722	13,671	13,161	13,119	13,093	12,691	12,678	12,666
8.000	16,583	16,372	16,216	14,811	14,764	14,704	14,113	14,065	14,036	13,575	13,560	13,546

should be fastened to the pipe at this point, and great care must be exercised to ensure that the inside of the pipe is not distorted in any way.

The diameter of the tap hole shall not be reduced within a length equal to 2.5 times the tap hole diameter as measured from the inside surface of the meter tube. If the fitting is welded to the pipe used to fabricate the meter tube, the tap hole shall not be drilled until after the welding is done.

In Table 3-D-2, the finished tap hole shall be $\pm\frac{1}{64}$ inch from the selected nominal tap hole diameter along the drilled length of the hole.

3–D.4 Computing the Flow of Natural Gas and Other Related Hydrocarbon Fluids Through Orifice Meters Equipped With Pipe Taps

3–D.4.1 GENERAL

The recommendations in 3-D.4.2 through 3-D.4.8 concerning calculations and computations are confined strictly to pipe tap orifice meters installed and operated according to the provisions of this appendix. The equations use inch-pound units and absolute values

Table 3-D-1—Continued

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18 812	19.000	19 250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	17,996	17,746	17,562	15,915	15,861	15,791	15,109	15,055	15,020	14,494	14,477	14,461
8.500	19,517	19,221	19,004	17,079	17,016	16,935	16,150	16,088	16,048	15,448	15,429	15,411
8.750	21,157	20,807	20,551	18,306	18,233	18,140	17,238	17,166	17,121	16,439	16,418	16,398
9.000	22,927	22,515	22,214	19,600	19,515	19,408	18,374	18,293	18,241	17,468	17,444	17,421
9.250	24,842	24,357	24,004	20,964	20,867	20,744	19,561	19,468	19,410	18,535	18,508	18,482
9.500	26,917	26,347	25,932	22,404	22,293	22,151	20,801	20,695	20,629	19,642	19,612	19,582
9.750	29,173	28,502	28,015	23,925	12,797	23,635	22,096	21,976	21,901	20,789	20,755	20,722
10.000	31,630	30,840	30,269	25,531	25,384	25,199	23,448	23,313	23,228	21,977	21,939	21,902
10.250	34,316	33,384	32,714	27,229	27,062	26,850	24,861	24,708	24,612	23,208	23,165	23,124
10.500		36,161	35,373	29,026	28,834	28,593	26,337	26,165	26,057	24,482	24,435	24,389
10.750				30,928	30,710	30,435	27,879	27,686	27,564	25,802	25,749	25,698
11 000				32,944	32,695	32,382	29,492	29,274	29,137	27,168	27,109	27,053
11.250				35,082	34,799	34,444	31,177	30,933	30,780	28,582	28,517	28,454
11.500				37,353	37,031	36,627	32,941	32,667	32,495	30,045	29,973	29,904
11.750				39,766	39,401	38,942	34,786	34,479	34,286	31,559	31,480	31,403
12.000				42,336	41,921	41,400	36,717	36,374	36,158	33,126	33,038	32,953
12.500				47,998	47,462	46,791	40,859	40,430	40,162	36,426	36,319	36,216
13.000				54,472	53,779	52,915	45,410	44,878	44,545	39,960	39,830	39,705
13.500							50,425	49,765	49,353	43,746	43,590	43,438
14.000							55,965	55,148	54,640	47,805	47,617	47,435
14.500							62,106	61,096	60,469	52,159	51,933	51,715
15.000							68,938	67,689	66,917	56,833	56,563	56,303
15.500							76,572	75,027	74,075	61,857	61,535	61,225
16.000								83,233	82,057	67,263	66,879	66,511
16.500										73,087	72,632	72,195
17.000										79,372	78,833	78,315
17.500										86,165	85,227	84,915
18 000										93,522	92,767	92,044
18.500										101,506	100,614	99,761
19.000										110,192	109,137	108,130
19.500										119,667	118,420	117,231
20.000										130,036	128,559	127,153

throughout. Constants and variables that have a subscript of 1 indicate upstream measurements; those that have a subscript of 2 indicate downstream measurements.

3-D.4.2 EQUATION

In the measurement of most gases, especially natural gas, the general practice is to express the flow rate in cubic feet per hour at some specified reference or base conditions of pressure and temperature (that is, in standard cubic feet per hour). To calculate the quantity of gas, the following equation shall be used:

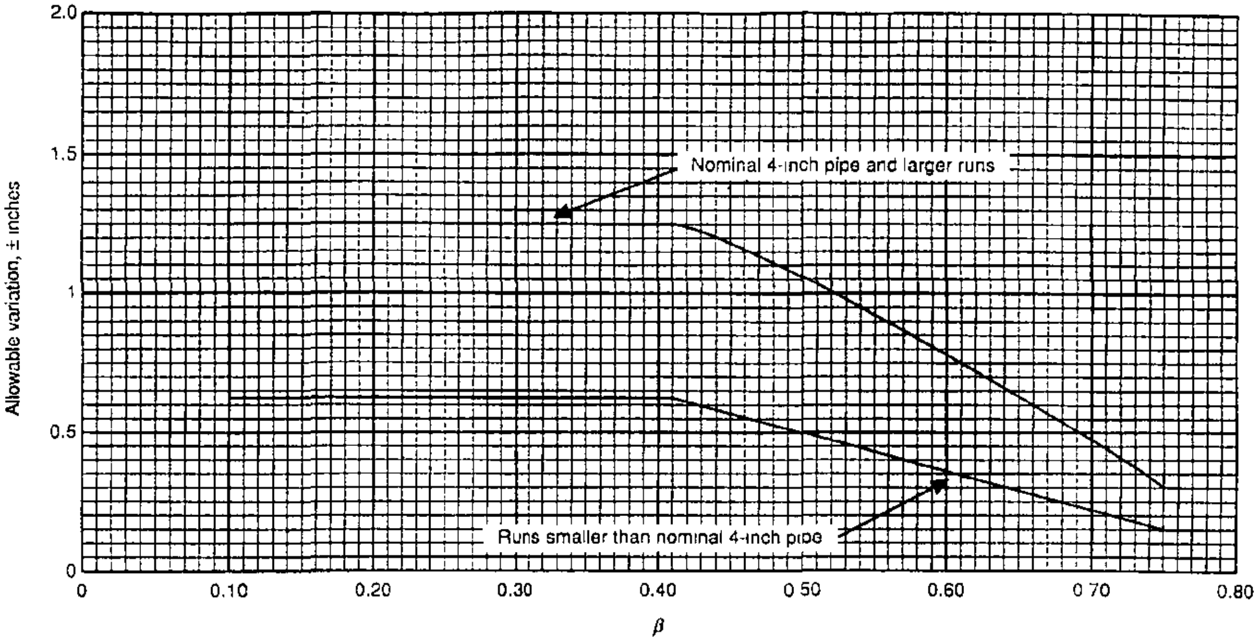
$$Q_v = C' \sqrt{h_w P_f} \qquad \text{(3-D-1)}$$

Where:

C' = orifice flow constant.
h_w = differential pressure at 60°F, in inches of water.
P_f = static pressure, in pounds force per square inch absolute.
Q_v = volume flow rate at base conditions, in standard cubic feet per hour.

3-D.4.3 ORIFICE FLOW CONSTANT (C')

The orifice flow constant, C', is defined as the rate of airflow as a real gas, in standard cubic feet per hour, when the extension, $(h_w P_f)^{0.5}$, equals unity. The orifice flow constant



Note. A maximum β ratio of 0.75 should be used in the design of new installations.

Figure 3-D-2—Allowable Variations in Pressure Tap Hole Location

should not be confused with the flow coefficient or coefficient of discharge (K). The following equation is used to calculate the orifice flow constant:

$$C' = F_b F_r Y F_{pb} F_{tb} F_{tf} F_{gr} F_{pv} \qquad (3\text{-D-2})$$

Where:

F_b = basic orifice factor.
F_{gr} = real specific gravity (relative density) factor.
F_{pb} = base pressure factor.
F_{pv} = supercompressibility factor (from A.G.A. Transmission Measurement Committee Report No. 8).
F_r = Reynolds number factor.
F_{tb} = base temperature factor.
F_{tf} = flowing temperature factor.
Y = expansion factor.

Table 3-D-2—Meter Tube Pressure Tap Holes (Dimensions in Inches)

Meter Tube Nominal Inside Diameter	Nominal Tap Hole Diameter		
	Recommended	Maximum	Minimum
<2	¼	¼	¼
2 or 3	⅜	⅜	¼
≥4	½	½	⅜

Note: The finished tap hole shall be ±1/64 inch from the selected nominal tap hole diameter along the drilled length of the hole.

The sequence of multiplication in Equation 2 is not binding; however, to duplicate the results obtained using Equation 2, the sequence of multiplication and the manner of rounding or truncation should be agreed upon and practiced. Trim factors to compensate for the type of instrumentation used, the calibration methods, and the elements of meter location are treated separately (see Appendix 3-A). These trim factors may be applied as a multiplier to C'.

The values of all the C' factors are detailed in subsequent sections of this appendix. Both equations and tabular data based on the equations are provided. The tables are to be used as an alternative to calculations by equations or to check computed results.

3–D.4.4 COEFFICIENTS OF DISCHARGE (K)

To calculate the coefficients of discharge, K, the following empirical equations are used:

$$K_o = \frac{K_e}{1 + \frac{15E}{1{,}000{,}000d}} \quad \text{(3-D-3)}$$

Where

$$K_e = 0.5925 + \frac{0.0182}{D} + \left(0.44 - \frac{0.06}{D}\right)\beta^2 + \left(0.935 + \frac{0.225}{D}\right)\beta^5 + 1.35\beta^{14} + \frac{1.43}{\sqrt{D}}(0.25 - \beta)^{\frac{5}{2}} \quad \text{(3-D-4)}$$

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + B) \quad \text{(3-D-5)}$$

$$B = \frac{875}{D} + 75 \quad \text{(3-D-6)}$$

Note: In Equation 3-D-4, the signs of some of the terms with fractional exponents become negative for some values of β. In such cases, these terms are to be neglected or their value treated as zero, and where these terms are a factor to another term, the whole product is to be treated as zero.

Where:

d = measured orifice diameter, in inches.
D = measured inside meter tube diameter, in inches.
K_e = coefficient of discharge when Reynolds number is equal to $(1{,}000{,}000d)/15$.
K_o = coefficient of discharge when Reynolds number equals infinity, which will be the minimum value for any particular orifice and meter tube size.
β = beta ratio
= d/D.

These values will be used in subsequent intermediate calculations of the orifice flow constant factors.

3–D.4.5 BASIC ORIFICE FACTOR (F_b)

To calculate the basic orifice factor, F_b, use the following equation and note the standard conditions:

$$F_b = 338.178 d^2 K_o \quad \text{(3-D-7)}$$

When

P_b (base pressure) = 14.73 pounds force per square inch absolute
Specific gravity = 1.000
T_b (base temperature) = 60°F (519.67°R)

Table 3-D-1 was developed using Equation 3-D-7 and various combinations of d and D; to use it, however, the measured inside diameter (D) of the meter tube must be within the limits specified in 3-D.3.2 and Figure 3-D-1. Table 3-D-2 may not be interpolated.

3-D.4.6 REYNOLDS NUMBER FACTOR (F_r)

To calculate the Reynolds number factor, F_r, use the following equations:

$$F_r = 1 + \frac{E}{Re_d} \quad \text{(3-D-8)}$$

$$Re_d = 220{,}858\, dF_{pv}\sqrt{\rho h_w}$$
$$\times (0.613408 - 0.152756\beta + 0.803833\beta^2 - 1.701111\beta^3 + 1.569336\beta^4) \quad \text{(3-D-9)}$$

$$\rho = \left(\frac{P_f}{14.7}\right)\left(\frac{491.67}{T_f}\right)G \quad \text{(3-D-10)}$$

Where:

G = specific gravity.
Re_d = orifice bore Reynolds number.
T_f = absolute flowing temperature, in degrees Rankine.
ρ = specific weight of a gas at 14.7 pounds force per square inch absolute and 32°F.

Table 3-D-3, which may not be interpolated, may be used to determine the value of b; this value may then be applied to Equation 3-D-11:

Table 3-D-3—b Values for Determining Reynolds Number Factor F_r for Pipe Taps (All Dimensions in Inches)

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 2 Inches			Published Inside Diameters at Nominal Pipe Size of 3 Inches				Published Inside Diameters at Nominal Pipe Size of 4 Inches			
	1.687	1.939	2.067	2.300	2.624	2.900	3.068	3.152	3.438	3.826	4 026
0.250	0.1106	0.1091	0.1087	0.1081	0.1078	0.1078	0.1079	0.1079	0.1081	0.1084	0.1085
0.375	0.0890	0 0878	0.0877	0.0879	0.0888	0.0898	0 0905	0.0908	0.0918	0.0932	0.0939
0.500	0.0758	0 0734	0.0729	0.0728	0 0737	0.0750	0 0758	0.0763	0.0778	0.0800	0 0810
0.625	0 0694	0 0647	0.0635	0.0624	0.0624	0.0634	0 0642	0.0646	0 0662	0.0685	0 0697
0.750	0.0676	0.0608	0.0586	0.0559	0.0546	0.0548	0 0552	0.0555	0.0568	0.0590	0.0602
0.875	0.0684	0.0602	0.0570	0.0528	0.0497	0.0488	0.0488	0.0489	0.0496	0.0513	0.0524
1.000	0.0702	0.0614	0.0576	0.0522	0.0473	0.0452	0.0445	0.0443	0.0443	0.0453	0.0461
1.125	0.0709	0 0635	0.0595	0.0532	0.0469	0.0435	0.0422	0.0417	0.0407	0.0408	0 0412
1.250		0.0650	0.0617	0.0552	0.0478	0.0434	0.0414	0.0406	0.0387	0 0376	0.0377
1.375			0.0629	0.0575	0.0496	0.0443	0.0418	0.0408	0.0379	0.0358	0.0353
1.500				0.0590	0.0518	0 0461	0.0431	0 0418	0 0382	0.0350	0.0341
1.625					0.0539	0.0482	0.0450	0.0435	0 0392	0.0351	0 0336
1.750					0.0554	0.0504	0.0471	0.0456	0.0408	0.0359	0.0340
1.875						0.0521	0.0492	0.0477	0.0427	0.0372	0.0349
2.000						0.0532	0.0508	0.0495	0.0448	0.0388	0.0363
2.125							0.0519	0.0509	0.0467	0 0407	0.0380
2.250									0.0483	0.0427	0.0398
2.375									0.0494	0.0445	0.0417
2.500										0 0461	0.0435
2.625										0.0472	0.0450
2.750											0.0462

Note: The b values are calculated from the following equation:

$$b = \frac{E}{12{,}835dK}$$

Where:

d = mean orifice diameter, in inches.
E = value from Equation 3-D-5.
K = value approximated from Table 3-D-4.

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}} \qquad (3\text{-D-11})$$

$$b = \frac{E}{12{,}835dK} \qquad (3\text{-D-12})$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 6 Inches				Published Inside Diameters at Nominal Pipe Size of 8 Inches			Published Inside Diameters at Nominal Pipe Size of 10 Inches			Published Inside Diameters at Nominal Pipe Size of 12 Inches		
	4.897	5.187	5.761	6.065	7.625	7.981	8.071	9.562	10.020	10.136	11.374	11.938	12.090
0.500	0.0850	0.0862	0.0883	0.0893									
0.625	0.0747	0.0762	0.0789	0.0802									
0.750	0.0655	0.0672	0.0703	0.0719									
0.875	0.0575	0.0592	0.0625	0.0642	0.0716	0.0730	0.0734						
1.000	0.0506	0.0523	0.0556	0.0573	0.0652	0.0668	0.0672	0.0728					
1.125	0.0448	0.0464	0.0495	0.0512	0.0593	0.0609	0.0613	0.0674	0.0691	0.0695			
1.250	0.0401	0.0414	0.0442	0.0458	0.0538	0.0555	0.0560	0.0624	0.0641	0.0646	0.0687	0.0704	0.0708
1.375	0.0363	0.0373	0.0397	0.0412	0.0489	0.0506	0.0511	0.0576	0.0594	0.0599	0.0643	0.0661	0.0666
1.500	0.0334	0.0341	0.0360	0.0372	0.0445	0.0462	0.0466	0.0532	0.0550	0.0555	0.0601	0.0620	0.0625
1.625	0.0313	0.0315	0.0329	0.0339	0.0405	0.0421	0.0425	0.0490	0.0509	0.0514	0.0561	0.0580	0.0585
1.750	0.0300	0.0298	0.0304	0.0311	0.0369	0.0384	0.0388	0.0452	0.0471	0.0476	0.0523	0.0543	0.0548
1.875	0.0293	0.0287	0.0285	0.0290	0.0338	0.0352	0.0355	0.0417	0.0436	0.0440	0.0488	0.0508	0.0513
2.000	0.0292	0.0281	0.0273	0.0273	0.0311	0.0323	0.0327	0.0385	0.0403	0.0407	0.0454	0.0475	0.0480
2.125	0.0297	0.0281	0.0265	0.0262	0.0288	0.0299	0.0301	0.0355	0.0373	0.0377	0.0423	0.0443	0.0449
2.250	0.0305	0.0285	0.0261	0.0256	0.0268	0.0277	0.0280	0.0329	0.0345	0.0349	0.0394	0.0414	0.0419
2.375	0.0316	0.0293	0.0262	0.0253	0.0252	0.0259	0.0261	0.0305	0.0320	0.0324	0.0367	0.0387	0.0392
2.500	0.0330	0.0304	0.0267	0.0254	0.0239	0.0244	0.0246	0.0283	0.0298	0.0301	0.0342	0.0361	0.0366
2.625	0.0345	0.0317	0.0274	0.0258	0.0230	0.0232	0.0233	0.0265	0.0277	0.0281	0.0319	0.0337	0.0342
2.750	0.0362	0.0332	0.0284	0.0265	0.0224	0.0224	0.0224	0.0248	0.0260	0.0263	0.0298	0.0316	0.0320
2.875	0.0379	0.0348	0.0295	0.0274	0.0220	0.0218	0.0218	0.0234	0.0244	0.0246	0.0279	0.0295	0.0300
3.000	0.0395	0.0364	0.0308	0.0285	0.0219	0.0214	0.0213	0.0222	0.0230	0.0233	0.0262	0.0277	0.0281
3.125	0.0410	0.0380	0.0323	0.0297	0.0220	0.0213	0.0211	0.0212	0.0218	0.0220	0.0246	0.0260	0.0264
3.250	0.0422	0.0394	0.0338	0.0311	0.0223	0.0214	0.0212	0.0205	0.0209	0.0210	0.0232	0.0245	0.0249
3.375	0.0433	0.0408	0.0353	0.0325	0.0228	0.0217	0.0214	0.0199	0.0201	0.0202	0.0220	0.0232	0.0235
3.500		0.0419	0.0367	0.0339	0.0235	0.0221	0.0218	0.0195	0.0195	0.0196	0.0210	0.0220	0.0223
3.625		0.0428	0.0381	0.0354	0.0243	0.0227	0.0224	0.0193	0.0191	0.0191	0.0200	0.0209	0.0212
3.750			0.0393	0.0367	0.0252	0.0234	0.0230	0.0192	0.0188	0.0188	0.0193	0.0200	0.0202
3.875			0.0404	0.0380	0.0262	0.0243	0.0238	0.0193	0.0187	0.0186	0.0187	0.0192	0.0194
4.000			0.0413	0.0391	0.0273	0.0252	0.0248	0.0195	0.0187	0.0186	0.0182	0.0185	0.0187
4.250					0.0297	0.0273	0.0268	0.0203	0.0192	0.0189	0.0176	0.0176	0.0177
4.500					0.0321	0.0296	0.0290	0.0215	0.0200	0.0197	0.0175	0.0172	0.0171
4.750					0.0344	0.0320	0.0314	0.0230	0.0212	0.0208	0.0178	0.0171	0.0170
5.000					0.0364	0.0342	0.0336	0.0248	0.0228	0.0223	0.0185	0.0175	0.0172
5.250					0.0381	0.0361	0.0356	0.0267	0.0245	0.0239	0.0195	0.0181	0.0178
5.500						0.0377	0.0373	0.0287	0.0263	0.0257	0.0207	0.0190	0.0186
5.750								0.0307	0.0282	0.0276	0.0221	0.0202	0.0197
6.000								0.0326	0.0302	0.0295	0.0236	0.0215	0.0210
6.250								0.0343	0.0320	0.0314	0.0253	0.0230	0.0224
6.500								0.0358	0.0336	0.0331	0.0270	0.0246	0.0240
6.750									0.0351	0.0346	0.0288	0.0262	0.0256
7.000									0.0363	0.0359	0.0304	0.0279	0.0272
7.250											0.0320	0.0295	0.0288
7.500											0.0334	0.0310	0.0304
7.750											0.0347	0.0325	0.0318
8.000												0.0338	0.0332
8.250												0.0349	0.0344

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches: 14.688	15.000	15.250	Published Inside Diameters at Nominal Pipe Size of 20 Inches: 18.812	19.000	19.250	Published Inside Diameters at Nominal Pipe Size of 24 Inches: 22.624	23.000	23.250	Published Inside Diameters at Nominal Pipe Size of 30 Inches: 28.750	29.000	29.250
1.500	0.0697	0.0705										
1.625	0.0662	0.0670	0.0676									
1.750	0.0628	0.0636	0.0642									
1.875	0.0595	0.0603	0.0610									
2.000	0.0563	0.0571	0.0578	0.0663	0.0667	0.0672						
2.125	0.0532	0.0541	0.0548	0.0635	0.0639	0.0645						
2.250	0.0503	0.0512	0.0519	0.0609	0.0613	0.0618						
2.375	0.0475	0.0485	0.0492	0.0583	0.0588	0.0593	0.0658	0.0665	0.0669			
2.500	0.0449	0.0458	0.0466	0.0558	0.0562	0.0568	0.0635	0.0642	0.0646			
2.625	0.0424	0.0433	0.0441	0.0534	0.0538	0.0544	0.0613	0.0620	0.0624			
2.750	0.0400	0.0409	0.0417	0.0510	0.0515	0.0520	0.0591	0.0598	0.0603			
2.875	0.0378	0.0387	0.0394	0.0488	0.0492	0.0498	0.0570	0.0577	0.0582	0.0669		
3.000	0.0356	0.0365	0.0372	0.0466	0.0470	0.0476	0.0549	0.0556	0.0561	0.0650	0.0654	0.0657
3.125	0.0336	0.0345	0.0352	0.0445	0.0449	0.0455	0.0529	0.0536	0.0541	0.0632	0.0636	0.0639
3.250	0.0317	0.0326	0.0333	0.0425	0.0429	0.0435	0.0509	0.0517	0.0521	0.0615	0.0618	0.0622
3.375	0.0300	0.0308	0.0314	0.0405	0.0410	0.0416	0.0490	0.0497	0.0502	0.0597	0.0601	0.0604
3.500	0.0283	0.0291	0.0297	0.0387	0.0391	0.0397	0.0471	0.0479	0.0484	0.0580	0.0584	0.0587
3.625	0.0268	0.0275	0.0281	0.0369	0.0373	0.0379	0.0453	0.0461	0.0466	0.0563	0.0567	0.0571
3.750	0.0254	0.0261	0.0267	0.0352	0.0356	0.0362	0.0436	0.0444	0.0449	0.0547	0.0551	0.0554
3.875	0.0240	0.0247	0.0253	0.0336	0.0340	0.0346	0.0419	0.0427	0.0432	0.0530	0.0534	0.0538
4.000	0.0228	0.0235	0.0240	0.0320	0.0324	0.0330	0.0403	0.0411	0.0416	0.0515	0.0519	0.0523
4.250	0.0207	0.0213	0.0217	0.0291	0.0295	0.0301	0.0372	0.0380	0.0385	0.0484	0.0488	0.0492
4.500	0.0190	0.0194	0.0198	0.0265	0.0269	0.0274	0.0343	0.0351	0.0356	0.0455	0.0459	0.0463
4.750	0.0176	0.0180	0.0183	0.0242	0.0246	0.0250	0.0316	0.0324	0.0329	0.0427	0.0431	0.0435
5.000	0.0166	0.0168	0.0171	0.0221	0.0225	0.0229	0.0292	0.0299	0.0303	0.0401	0.0405	0.0409
5.250	0.0160	0.0161	0.0162	0.0203	0.0206	0.0210	0.0269	0.0276	0.0280	0.0376	0.0380	0.0384
5.500	0.0156	0.0156	0.0156	0.0188	0.0190	0.0194	0.0248	0.0255	0.0259	0.0352	0.0356	0.0360
5.750	0.0155	0.0154	0.0153	0.0175	0.0177	0.0180	0.0230	0.0236	0.0240	0.0330	0.0334	0.0338
6.000	0.0157	0.0154	0.0153	0.0164	0.0165	0.0168	0.0213	0.0218	0.0222	0.0309	0.0313	0.0317
6.250	0.0161	0.0157	0.0154	0.0155	0.0156	0.0158	0.0197	0.0203	0.0206	0.0289	0.0293	0.0297
6.500	0.0167	0.0162	0.0159	0.0148	0.0149	0.0151	0.0184	0.0189	0.0192	0.0271	0.0274	0.0278
6.750	0.0175	0.0169	0.0164	0.0144	0.0144	0.0145	0.0172	0.0176	0.0179	0.0253	0.0257	0.0261
7.000	0.0184	0.0177	0.0172	0.0141	0.0141	0.0141	0.0162	0.0166	0.0168	0.0237	0.0241	0.0244
7.250	0.0195	0.0187	0.0181	0.0140	0.0140	0.0139	0.0153	0.0156	0.0159	0.0223	0.0226	0.0229
7.500	0.0206	0.0198	0.0191	0.0140	0.0140	0.0139	0.0146	0.0149	0.0150	0.0209	0.0212	0.0215
7.750	0.0219	0.0209	0.0202	0.0143	0.0141	0.0140	0.0140	0.0142	0.0144	0.0196	0.0199	0.0202
8.000	0.0232	0.0222	0.0214	0.0146	0.0144	0.0142	0.0136	0.0138	0.0139	0.0185	0.0187	0.0190

Table 3-D-4 must be used to determine the value of K in Equation 3-D-12. First-order linear interpolation of Table 3-D-4 is permissible. In calculating the extension for determinations of F_r, average or estimated values may be used.

3-D.4.7 EXPANSION FACTOR (Y)

3-D.4.7.1 Expansion Factor Based on Upstream Static Pressure (Y_1)

If the static pressure is measured at the upstream pressure tap, the calculations for the expansion factor, Y_1, use the following equations:

$$Y_1 = 1 - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_1}{k} \qquad \text{(3-D-13)}$$

Table 3-D-3—Continued

$$F_r = 1 + \frac{b}{\sqrt{h_w P_f}}$$

Orifice Diameter	Published Inside Diameters at Nominal Pipe Size of 16 Inches			Published Inside Diameters at Nominal Pipe Size of 20 Inches			Published Inside Diameters at Nominal Pipe Size of 24 Inches			Published Inside Diameters at Nominal Pipe Size of 30 Inches		
	14.688	15.000	15.250	18.812	19.000	19.250	22.624	23.000	23.250	28.750	29.000	29.250
8.250	0.0246	0.0235	0.0227	0.0151	0.0149	0.0146	0.0133	0.0134	0.0135	0.0174	0.0177	0.0179
8.500	0.0260	0.0249	0.0240	0.0157	0.0154	0.0151	0.0132	0.0132	0.0132	0.0165	0.0167	0.0170
8.750	0.0273	0.0262	0.0253	0.0163	0.0160	0.0157	0.0131	0.0130	0.0130	0.0156	0.0158	0.0161
9.000	0.0286	0.0276	0.0267	0.0171	0.0168	0.0163	0.0131	0.0130	0.0130	0.0149	0.0151	0.0153
9.250	0.0299	0.0288	0.0280	0.0180	0.0176	0.0171	0.0133	0.0131	0.0130	0.0142	0.0144	0.0146
9.500	0.0311	0.0301	0.0292	0.0189	0.0185	0.0180	0.0136	0.0133	0.0132	0.0137	0.0138	0.0140
9.750	0.0322	0.0312	0.0304	0.0198	0.0194	0.0189	0.0139	0.0136	0.0134	0.0132	0.0133	0.0135
10.000	0.0332	0.0323	0.0315	0.0209	0.0204	0.0198	0.0143	0.0140	0.0138	0.0129	0.0129	0.0130
10.250	0.0341	0.0333	0.0326	0.0219	0.0214	0.0208	0.0149	0.0144	0.0142	0.0126	0.0126	0.0127
10.500		0.0341	0.0335	0.0230	0.0225	0.0219	0.0154	0.0150	0.0147	0.0123	0.0124	0.0124
10.750				0.0241	0.0236	0.0229	0.0161	0.0155	0.0152	0.0122	0.0122	0.0122
11.000				0.0252	0.0247	0.0240	0.0168	0.0162	0.0158	0.0121	0.0121	0.0121
11.250				0.0263	0.0258	0.0251	0.0175	0.0169	0.0165	0.0121	0.0121	0.0121
11.500				0.0273	0.0268	0.0261	0.0183	0.0176	0.0172	0.0122	0.0122	0.0121
11.750				0.0284	0.0278	0.0272	0.0191	0.0184	0.0180	0.0124	0.0123	0.0122
12.000				0.0293	0.0288	0.0282	0.0200	0.0192	0.0188	0.0126	0.0124	0.0123
12.500				0.0312	0.0307	0.0301	0.0218	0.0210	0.0205	0.0131	0.0130	0.0128
13.000				0.0327	0.0323	0.0318	0.0236	0.0228	0.0222	0.0139	0.0137	0.0135
13.500							0.0255	0.0246	0.0240	0.0148	0.0146	0.0143
14.000							0.0272	0.0264	0.0258	0.0159	0.0156	0.0153
14.500							0.0289	0.0280	0.0275	0.0172	0.0168	0.0165
15.000							0.0304	0.0296	0.0291	0.0185	0.0181	0.0177
15.500							0.0318	0.0311	0.0306	0.0199	0.0194	0.0191
16.000								0.0323	0.0319	0.0213	0.0209	0.0205
16.500										0.0228	0.0223	0.0219
17.000										0.0242	0.0238	0.0233
17.500										0.0257	0.0252	0.0248
18.000										0.0270	0.0266	0.0261
18.500										0.0283	0.0279	0.0275
19.000										0.0296	0.0292	0.0288
19.500										0.0307	0.0303	0.0299
20.000										0.0317	0.0313	0.0310

$$x_1 = \frac{P_{f_1} - P_{f_2}}{P_{f_1}} = \frac{h_w}{27.707\, P_{f_1}} \qquad \text{(3-D-14)}$$

Where:

k = ratio of specific heats, c_p/c_v (that is, the ratio of the specific heat of a gas at constant pressure to the specific heat of the gas at constant volume at standard conditions).

x_1/k = acoustic ratio.

Table 3-D-5 was developed using Equations 3-D-13 and 3-D-14 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-5 is permissible.

The values of Y_1 are subject to an uncertainty varying from 0 when $x_1 = 0$ to ±0.5 percent when $x_1 = 0.2$. For larger values of x_1, a somewhat larger uncertainity can be expected. Equation 3-D-13 may be used over a range of $0.1 \le \beta \le 0.7$.

Table 3-D-4—Values of K to Be Used in Determining R_d for Calculation of F_c Factor

β	K (pipe)
0.100	0.607
0.125	0.608
0.150	0.611
0.175	0.614
0.200	0.618
0.225	0.623
0.250	0.628
0.275	0.634
0.300	0.641
0.325	0.650
0.350	0.658
0.375	0.668
0.400	0.680
0.425	0.692
0.450	0.707
0.475	0.724
0.500	0.742
0.525	0.763
0.550	0.785
0.575	0.810
0.600	0.837
0.625	0.869
0.650	0.904
0.675	0.943
0.700	0.988

3–D.4.7.2 Expansion Factor Based on Downstream Static Pressure (Y_2)

If the static pressure is measured at the downstream pressure tap, the calculations for the expansion factor, Y_2, use the following equations:

$$Y_2 = \sqrt{1 + x_2} - [0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\frac{x_2}{k\sqrt{1 + x_2}} \quad (3\text{-D-15})$$

$$x_2 = \frac{P_{f_1} - P_{f_2}}{P_{f_2}} = \frac{h_w}{27.707 P_{f_2}} \quad (3\text{-D-16})$$

Table 3-D-6 was developed using Equations 3-D-15 and 3-D-16 with a value of $k = 1.3$. First- or second-order linear interpolation of Table 3-D-6 is permissible.

3–D.4.8 OTHER C′ FACTORS

The remaining orifice flow constant C' factors (namely, F_{pb}, F_{tb}, F_{tf}, F_{gr}, and F_{pv}) are calculated exactly as described in the body of this standard. Computations using equations or tables are permissible with these factors when calculating the flow of natural gas through orifice meters equipped with pipe taps.

3–D.4.9 EXAMPLES

3–D.4.9.1 Example 1

Given the following physical parameters and flowing conditions, calculate the flow rate for a pipe tap orifice meter through one meter tube:

Tube diameter	2.067 in
Orifice diameter	1 in
Static pressure	500 psig (measured upstream)
Differential pressure	50 inches of water at 60°F

Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)
Flowing temperature	100°F
Base temperature	60°F
Relative density (specific gravity)	0.600
Carbon dioxide	0.5 mole percent
Nitrogen	0.5 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.483793
Extension = 160.421
Basic orifice factor (F_b) = 243.279
(from Equations 3-D-3, 3-D-4, 3-D-5, 3-D-6, and 3-D-7; or Table 3-D-2)

Table 3-D-5—Expansion Factors for Pipe Taps (Y_1): Static Pressure Taken From Upstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9990	0.9989	0.9988	0.9985	0.9984	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
0.2	0.9981	0.9979	0.9976	0.9971	0.9968	0.9964	0.9962	0.9961	0.9959	0.9957	0.9954
0.3	0.9971	0.9968	0.9964	0.9956	0.9952	0.9946	0.9944	0.9941	0.9938	0.9935	0.9931
0.4	0.9962	0.9958	0.9951	0.9942	0.9936	0.9928	0.9925	0.9921	0.9917	0.9913	0.9908
0.5	0.9952	0.9947	0.9939	0.9927	0.9919	0.9910	0.9906	0.9902	0.9897	0.9891	0.9885
0.6	0.9943	0.9937	0.9927	0.9913	0.9903	0.9892	0.9887	0.9882	0.9876	0.9870	0.9862
0.7	0.9933	0.9926	0.9915	0.9898	0.9887	0.9874	0.9869	0.9862	0.9856	0.9848	0.9840
0.8	0.9923	0.9916	0.9903	0.9883	0.9871	0.9857	0.9850	0.9843	0.9835	0.9826	0.9817
0.9	0.9914	0.9905	0.9891	0.9869	0.9855	0.9839	0.9831	0.9823	0.9814	0.9805	0.9794
1.0	0.9904	0.9895	0.9878	0.9854	0.9839	0.9821	0.9812	0.9803	0.9794	0.9783	0.9771
1.1	0.9895	0.9884	0.9866	0.9840	0.9823	0.9803	0.9794	0.9784	0.9773	0.9761	0.9748
1.2	0.9885	0.9874	0.9854	0.9825	0.9807	0.9785	0.9775	0.9764	0.9752	0.9739	0.9725
1.3	0.9876	0.9863	0.9842	0.9811	0.9791	0.9767	0.9756	0.9744	0.9732	0.9718	0.9702
1.4	0.9866	0.9853	0.9830	0.9796	0.9775	0.9749	0.9737	0.9725	0.9711	0.9696	0.9679
1.5	0.9857	0.9842	0.9818	0.9782	0.9758	0.9731	0.9719	0.9705	0.9690	0.9674	0.9656
1.6	0.9847	0.9832	0.9805	0.9767	0.9742	0.9713	0.9700	0.9685	0.9670	0.9652	0.9633
1.7	0.9837	0.9821	0.9793	0.9752	0.9726	0.9695	0.9681	0.9666	0.9649	0.9631	0.9610
1.8	0.9828	0.9811	0.9781	0.9738	0.9710	0.9677	0.9662	0.9646	0.9628	0.9609	0.9587
1.9	0.9818	0.9800	0.9769	0.9723	0.9694	0.9659	0.9643	0.9626	0.9608	0.9587	0.9565
2.0	0.9809	0.9790	0.9757	0.9709	0.9678	0.9641	0.9625	0.9607	0.9587	0.9566	0.9542
2.1	0.9799	0.9779	0.9745	0.9694	0.9662	0.9623	0.9606	0.9587	0.9566	0.9544	0.9519
2.2	0.9790	0.9768	0.9732	0.9680	0.9646	0.9605	0.9587	0.9567	0.9546	0.9522	0.9496
2.3	0.9780	0.9758	0.9720	0.9665	0.9630	0.9587	0.9568	0.9548	0.9525	0.9500	0.9473
2.4	0.9770	0.9747	0.9708	0.9650	0.9613	0.9570	0.9550	0.9528	0.9505	0.9479	0.9450
2.5	0.9761	0.9737	0.9696	0.9636	0.9597	0.9552	0.9531	0.9508	0.9484	0.9457	0.9427
2.6	0.9751	0.9726	0.9681	0.9621	0.9581	0.9534	0.9512	0.9489	0.9463	0.9435	0.9404
2.7	0.9742	0.9716	0.9672	0.9607	0.9565	0.9516	0.9493	0.9469	0.9443	0.9414	0.9381
2.8	0.9732	0.9705	0.9659	0.9592	0.9549	0.9498	0.9475	0.9449	0.9422	0.9392	0.9358
2.9	0.9723	0.9695	0.9647	0.9578	0.9533	0.9480	0.9456	0.9430	0.9401	0.9370	0.9335
3.0	0.9713	0.9684	0.9635	0.9563	0.9517	0.9462	0.9437	0.9410	0.9381	0.9348	0.9312
3.1	0.9704	0.9674	0.9623	0.9549	0.9501	0.9444	0.9418	0.9390	0.9360	0.9327	0.9290
3.2	0.9694	0.9663	0.9611	0.9534	0.9485	0.9426	0.9400	0.9371	0.9339	0.9305	0.9267
3.3	0.9684	0.9653	0.9599	0.9519	0.9469	0.9408	0.9381	0.9351	0.9319	0.9283	0.9244
3.4	0.9675	0.9642	0.9587	0.9505	0.9452	0.9390	0.9362	0.9331	0.9298	0.9261	0.9221
3.5	0.9665	0.9632	0.9574	0.9490	0.9436	0.9372	0.9343	0.9312	0.9277	0.9240	0.9198
3.6	0.9656	0.9621	0.9562	0.9476	0.9420	0.9354	0.9324	0.9292	0.9257	0.9218	0.9175
3.7	0.9646	0.9611	0.9550	0.9461	0.9404	0.9336	0.9306	0.9272	0.9236	0.9196	0.9152
3.8	0.9637	0.9600	0.9538	0.9447	0.9388	0.9318	0.9287	0.9253	0.9216	0.9175	0.9129
3.9	0.9627	0.9590	0.9526	0.9432	0.9372	0.9301	0.9263	0.9233	0.9195	0.9153	0.9106
4.0	0.9617	0.9579	0.9514	0.9417	0.9356	0.9283	0.9249	0.9213	0.9174	0.9131	0.9083

Table 3-D-5—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9976	0.9976	0.9975	0.9974	0.9973	0.9972	0.9971	0.9970	0.9969	0.9968
0.2	0.9953	0.9951	0.9950	0.9948	0.9947	0.9945	0.9943	0.9941	0.9938	0.9935
0.3	0.9929	0.9927	0.9925	0.9923	0.9920	0.9917	0.9914	0.9911	0.9907	0.9903
0.4	0.9906	0.9903	0.9900	0.9897	0.9893	0.9890	0.9986	0.9881	0.9876	0.9871
0.5	0.9882	0.9879	0.9875	0.9871	0.9867	0.9862	0.9857	0.9851	0.9845	0.9389
0.6	0.9859	0.9854	0.9850	0.9845	0.9840	0.9834	0.9828	0.9822	0.9814	0.9806
0.7	0.9835	0.9830	0.9825	0.9819	0.9813	0.9807	0.9800	0.9792	0.9784	0.9774
0.8	0.9811	0.9806	0.9800	0.9794	0.9787	0.9779	0.9771	0.9762	0.9753	0.9742
0.9	0.9788	0.9782	0.9775	0.9768	0.9760	0.9752	0.9742	0.9733	0.9722	0.9710
1.0	0.9764	0.9757	0.9750	0.9742	0.9733	0.9724	0.9714	0.9703	0.9691	0.9677
1.1	0.9741	0.9733	0.9725	0.9716	0.9707	0.9696	0.9685	0.9673	0.9660	0.9645
1.2	0.9717	0.9709	0.9700	0.9690	0.9680	0.9669	0.9657	0.9643	0.9629	0.9613
1.3	0.9694	0.9685	0.9675	0.9664	0.9653	0.9641	0.9628	0.9614	0.9598	0.9581
1.4	0.9670	0.9660	0.9650	0.9639	0.9627	0.9614	0.9599	0.9584	0.9567	0.9548
1.5	0.9646	0.9636	0.9625	0.9613	0.9600	0.9586	0.9571	0.9554	0.9536	0.9516
1.6	0.9623	0.9612	0.9600	0.9587	0.9573	0.9558	0.9542	0.9525	0.9505	0.9484
1.7	0.9599	0.9587	0.9575	0.9561	0.9547	0.9531	0.9514	0.9495	0.9474	0.9452
1.8	0.9576	0.9563	0.9550	0.9535	0.9520	0.9503	0.9485	0.9465	0.9443	0.9419
1.9	0.9552	0.9539	0.9525	0.9510	0.9493	0.9476	0.9456	0.9435	0.9412	0.9387
2.0	0.9529	0.9515	0.9500	0.9484	0.9467	0.9448	0.9428	0.9406	0.9381	0.9355
2.1	0.9505	0.9490	0.9475	0.9458	0.9440	0.9420	0.9399	0.9376	0.9351	0.9323
2.2	0.9481	0.9466	0.9450	0.9432	0.9413	0.9393	0.9371	0.9346	0.9320	0.9290
2.3	0.9458	0.9442	0.9425	0.9406	0.9387	0.9365	0.9342	0.9317	0.9289	0.9258
2.4	0.9434	0.9418	0.9400	0.9381	0.9360	0.9338	0.9313	0.9287	0.9258	0.9226
2.5	0.9411	0.9393	0.9375	0.9355	0.9333	0.9310	0.9285	0.9257	0.9227	0.9194
2.6	0.9387	0.9369	0.9350	0.9329	0.9307	0.9282	0.9256	0.9227	0.9196	0.9161
2.7	0.9364	0.9345	0.9325	0.9303	0.9280	0.9255	0.9227	0.9198	0.9165	0.9129
2.8	0.9340	0.9321	0.9300	0.9277	0.9253	0.9227	0.9199	0.9168	0.9134	0.9097
2.9	0.9316	0.9296	0.9275	0.9252	0.9227	0.9200	0.9170	0.9138	0.9103	0.9064
3.0	0.9293	0.9272	0.9250	0.9226	0.9200	0.9172	0.9142	0.9108	0.9072	0.9032
3.1	0.9269	0.9248	0.9225	0.9200	0.9173	0.9144	0.9113	0.9079	0.9041	0.9000
3.2	0.9246	0.9223	0.9200	0.9174	0.9147	0.9117	0.9084	0.9049	0.9010	0.8968
3.3	0.9222	0.9199	0.9175	0.9148	0.9120	0.9089	0.9056	0.9019	0.8979	0.8935
3.4	0.9199	0.9175	0.9150	0.9122	0.9093	0.9062	0.9027	0.8990	0.8948	0.8903
3.5	0.9175	0.9151	0.9125	0.9097	0.9067	0.9034	0.8999	0.8960	0.8918	0.8817
3.6	0.9151	0.9126	0.9100	0.9071	0.9040	0.9006	0.8970	0.8930	0.8887	0.8839
3.7	0.9128	0.9102	0.9075	0.9045	0.9013	0.8979	0.8941	0.8900	0.8856	0.8806
3.8	0.9104	0.9078	0.9050	0.9019	0.8987	0.8951	0.8913	0.8871	0.8825	0.8774
3.9	0.9081	0.9054	0.9025	0.8993	0.8960	0.8924	0.8884	0.8841	0.8794	0.8742
4.0	0.9057	0.9029	0.9000	0.8968	0.8933	0.8896	0.8856	0.8811	0.8763	0.8710

Reynolds number factor (F_r) = 1.0004
(from Equations 3-D-5, 3-D-8, 3-D-9, and 3-D-10; or Table 3-D-1 and Equation 3-D-11; or Table 3-D-3 and Equations 3-D-5, 3-D-11, and 3-D-12)
Expansion factor (Y_1) = 0.9983
(from Equations 3-D-13 and 3-D-14 or Table 3-D-4)
Base pressure factor (F_{pb}) = 1.0000
Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 0.9636
Relative density factor (F_{gr}) = 1.2910
Supercompressibility factor (F_{pv}) = 1.0299
Orifice flow constant (C') = 311.284
(from Equation 3-D-2)

Flow rate (Q_v) = 49.9367 MSCFH
= 1.19848 MMSCFD
(from Equation 3-D-1)

3-D.4.9.2 Example 2

Given the following physical parameters and flowing conditions, calculate the flow rate from a pipe tap orifice meter through one meter tube:

Tube diameter	10.020 in
Orifice diameter	4.5 in
Static pressure	350 psig (measured upstream)
Differential pressure	40 inches of water at 60°F
Base pressure	14.73 psia
Atmospheric pressure	14.7 psia (barometric)

Table 3-D-6—Expansion Factors for Pipe Taps (Y_2): Static Pressure Taken From Downstream Taps

	$\beta = d/D$										
h_w/P_{f_1}	0.1	0.2	0.3	0.4	0.45	0.50	0.52	0.54	0.56	0.58	0.60
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	1.0008	1.0008	1.0006	1.0003	1.0002	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995
0.2	1.0017	1.0015	1.0012	1.0007	1.0004	1.0000	0.9999	0.9997	0.9995	0.9993	0.9990
0.3	1.0025	1.0023	1.0018	1.0010	1.0006	1.0000	0.9998	0.9995	0.9992	0.9989	0.9986
0.4	1.0034	1.0030	1.0024	1.0014	1.0008	1.0001	0.9997	0.9994	0.9990	0.9986	0.9981
0.5	1.0042	1.0038	1.0030	1.0018	1.0010	1.0001	0.9997	0.9992	0.9988	0.9982	0.9976
0.6	1.0051	1.0045	1.0036	1.0021	1.0012	1.0001	0.9996	0.9991	0.9985	0.9979	0.9972
0.7	1.0059	1.0053	1.0041	1.0025	1.0014	1.0002	0.9996	0.9990	0.9983	0.9975	0.9967
0.8	1.0068	1.0060	1.0047	1.0028	1.0016	1.0002	0.9995	0.9988	0.9980	0.9972	0.9962
0.9	1.0076	1.0068	1.0053	1.0032	1.0018	1.0002	0.9995	0.9987	0.9978	0.9969	0.9958
1.0	1.0085	1.0075	1.0059	1.0036	1.0021	1.0003	0.9994	0.9986	0.9976	0.9965	0.9954
1.1	1.0093	1.0083	1.0065	1.0039	1.0023	1.0003	0.9994	0.9984	0.9974	0.9962	0.9949
1.2	1.0102	1.0091	1.0071	1.0043	1.0025	1.0004	0.9994	0.9983	0.9972	0.9959	0.9945
1.3	1.0110	1.0098	1.0077	1.0047	1.0027	1.0004	0.9994	0.9982	0.9970	0.9956	0.9941
1.4	1.0119	1.0106	1.0083	1.0051	1.0030	1.0004	0.9993	0.9981	0.9968	0.9953	0.9936
1.5	1.0127	1.0113	1.0089	1.0054	1.0032	1.0005	0.9993	0.9980	0.9966	0.9950	0.9932
1.6	1.0136	1.0121	1.0096	1.0058	1.0034	1.0006	0.9993	0.9979	0.9964	0.9947	0.9928
1.7	1.0144	1.0128	1.0102	1.0062	1.0036	1.0006	0.9992	0.9978	0.9962	0.9944	0.9924
1.8	1.0153	1.0136	1.0108	1.0066	1.0039	1.0007	0.9992	0.9977	0.9960	0.9941	0.9920
1.9	1.0161	1.0144	1.0114	1.0070	1.0041	1.0008	0.9992	0.9976	0.9958	0.9938	0.9916
2.0	1.0170	1.0151	1.0120	1.0073	1.0044	1.0008	0.9992	0.9975	0.9956	0.9935	0.9912
2.1	1.0178	1.0159	1.0126	1.0077	1.0046	1.0009	0.9992	0.9974	0.9954	0.9932	0.9908
2.2	1.0187	1.0167	1.0132	1.0081	1.0048	1.0010	0.9992	0.9973	0.9952	0.9929	0.9904
2.3	1.0195	1.0174	1.0138	1.0085	1.0051	1.0010	0.9992	0.9972	0.9950	0.9927	0.9900
2.4	1.0204	1.0182	1.0144	1.0089	1.0053	1.0011	0.9992	0.9971	0.9949	0.9924	0.9896
2.5	1.0212	1.0189	1.0150	1.0093	1.0056	1.0012	0.9992	0.9971	0.9947	0.9921	0.9893
2.6	1.0221	1.0197	1.0156	1.0097	1.0058	1.0013	0.9992	0.9970	0.9945	0.9919	0.9889
2.7	1.0229	1.0205	1.0162	1.0101	1.0061	1.0014	0.9992	0.9969	0.9944	0.9916	0.9885
2.8	1.0238	1.0212	1.0169	1.0104	1.0063	1.0014	0.9992	0.9968	0.9942	0.9914	0.9882
2.9	1.0246	1.0220	1.0175	1.0108	1.0066	1.0015	0.9992	0.9968	0.9941	0.9911	0.9878
3.0	1.0255	1.0228	1.0181	1.0112	1.0068	1.0016	0.9993	0.9967	0.9939	0.9908	0.9874
3.1	1.0264	1.0235	1.0187	1.0116	1.0071	1.0017	0.9993	0.9966	0.9938	0.9906	0.9871
3.2	1.0272	1.0243	1.0193	1.0120	1.0074	1.0018	0.9993	0.9966	0.9936	0.9904	0.9867
3.3	1.0280	1.0250	1.0199	1.0124	1.0076	1.0019	0.9993	0.9965	0.9935	0.9901	0.9864
3.4	1.0289	1.0258	1.0206	1.0128	1.0079	1.0020	0.9994	0.9965	0.9933	0.9899	0.9860
3.5	1.0298	1.0266	1.0212	1.0133	1.0082	1.0021	0.9994	0.9964	0.9932	0.9896	0.9857
3.6	1.0306	1.0273	1.0218	1.0137	1.0084	1.0022	0.9994	0.9964	0.9931	0.9894	0.9854
3.7	1.0314	1.0281	1.0224	1.0141	1.0087	1.0024	0.9994	0.9963	0.9929	0.9892	0.9850
3.8	1.0323	1.0289	1.0230	1.0145	1.0090	1.0025	0.9995	0.9963	0.9928	0.9890	0.9847
3.9	1.0332	1.0296	1.0237	1.0149	1.0093	1.0026	0.9995	0.9963	0.9927	0.9888	0.9844
4.0	1.0340	1.0304	1.0243	1.0153	1.0095	1.0027	0.9996	0.9962	0.9926	0.9885	0.9840

Table 3-D-6—Continued

	$\beta = d/D$									
h_w/P_{f_1}	0.61	0.62	0.63	0.64	0.65	0.66	0.67	0.68	0.69	0.70
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.9994	0.9994	0.9993	0.9992	0.9991	0.9990	0.9989	0.9988	0.9987	0.9986
0.2	0.9989	0.9988	0.9986	0.9985	0.9983	0.9981	0.9979	0.9977	0.9974	0.9972
0.3	0.9984	0.9982	0.9979	0.9977	0.9974	0.9972	0.9969	0.9965	0.9962	0.9958
0.4	0.9978	0.9976	0.9972	0.9969	0.9966	0.9962	0.9958	0.9954	0.9949	0.9944
0.5	0.9973	0.9970	0.9966	0.9962	0.9958	0.9953	0.9948	0.9942	0.9936	0.9930
0.6	0.9968	0.9964	0.9959	0.9954	0.9949	0.9944	0.9938	0.9931	0.9924	0.9916
0.7	0.9962	0.9958	0.9953	0.9947	0.9941	0.9935	0.9928	0.9920	0.9912	0.9902
0.8	0.9957	0.9952	0.9946	0.9940	0.9933	0.9926	0.9918	0.9909	0.9899	0.9889
0.9	0.9952	0.9946	0.9940	0.9932	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875
1.0	0.9947	0.9940	0.9933	0.9925	0.9917	0.9908	0.9898	0.9887	0.9875	0.9862
1.1	0.9942	0.9935	0.9927	0.9918	0.9909	0.9899	0.9888	0.9876	0.9863	0.9848
1.2	0.9937	0.9929	0.9920	0.9911	0.9901	0.9890	0.9878	0.9865	0.9851	0.9835
1.3	0.9932	0.9924	0.9914	0.9904	0.9893	0.9881	0.9868	0.9854	0.9839	0.9822
1.4	0.9928	0.9918	0.9908	0.9897	0.9885	0.9872	0.9859	0.9844	0.9827	0.9809
1.5	0.9923	0.9912	0.9902	0.9890	0.9877	0.9864	0.9849	0.9833	0.9815	0.9796
1.6	0.9918	0.9907	0.9896	0.9883	0.9870	0.9855	0.9840	0.9822	0.9804	0.9783
1.7	0.9913	0.9902	0.9889	0.9876	0.9862	0.9847	0.9830	0.9812	0.9792	0.9770
1.8	0.9908	0.9896	0.9883	0.9870	0.9854	0.9838	0.9821	0.9801	0.9780	0.9757
1.9	0.9904	0.9891	0.9877	0.9863	0.9847	0.9830	0.9811	0.9791	0.9769	0.9744
2.0	0.9899	0.9886	0.9872	0.9856	0.9840	0.9822	0.9802	0.9781	0.9757	0.9732
2.1	0.9895	0.9881	0.9866	0.9849	0.9832	0.9813	0.9793	0.9770	0.9746	0.9719
2.2	0.9890	0.9876	0.9860	0.9843	0.9825	0.9805	0.9784	0.9760	0.9734	0.9706
2.3	0.9886	0.9870	0.9854	0.9836	0.9817	0.9797	0.9774	0.9750	0.9723	0.9694
2.4	0.9881	0.9865	0.9948	0.9830	0.9810	0.9789	0.9765	0.9740	0.9712	0.9681
2.5	0.9877	0.9860	0.9842	0.9823	0.9803	0.9780	0.9756	0.9730	0.9701	0.9669
2.6	0.9873	0.9855	0.9837	0.9817	0.9796	0.9772	0.9747	0.9720	0.9690	0.9657
2.7	0.9868	0.9850	0.9831	0.9811	0.9788	0.9764	0.9738	0.9710	0.9679	0.9644
2.8	0.9864	0.9846	0.9826	0.9804	0.9781	0.9757	0.9730	0.9700	0.9668	0.9632
2.9	0.9860	0.9841	0.9820	0.9798	0.9774	0.9749	0.9721	0.9690	0.9657	0.9620
3.0	0.9856	0.9836	0.9815	0.9792	0.9767	0.9741	0.9712	0.9681	0.9646	0.9608
3.1	0.9852	0.9831	0.9809	0.9786	0.9760	0.9733	0.9703	0.9671	0.9635	0.9596
3.2	0.9848	0.9826	0.9804	0.9780	0.9754	0.9725	0.9695	0.9661	0.9625	0.9584
3.3	0.9843	0.9822	0.9798	0.9774	0.9747	0.9718	0.9686	0.9652	0.9614	0.9572
3.4	0.9839	0.9817	0.9793	0.9768	0.9740	0.9710	0.9678	0.9642	0.9603	0.9561
3.5	0.9835	0.9812	0.9788	0.9762	0.9733	0.9702	0.9669	0.9633	0.9593	0.9549
3.6	0.9832	0.9808	0.9783	0.9756	0.9727	0.9695	0.9661	0.9623	0.9582	0.9537
3.7	0.9828	0.9803	0.9778	0.9750	0.9720	0.9688	0.9652	0.9614	0.9572	0.9526
3.8	0.9824	0.9799	0.9772	0.9744	0.9713	0.9680	0.9644	0.9605	0.9562	0.9514
3.9	0.9820	0.9794	0.9767	0.9738	0.9707	0.9673	0.9636	0.9596	0.9551	0.9503
4.0	0.9816	0.9790	0.9762	0.9732	0.9700	0.9665	0.9628	0.9586	0.9541	0.9491

Flowing temperature	60°F
Base temperature	60°F
Relative density (specific gravity)	0.620
Carbon dioxide	2 mole percent
Nitrogen	3 mole percent
Differential pressure device	Bellows (recorder, dry)

The solution is calculated as follows:

Diameter ratio (β) = 0.449102
Extension = 120.781
Basic orifice factor (F_b) = 4776.30
Reynolds number factor (F_r) = 1.0002
Expansion factor (Y_1) = 0.9982
Base pressure factor (F_{pb}) = 1.0000

Base temperature factor (F_{tb}) = 1.0000
Flowing temperature factor (F_{tf}) = 1.0000
Relative density factor (F_{gr}) = 1.2700
Supercompressibility factor (F_{pv}) = 1.0273
Orifice flow constant (C') = 6221.53
Flow rate (Q_v) = 751.441 MSCFH
= 18.0346 MMSCFD

3–D.4.10 ADJUSTMENTS FOR INSTRUMENTATION CALIBRATION AND USE

Other multiplying factors may be applied to the orifice flow constant, C', as a function of the type of instrumentation applied, the method of calibration, the meter environment, or any combination of these. These factors are discussed in the body of the standard and in other appendixes to the standard. These factors are calculated and applied independently of tap type. With these factors, the orifice flow rate is calculated using the following equation:

$$Q_v = C' F_{hg} F_a F_{am} F_{wl} F_{wt} F_{pwl} F_{hgm} F_{hgt} \sqrt{h_w P_f} \qquad (3\text{-D-}17)$$

Where:

F_{hg} = mercury manometer factor (formerly F_m).
F_a = orifice thermal expansion factor.
F_{am} = correction for air over water in a water manometer during differential instrument calibration.
F_{wl} = local gravitational correction for water column calibration.
F_{wt} = water density correction (temperature or composition) for water column calibration.
F_{pwl} = local gravitational correction for deadweight tester static pressure calibration.
F_{hgm} = correction for gas column in a mercury manometer.
F_{hgt} = mercury manometer span correction for instrument temperature change after calibration.

APPENDIX 3-E—SI CONVERSIONS

This appendix contains tables of SI conversions that are pertinent to the information in this part of Chapter 14, Section 3. For additional information on SI units, refer to Chapter 15.

Table 3-E-1—Volume Reference Conditions for Custody Transfer Operations: Natural Gas Volume

Common Reference Conditions (ft^3)		To Convert From	
Pressure (psia)	Temperature (°F)	ft^3 to m^3, Multiply by	m^3 to ft^3, Multiply by
14.4	60	0.02769321	36.10994
14.65	60	0.02817399	35.49373
14.696	60	0.02826245	35.38263
14.7	60	0.02827015	35.37300
14 73	60	0.02832784	35.30096
14.7347	60	0 02833688	35.28970
14.735	60	0.02833746	35.28898
14.9	60	0.02865478	34.89819
15.025	60	0.02889517	34.60786

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa. The following methodology was used to obtain the conversion factors:

$$\left(\frac{ft^3}{m^3}\right)\left(\frac{T_{imp}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{imp}}\right) = \text{factor}$$

Table 3-E-2—Energy Reference Conditions

Unit	Used in	Definition	To Convert Btu to J, Multiply by
Btu_{IT}	International steam tables	1 Btu/lbm = 2326 J/kg	1055.056

Table 3-E-3—Heating Value Reference Conditions

Reference Conditions (ft^3)		
Pressure (psia)	Temperature (°F)	To Convert From Btu_{IT}/ft^3 to MJ/m^3, Multiply by
14.4	60	0.03809801
14.65	60	0.03744787
14.696	60	0.03733066
14.7	60	0.03732050
14.73	60	0.03724449
14.7347	60	0.03723261
14.735	60	0.03723185
14.9	60	0.03681955
15.025	60	0.03651323

Note: The following standard conditions were used for inch-pound units—a temperature of 60°F and a pressure of 14.73 pounds per square inch absolute. The following standard conditions were used for SI units—a temperature of 15°C and an absolute pressure of 101.325 kPa The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa; 1 Btu_{IT} = 1055.056 J. The following methodology was used to obtain the conversion factors:

$$\left(\frac{J}{Btu}\right)\left(\frac{MJ}{1 \times 10^6\ J}\right)\left(\frac{ft^3}{m^3}\right)\left(\frac{T_{imp}}{T_{SI}}\right)\left(\frac{P_{SI}}{P_{imp}}\right) = \text{factor}$$

APPENDIX F—HEATING VALUE CALCULATION

3–F.1 General

Heating value is a gas property evaluated on a per-unit mass basis (H_m). This property is technically termed an "ideal property" (H_m^{id}). From a practical standpoint, in mass measurement there is no difference between the "ideal" and the "real." The value is converted to a heating value per cubic foot (HV) using the following relationships. The more common convention has been applied in this appendix.

$$HV = H_m \frac{\rho_b^{id}}{Z_b} = H_m \rho_b \qquad (3\text{-F-1})$$

The value of HV is used as a factor in calculating the energy flow rate, or the total energy passing through the flow meter. HV is also used for product specifications.

It is also convenient to define the following:

$$HV = \frac{H_v^{id}}{Z_b} \qquad (3\text{-F-2})$$

3–F.2 Heating Value Symbols

Symbol	Description	Units
H_m	Heating value per pound mass	Btu/lbm
H_m^{id}	Ideal heating value per pound mass	Btu/lbm
H_v^{id}	Ideal heating value per cubic foot	Btu/ft³
HV	Gross heating value	Btu/ft³
Mr_i	Molar mass of component	lbm/lb-mol
P_b	Base pressure	lbf/in² (abs)
P_{f1}	Flowing pressure (upstream tap)	lbf/in² (abs)
P_v	Vapor pressure of water	lbf/in² (abs)
°R	Absolute temperature	—
T_b	Base temperature	°R
Z_b	Gas compressibility at base conditions (P_b, T_b)	—
ρ_b	Density at base conditions (P_b, T_b)	lbm/ft³
ρ_b^{id}	Ideal density at base conditions	lbm/ft³
ϕ	Mole fraction	%/100
ϕ_w	Mole fraction water	%/100

3–F.3 Heating Value

The gross heating value is an ideal gas property based on the ideal reaction:

$$Fuel^{id} + O_2^{id} \rightarrow CO_2^{id} + H_2O_l + SO_2^{id} \qquad (3\text{-F-3})$$

Where:

Superscript id = ideal gas.
Subscript l = liquid.

(Each fuel requires different stoichiometric coefficients.) This gross ideal heating value includes the energy obtained from the condensation of the water vapor (formed by the ideal reaction expressed in the equation) to the liquid phase.

It should be noted that the gross heating value is expressed per unit (pound mass or cubic foot) of dry gas. Although water is a product of combustion, it is not indicated on the left-hand side of Equation 3-F-3 in either the fuel or the oxygen; water is a result, not a part, of the reaction.

Heating value may be determined directly by a calorimeter, either on line or from a sample cylinder. Heating value may also be calculated from gas analysis.

3-F.4 Physical Properties

Table 3-F-1 lists physical properties of many of the compounds present in natural gas in various hydrocarbon mixtures. The data in Table 3-F-1 have been adjusted to base or standard conditions, as defined in 3.2.3.4.

Table 3-F-1 provides the best currently available data on physical properties and is taken from GPA 2145-91. These data are subject to modification yearly as additional research is accomplished. Future revisions to GPA 2145 may include updated values. The values of the most recent edition of GPA 2145 should be used. The user of the GPA tables is cautioned that the information presented in them is calculated from different base conditions and that conversion is required when the information is used with Part 3 (see 3.5.2).

3-F.5 Heating Value Determined on a Volume Basis

A calculation of a mixture's gross ideal heating value, using H_v values from Table 3-F-1 and using mole fractions of the gas composition, involves determining the heating value per unit volume of real gas. *HV* can be determined by using Equation 3-F-2 and the following relationship:

Table 3-F-1—Physical Properties of Gases at Exactly 14.73 Pounds Force per Square Inch Absolute and 60°F (See Note 1)

								Thermal Energy	
Compound	Formula	*Mr* (Note 2)	P_c (psia) (Note 3)	T_c (°R) (Note 3)	G_i (Note 4)	Ideal Density (lbm/ft³) (Note 5)	Viscosity (cp) (Note 6)	H_m^{id} (Btu/lbm) (Note 7)	H_v^{id} (Btu/ft³) (Note 7)
Hydrogen	H_2	2.0159	187.5	59.36	0.06960	0.00532	0.00871	61,025	324.9
Helium	He	4.0026	32.9	9.34	0.13820	0.01057	0.01927	0	0
Water	H_2O	18 0153	3,200.1	1,164.85	0 62202	0.04758		1,059.8	50.4
Carbon monoxide	CO	28.010	507.5	239.26	0 96711	0.07398	0.01725	4,342.4	321.3
Nitrogen	N_2	28.0134	493.1	227.16	0.96723	0.07399	0.01735	0	0
Oxygen	O_2	31.9988	731.4	278.24	1.10484	0.08452	0.02006	0	0
Hydrogen sulfide	H_2S	34.08	1306	672.12	1.17669	0.09001	0.01240	7,094.2	638.6
Argon	Ar	39.948	710.4	271.55	1.37930	0.10551	0.02201	0	0
Carbon dioxide	CO_2	44 010	1,071.0	547.42	1 51955	0 11624	0.01[illegible]39	0	0
Air (Note 8)		28.9625	546.9	238.36	1.00000	0.07650	0.0[illegible]	0	0
Methane	CH_4	16.043	667.0	343.00	0.55392	0.04237	0.0[illegible]	23,891	1,012.3
Ethane	C_2H_6	30.070	707 8	549.76	1 03824	0.07942	0[illegible]	22,333	1,773 7
Propane	C_3H_8	44.097	615.0	665.64	1.52256	0.11647	0[illegible]	21,653	2,521.9
iso-Butane	C_4H_{10}	58.123	527.9	734.13	2.00684	0.15351	0.0[illegible]	21,232	3,259.4
n-Butane	C_4H_{10}	58.123	548.8	765.25	2.00684	0.15351	0.00724	21,300	3,269.8
iso-Pentane	C_5H_{12}	72.150	490.4	828.70	2.49115	0.19057		21,043	4,010 2
n-Pentane	C_5H_{12}	72.150	488.1	845.44	2.49115	0.19057		21,085	4,018.2
n-Hexane	C_6H_{14}	86.177	439.5	911.47	2.97547	0.22762		20,943	4,766.9
n-Heptane	C_7H_{16}	100.204	397.4	970.57	3.45978	0.26466		20,839	5,515 2
n-Octane	C_8H_{18}	114.231	361.1	1,017.67	3.94410	0.30172		20,759	6,263.4
n-Nonane	C_9H_{20}	128.258	330.7	1,070.57	4.42842	0.33876		20,701	7,012 7
n-Decane	$C_{10}H_{22}$	142.285	304.6	1,111.87	4.91273	0.37581		20,651	7,760.8

Notes:
1. The source for the data in this table is Gas Processors Association 2145-91. The accuracy of the experimental numbers is estimated to be 1 in 1000; the additional figures are for calculation consistency.
2. The following molecular weights were used: C = 12.011; H = 1.00794; O = 15.9994; N = 14.0067; and S = 32.06 (1979).
3. The data in these columns come from the Thermodynamics Research Center, Texas A&M University, IUPAC and National Bureau of Standards selections.
4. The ideal relative density is the ratio of the molecular weight of the gas to that of air (Mr/Mr_a).
5. Ideal density = 0.0026413*Mr* at 60°F and 14.73 pounds force per square inch absolute.
6. The data in this column are from N. B. Vargaftik, *Tables on Thermodynamic Properties of Liquids and Gases* (2nd ed.), New York, Wiley, 1975.
7. See Equation 3-F-3. Depending on the fuel, the reaction has various stoichiometric coefficients The H_m^{id} column comes from data, whereas the H_v^{id} comes from multiplying H_m^{id} by the ideal gas density. The ideal energy released as heat is H_m^{id} multiplied by the real gas flow rate (in cubic feet per hour) divided by Z. Water has gross values for H_m^{id} and H_v^{id} (the ideal enthalpy of condensation).
8. The data in this row are from F. E. Jones, *National Bureau of Standards Journal of Research*, 1978, Volume 83, p. 491.

$$H_v^{id} = \phi_1 (H_{vi}^{id})_1 + \phi_2 (H_{vi}^{id})_2 + \ldots + \phi_n (H_{vi}^{id})_n \quad (3\text{-F-4})$$

Or

$$H_v^{id} = \sum_{i=1}^{n} \phi_i (H_{vi}^{id})_i \quad (3\text{-F-5})$$

When

$$HV = \frac{H_v^{id}}{Z_b} \quad (3\text{-F-2})$$

Where:

ϕ = mole fraction (percent/100).

3–F.6 Heating Value Determined on a Mass Basis

The question of compressibility factor disappears when the ideal heating value per pound mass is used with the mass flow rate. The following equation is applicable for using H_m and Mr values from Table 3-F-1 to calculate the heating value:

$$H_m^{id} = \frac{\phi_1 Mr_1 (H_m^{id})_1 + \phi_2 Mr_2 (H_m^{id})_2 + \ldots + \phi_n Mr_n (H_m^{id})_n}{\phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_n Mr_n} \quad (3\text{-F-6})$$

Or

$$H_m^{id} = \frac{\sum_{i=1}^{n} \phi_i Mr_i (H_m^{id})_i}{\sum_{i=1}^{n} \phi_i Mr_i} \quad (3\text{-F-7})$$

The result from Equation 3-F-7 can be converted to the gross heating value per cubic foot of real gas at base conditions by using Equation 3-F-1:

$$HV = H_m^{id} \frac{\rho_b^{id}}{Z_b} = H_m^{id} \rho_b$$

3–F.7 Heating Value of a Natural Gas Mixture Containing Water

To define heating value on a dry basis for gas containing water, the relationships in Equations 3-F-1 and 3-F-2 are valid if the mole fractions of the components are corrected for water content by using Equation 3-F-8 and the compressibility (Z) reflects the water content:

$$\phi_{i_{(corr)}} = \phi_i (1 - \phi_w) \quad (3\text{-F-8})$$

Where the gas is water saturated under flowing conditions, Raoult's law may be used to estimate the mole fraction of water:

$$\phi_w = \frac{P_w}{P_f} \quad (3\text{-F-9})$$

Where:

P_w = absolute vapor pressure of water at flowing conditions or T_f.

Therefore,

$$\phi_{i_{(corr)}} = \phi_i \left(1 - \frac{P_w}{P_f}\right) \quad (3\text{-F-10})$$

APPENDIX G—DEVELOPMENT OF CONSTANTS FOR FLOW EQUATIONS

3–G.1 General

The practical orifice flow equation used in Part 3 is given in Part 1 of this standard as Equation 1-2:

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \qquad (1\text{-}2)$$

Where:

$C_d(FT)$ = coefficient of discharge at a specific pipe Reynolds number for a flange-tapped orifice meter.
d = orifice plate bore diameter calculated at flowing temperature.
ΔP = orifice differential pressure.
E = velocity of approach factor.
q_m = mass flow rate.
$\rho_{t,p}$ = density of fluid at flowing conditions (P_f, T_f).

And

N_1 = factor that incorporates the "constants" from Equation 1-1 and the required numeric conversions, including the following:

$\frac{3.14159}{4}$ = constant in Equation 1-1.
$\sqrt{2(32.1740)}$ = constant in Equation 1-1.
$\sqrt{\frac{62.3663}{12}}$ = converts differential pressure (ΔP) from pounds force per square foot to inches of water at 60°F.
$\frac{1}{12^2}$ = converts the diameter of the orifice bore (d) from feet to inches.

Therefore,

$$N_1 = \left(\frac{3.14159}{4}\right)\sqrt{2(32.1740)}\sqrt{\frac{62.3663}{12}}\left(\frac{1}{12^2}\right)$$
$$= 0.0997424$$

(This is shown as the factor for U.S. units in Part 1, Table 1-2.)

Note: Some numeric constants do not have absolute values (for example, π and g_c). To express six significant digits accurately, the values were computed using double precision (16 significant digits). The results were then rounded to the values shown. In this appendix, for ease of understanding, the computations are shown to only six significant digits.

Mass flow can be modified to provide volume units by dividing the mass by the density at base conditions:

$$q_v = \frac{q_m}{\rho_b}$$

Where:

q_m = mass flow rate, in pounds mass per second.
q_v = volume flow rate at base conditions, in cubic feet per second.
ρ_b = density at base conditions, in pounds mass per cubic foot.

3–G.2 Symbols and Units

3–G.2.1 GENERAL

Some of the symbols and units listed below are specific to Appendix 3-B and were developed based on the customary inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in Part 1 should be used for consistent results.

3–G.2.2 SYMBOLS AND UNITS

Symbol	Description	Units/Value
$C_d(FT)$	Coefficient of discharge at a specified pipe Reynolds number for flanged-tapped orifice meter	—
d	Orifice plate bore diameter calculated at flowing temperature, T_f	in
D	Meter tube internal diameter calculated at flowing temperature, T_f	in
E_v	Velocity of approach factor	—
°F	Temperature, in degrees Fahrenheit	—
°R	Temperature, in degrees Rankine	459.67 + °F
F_n	Numeric conversion factor (see Appendix 3-B)	—
g_c	Gravitational constant	32.1740 (lbm-ft)/(lbf-sec²)
G_i	Ideal gas relative density (specific gravity)	—
G_r	Real gas relative density (specific gravity)	—
h_w	Orifice differential pressure	inches of water column at 60°F
N_1	Numeric conversion factor (see Part 1)	—
P	Pressure	lbf/in² (abs)
P_b	Base pressure	lbf/in² (abs)
P_{f_1}	Flowing pressure (upstream tap)	lbf/in² (abs)
P_s	Standard pressure	14.73 lbf/in² (abs)
Q_m	Mass flow rate per hour	lbm/hr
Q_v	Volume flow rate per hour at standard (base) conditions	ft³/hr
R	Universal gas constant	1545.35 (lbf-ft)/(lb-mol-°R)
T	Temperature	°R
T_b	Base temperature	°R
T_f	Flowing temperature	°R
T_s	Standard temperature	519.67°R
Y_1	Expansion factor (upstream tap)	—
Z_b	Compressibility at base conditions	—
$Z_{b_{air}}$	Compressibility of air at 14.73 psia and 60°F	0.999590
Z_{f_1}	Compressibility at upstream flowing conditions	—
Z_s	Compressibility at standard conditions (P_s, T_s)	—
β	Ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f	—
π	Universal constant	3.14159
ρ_b	Gas density at base conditions (P_b, T_b, and Z_b)	lbm/ft³
$\rho_{b_{air}}$	Density of air at base conditions (P_b, T_b, and Z_b)	lbm/ft³
$\rho_{t,p}$	Density at flowing conditions (P_f, T_f, and Z_f)	lbm/ft³
ρ_{t,p_1}	Density at flowing conditions (P_{f_1}, T_f, and Z_{f_1})	lbm/ft³

3–G.3 General Numeric Constant for Mass Flow

Equation 3-1 expresses flow in pounds mass per hour (Q_m) rather than pounds mass per second (q_m) and requires an additional factor, 3600, to convert from seconds to hours.

Therefore, in Equation 3-1,

$$N_1 = 0.0997424(3600)$$
$$= 359.072$$

And

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \quad (3\text{-}1)$$

Equation 3-4a is Equation 3-1 divided by ρ_b, as described above. The numeric constant is the same.

$$Q_b = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \quad (3\text{-}4a)$$

3–G.4 Numeric Constant for Mass Flow Developed From Ideal Gas Relative Density

Equation 3-2 substitutes Equation 3-55 for ρ_{t,p_1} in Equation 3-1.

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}}$$

Where:

28.9625 = molecular weight of dry air.
1545.35 = universal gas constant (R).
144 = factor to convert pressure from pounds force per square foot to pounds force per square inch.

In Equation 3-2, therefore,

$$N_1 = 359.072 \sqrt{28.9625\left(\frac{144}{1545.35}\right)}$$
$$= 589.885$$

And

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \quad (3\text{-}2)$$

3–G.5 Numeric Constant for Mass Flow Developed From Real Gas Relative Density

Equation 3-3 substitutes G_r for G_i in Equation 3-2 through the use of Equation 3-48:

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{b_{air}} Z_{f_1} T_f}}$$

And for standard conditions,

$$Z_{b_{air}} = Z_{s_{air}} = 0.999590 \text{ at } 14.73 \text{ psia and } 519.67°\text{R } (60°\text{F})$$

In Equation 3-3, therefore,

$$N_1 = \frac{589.885}{\sqrt{0.999590}}$$
$$= 590.006$$

And

$$Q_m = 590.006 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \quad (3\text{-}3)$$

3–G.6 Numeric Constant for Base Volume Developed From Ideal Gas Relative Density

The constant 359.072 in Equation 3-4a was developed in 3-G.3. Equation 3-5a substitutes Equation 3-55 for ρ_{t,p_1} and Equation 3-56 for ρ_b in Equation 3-4a.

$$Q_b = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \tag{3-4a}$$

$$Q_b = 359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}} \sqrt{\frac{Z_b R T_b}{P_b G_i (28.9625)(144)}}$$

Where:

1545.35 = universal gas constant (R).
28.9625 = molecular weight of dry air.
144 = factor to convert flowing pressure (P_{f_1}) from pounds force per square foot to pounds force per square inch.
144 = factor to convert base pressure (P_b) from pounds force per square foot to pounds force per square inch.

In Equation 3-5a, therefore,

$$N_1 = \frac{359.072 \sqrt{1545.35 \left(\frac{144}{28.9625}\right)}}{144}$$
$$= 218.573$$

And

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{3-5a}$$

For the following standard conditions:

$$P_b = P_s$$
$$= 14.73 \text{ lbf/in}^2 \text{ (abs)}$$
$$T_b = T_s$$
$$= 519.67°R\ (60°F)$$
$$Z_b = Z_s$$
$$= \text{compressibility of the gas at } P_s \text{ and } T_s$$

In Equation 3-5b,

$$N_1 = 218.573 \left(\frac{519.67}{14.73}\right)$$
$$= 7711.19$$

Therefore,

$$Q_v = 7711.19 C_d (FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{3-5b}$$

3–G.7 Numeric Constant for Base Volume Developed From Real Gas Relative Density

Equation 3-6a substitutes G_r for G_i in Equation 3-5a through the use of Equation 3-48. The inclusion of ρ_b moves this correction to the numerator:

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{Z_b Z_{b_{air}} P_{f_1} h_w}{G_r Z_{f_1} T_f}}$$

In Equation 3-6a, therefore,

$$N_1 = 218.573$$

For the following standard conditions:

$$\begin{aligned} P_b &= P_s \\ &= 14.73 \text{ lbf/in}^2 \text{ (abs)} \\ T_b &= T_s \\ &= 519.67°\text{R } (60°\text{F}) \\ Z_{b_{air}} &= Z_{s_{air}} \\ &= 0.999590 \end{aligned}$$

In Equation 3-6b,

$$\begin{aligned} N_1 &= 218.573 \left(\frac{519.67}{14.73} \right) \sqrt{0.999590} \\ &= 7709.61 \end{aligned}$$

$$Q_v = 7709.61 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \qquad (3\text{-}6b)$$

3–G.8 Numeric Constant for Standard Volume Developed From Real Gas Relative Density

In Appendix 3-B, F_n, as expressed in Equation 3-B-5, includes additional numeric ratios, as stated in Equation 3-B-1, including the following:

519.67 = base temperature at 60°F, expressed in degrees Rankine.

$\frac{1}{14.73}$ = base pressure of 14.73 pounds force per square inch absolute.

$\sqrt{\frac{1}{519.67}}$ = flowing temperature at 60°F, expressed in degrees Rankine.

$\sqrt{0.999590}$ = compressibility of air at the base pressure of 14.73 pounds force per square inch absolute and the base temperature of 519.57°R.

In Equation 3-B-5, therefore,

$$\begin{aligned} N_1 &= 218.573 \left(\frac{519.67}{14.73} \right) \sqrt{\frac{1}{519.67}} \\ &= 338.196 \end{aligned}$$

And

$$F_n = 338.196 E_v d^2 \qquad (3\text{-B-}5a)$$

Or

$$F_n = 338.196 E_v D^2 \beta^2 \qquad (3\text{-B-}5b)$$

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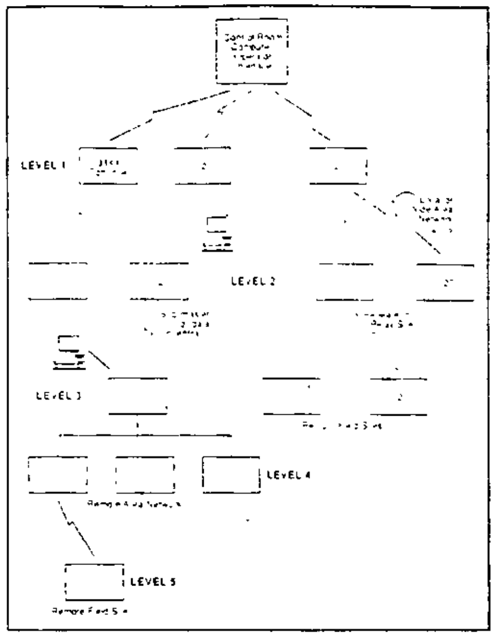
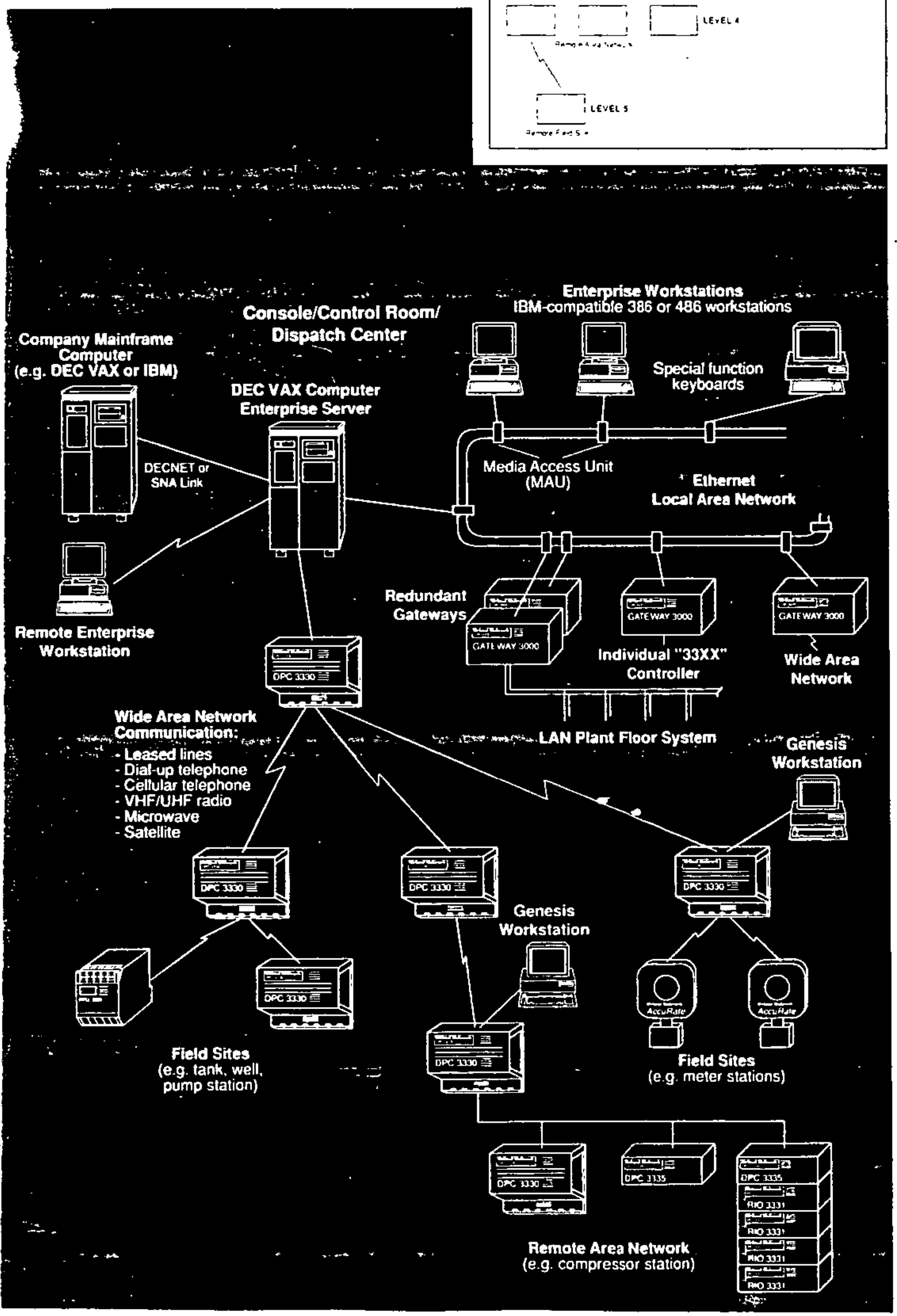
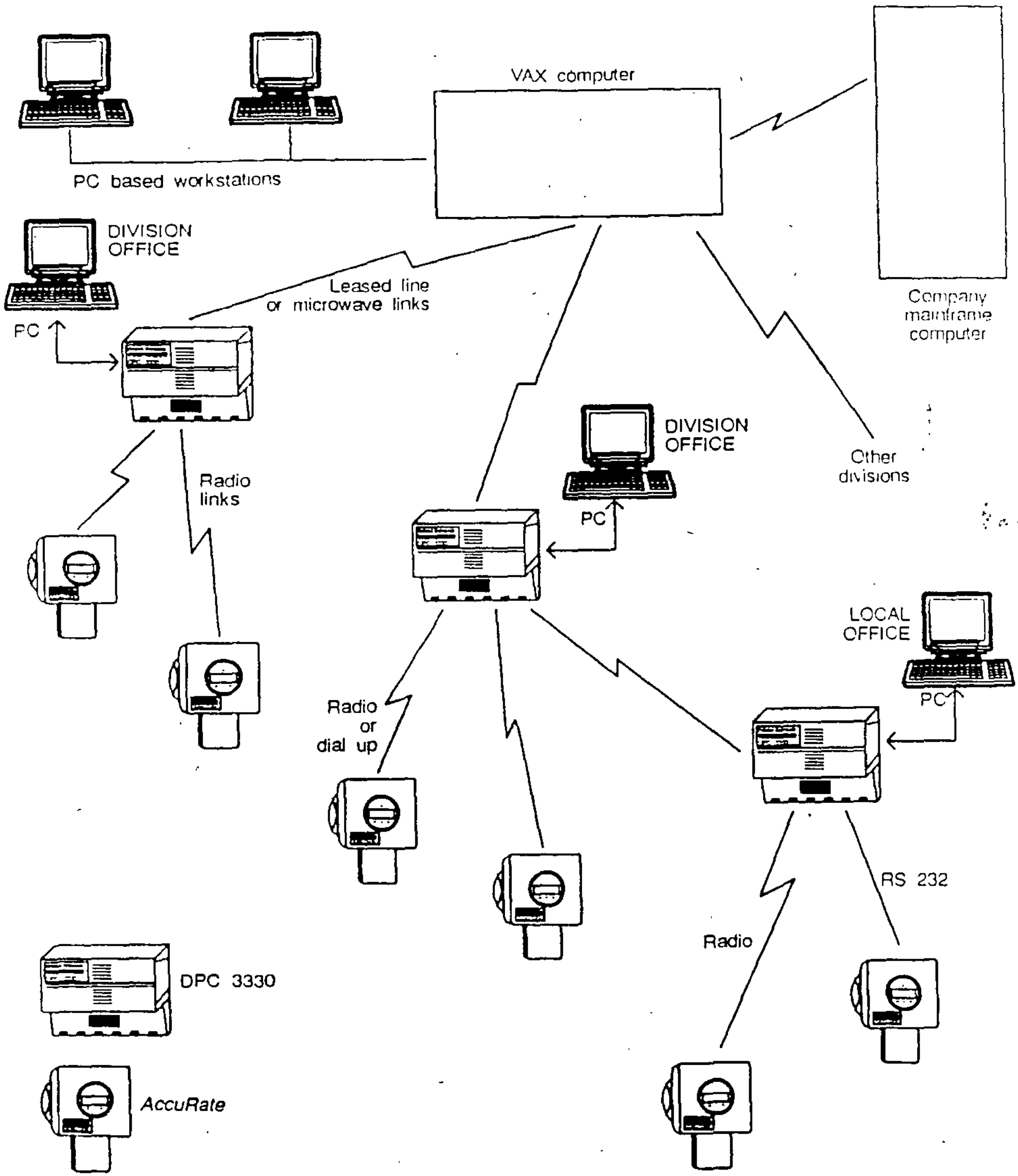


VAX-Based Enterprise System with Wide Area Network/SCADA Telecontrol System



Network Example -2-



Network 3000 Hardware

Intelligent distributed controllers for a real world environment.

Our "33XX" series controllers are designed to be your hardest workers Equally appropriate on a pipeline, water tank or plant floor, they offer maximum price/performance and are effective in configurations of a few to few thousand I/O points.

Every "33XX" controller provides a wide variety of process I/O - analog inputs/outputs, discrete inputs/outputs, high-speed pulse inputs and low level (millivolt, RTD, thermocouple) inputs — allowing them to wire into any instrumen-tation system

To satisfy every application, we offer modular wall-mounting and rack-mounting components, local and [illegible]te I/O terminations, stand-up or NEMA 4 cabinets and single or redundant hardware.

Every "33XX" controller features the following.
- 16-bit 80C186 microprocessor
- Optional math coprocessor
- Up to 512K EPROM and 128K RAM
- Optional RAM expansion
- Up to 4 serial RS 423/485 ports standard, rates to 1M baud
- Private and switched telephone line, radio, coaxial cable or fiber optic communications
- Modular process I/O
- Class I, Division 2, Groups A-D certified
- C37 90 surge protection
- ACCOL II modular, high-level languag[e]
- Optional LCD with keypad (DPC 333[0] DPC 3335)

The DPC 3330

Designed for those low I/O count applications for which the budget is limited but capability cannot be compromised. The DPC 3330 is the choice when that PLC, RTU, batch controller or flow computer you've budgeted won't do the job.
- Up to 96 DI/DO or 48 AI/AO or a combination
- Low power consumption
- Wide operating range: -40°C to +70°C

The DPC 3335

An extremely space-efficient, 5 1/4" high rack-mounting version of the DPC 3330. Use it alone for a unit process or multi-drop up to ten RIO 3331 racks for large DCS installations.
- Up to 80 DI/DO or 40 AI/AO or a combination
- With RIO 3331 racks: Up to 880 DI/DO or 440 AI/AO or a combination
- Hot replacement of I/O cards

The GW-3000 (Gateway 3000)

Bristol Babcock's 80386-based communications controller which interfaces our DPC "33XX" controllers to our Ethernet LAN. The GW-3000 also has redundancy capability (optional).

The RSP 3332 Redundancy Switch Panel

Used with dual DPC 3330 or DPC 3335 units when hot standby redundancy is required. The main processor, communication and power supply units are redundant; I/O is provided by RIO 3331 racks.
- Triple redundant switchover logic
- Two-to-one voting scheme
- Manual switchover from front panel

The RIO 3331

An intelligent I/O rack used to expand the I/O for the DPC 3330 as well as the DPC 3335. Like the DPC 3335, the RIO 3331 is contained in a low-profile 5 1/4" rack.
- Up to 80 DI/DO or 40 AI/AO or a combination
- Up to 10 RIO 3331 racks per DPC 3330 or DPC 3335 main unit
- 1M baud communication with main unit
- Hot replacement of I/O cards

Additional Network 3000 Products

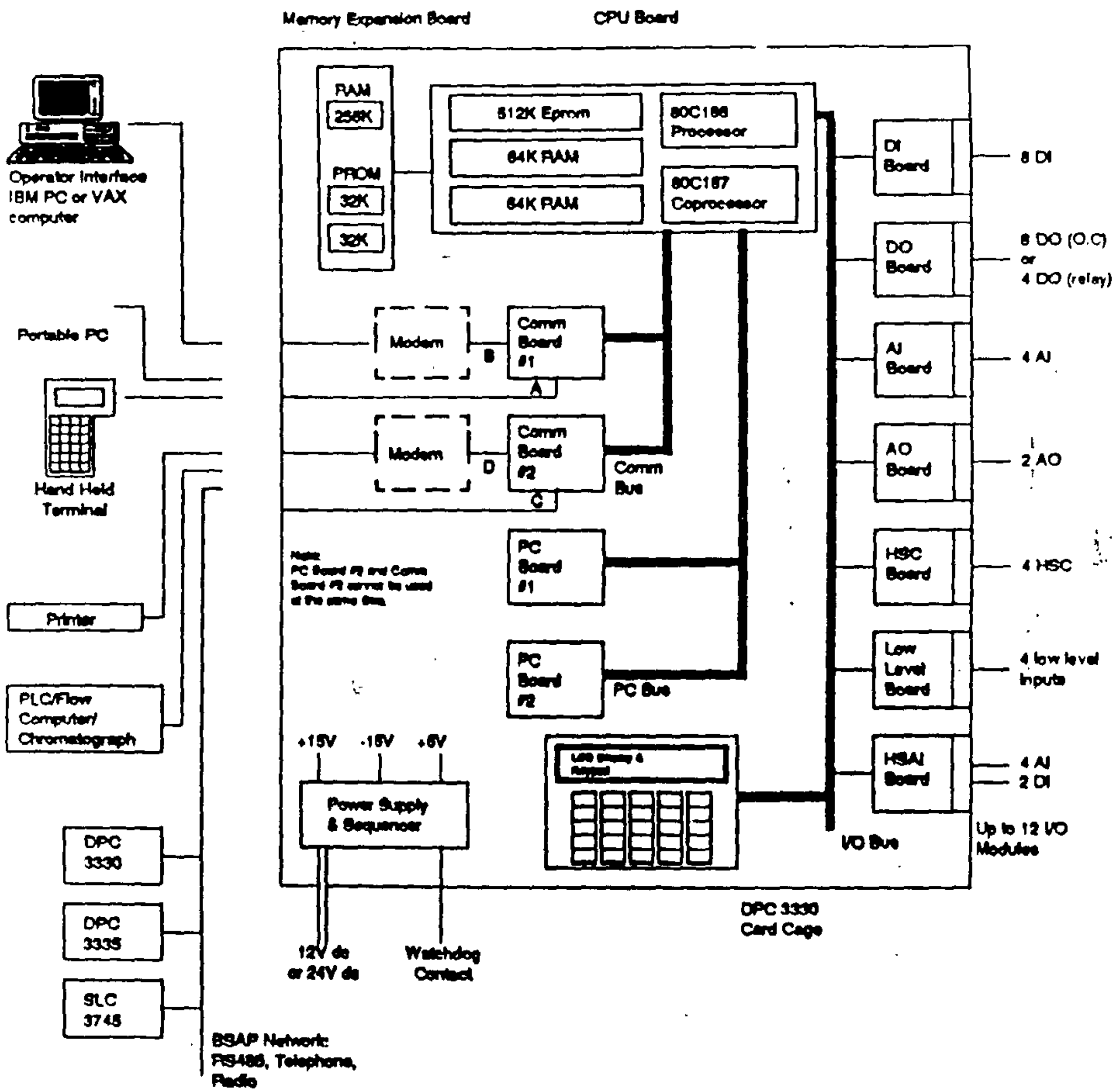
AccuRate Flow Computer

Applies full "33XX" capability to gas measurement and control. It satisfies advanced applications such as custody transfer.
- Class I, Division I rated
- Integrated package with solar panel and battery
- AGA 3, 5,7, 8, NX-19 calculations
- Flow/pressure control
- Network communication
- Audit trail and historical database
- Configuration via laptop computer

The RTU 3301 family of small, low I/O point RTUs

Provides economical gathering of remote data such as tank levels and status inputs. Models include:
- Analog input - 1 AI, 1 DI, 2 DO
- Discrete - 15 DIO
- Analog output - 1 AO, 3 DI
- Frequency input - 1 FI, 1 DI
- Thermocouple - 1 TI, 2 DI, 3 DO
- RTD - 1 RTD, 1 DI

BLOCK DIAGRAM



DPC 3330 with M & R Software

Why use a flow computer when you can take control of your M&R station? The DPC 3330 allows you to custom program your measurement and control system to meet the specific requirements of any M&R station. Don't want to program? Then use one of our standard M&R software packages that offer a comprehensive assortment of functions.

Unlike most flow computers, the DPC 3330 is not an RTU adapted to gas measurement. Instead, it is an intelligent distributed process controller which has been applied to a wide range of tasks, including pipeline compressor automation as well as measurement.

The Package

The DPC 3330 employs a modular, low power-consuming design that makes extensive use of CMOS electronics. Full sixteen-bit architecture provides the performance necessary for today's intensive applications.

The process I/O subsystem is completely modular, allowing the user to tailor the I/O to specific locations. Two package sizes — one accommodating six I/O modules, the other, twelve — are available. The modules can be used in any combination. All include surge protection meeting the IEEE-472 test. The following are available:

- Four analog inputs (4-20 mA/ 1-5V or 0-10V)
- Two analog outputs (4-20 mA/ 1-5V or 0-10V)
- Eight discrete inputs
- Eight discrete outputs (open collector)
- Four discrete outputs (relay)
- Four counter/frequency inputs (0-10 KHz)
- Four low level inputs (RTD, Thermocouple)

The DPC 3330 operates over −40°C to +70°C temperature range. It is FM-certified for Class I, Division 2 locations and is available in an optional NEMA IV enclosure. This low-cost platform is designed for ease in installation and maximum serviceability.

Communication

The communication capabilities of the DPC 3330 are very extensive:

- Four serial communication ports
- Up to two built-in modems (private-line or dial-up)
- Modems are radio-compatible
- Fully programmable ASCII communication with hand-held terminals, printers, computers, chromatographs, etc.
- Network communication as both a master and slave
- Multip[illegible] built-in communication protoc[illegible] including Bristol Babco[illegible] Modbus (ASCII, binary, and flow computer variations), Teledyne Geotech, and more
- Up to two ports can connect to a 187.5K baud LAN
- Built-in LCD/keypad, for local operations, does not use a serial port

A full complement of peripherals and networks can be connected, simultaneously. For example, a hand-held terminal, printer, Bristol Babcock network and another network can all be used at once.

Software

The DPC 3330 uses ACCOL II™, Bristol Babcock's high-level measurement and control language. Programming is as easy as filling in blanks on menu displays. ACCOL II features:

- Forty software modules, including:
  - Gas Flow Modules — AGA3, AGA5, AGA7, NX19, AGA8, and characterizer
  - Control Modules — averager, comparator, integrator, multiplexer, PID controller, sequencer, timer
  - Full math calculator (twenty-three functions)
  - Audit trail
  - Data storage
  - ASCII communication, network communication
  - Display/keypad
- Multitasking: Up to 127 tasks per DPC 3330
- Minimum task execution interval: 0.02 sec
- Twelve programming statements
- Advanced debugging and documentation utilities

Standard M&R Software Features

- Two preconfigured packages allow immediate start-up without programming
- Three-run package, for six I/O module DPC 3330
- Six-run package, for twelve I/O module DPC 3330
- Three-run package available on PROM
- AGA3/NX19, AGA5, AGA7 per run
- All calculations done once per second
- Run switching
- Auto-selector flow/pressure controller
- Stacked transmitter on primary run
- Input linearization
- Thirty-five day storage
- Audit trail
- Overrides on all inputs
- Sampler trigger
- Communications ports
  - Hand-held terminal/data storage device
  - Printer (with preconfigured reports) or a customer ASCII port
  - Chromatograph
  - Bristol Babcock network

Since the M&R software is written in ACCOL II, it can be modified, by the user, for specific requirements.

Bristol Babcock

Bristol Babcock is a leader in instrumentation used in the gas industry and has been in measurement for over 100 years. We were a pioneer in mechanical, analog, and digital flow computers.

Today, we offer not only a complete product line, but also a full complement of services to meet your needs. Our application services, systems engineering, and radio communication services are available to help you with any size project. Please call us to discuss your requirements.

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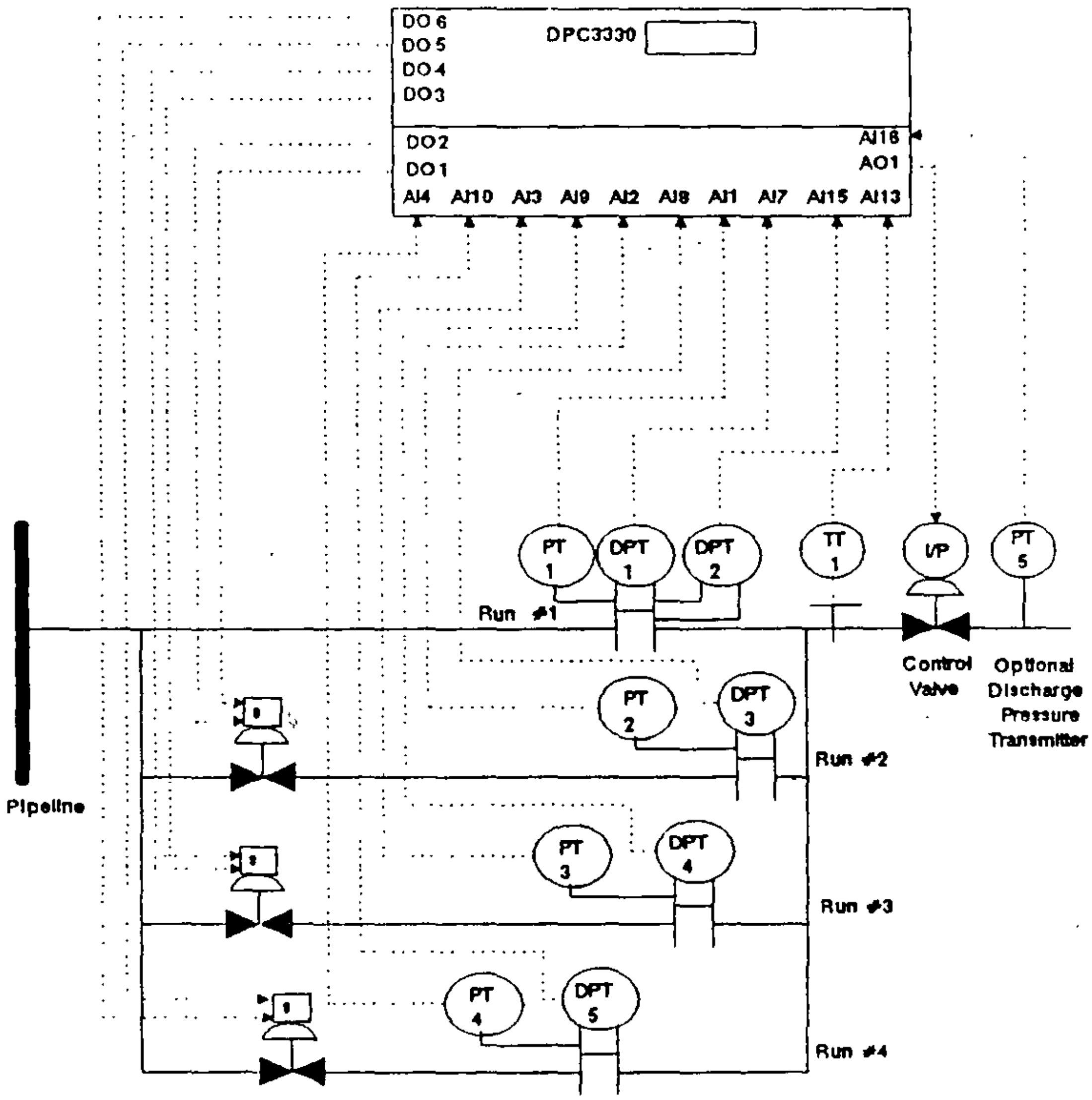
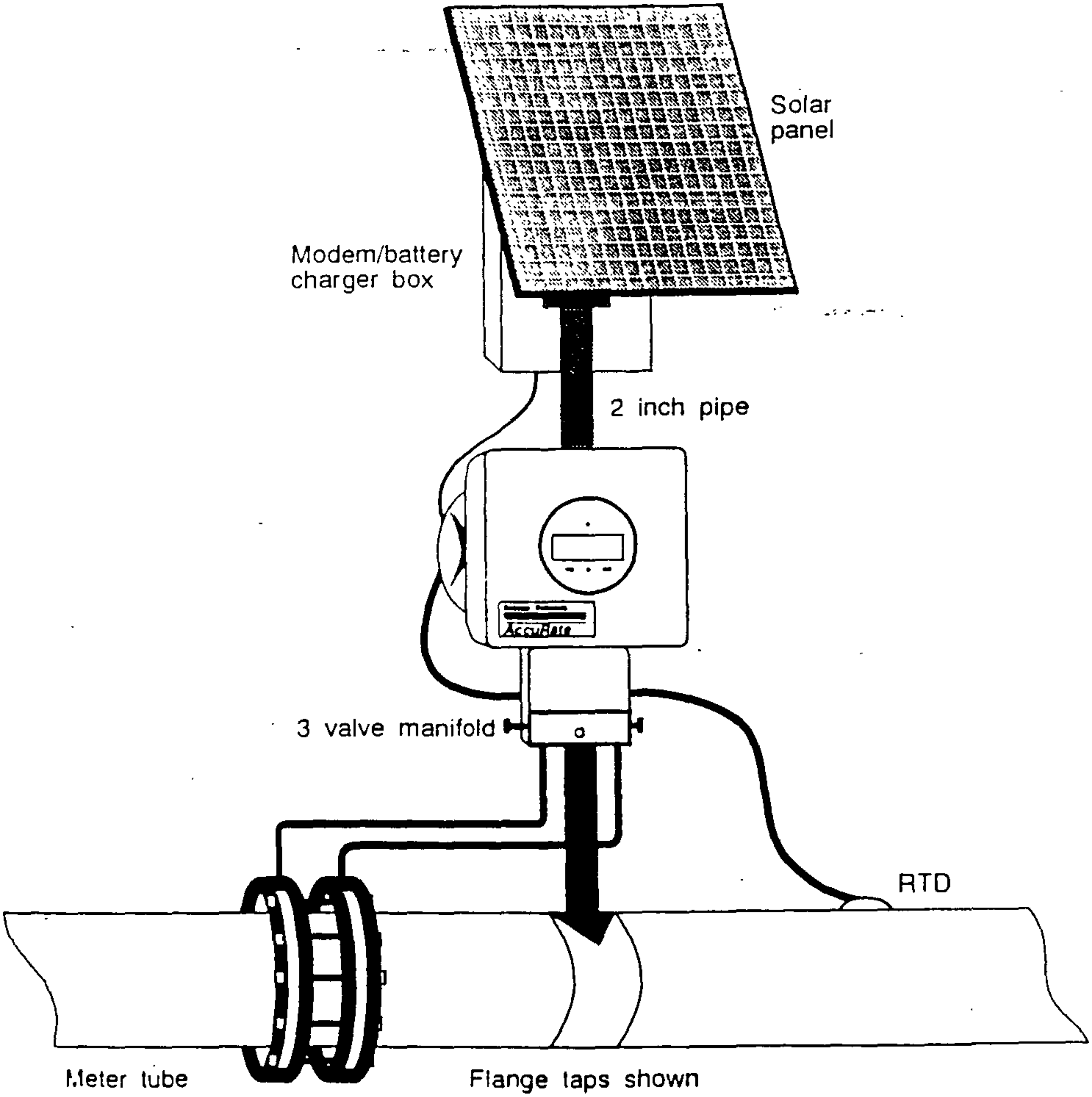
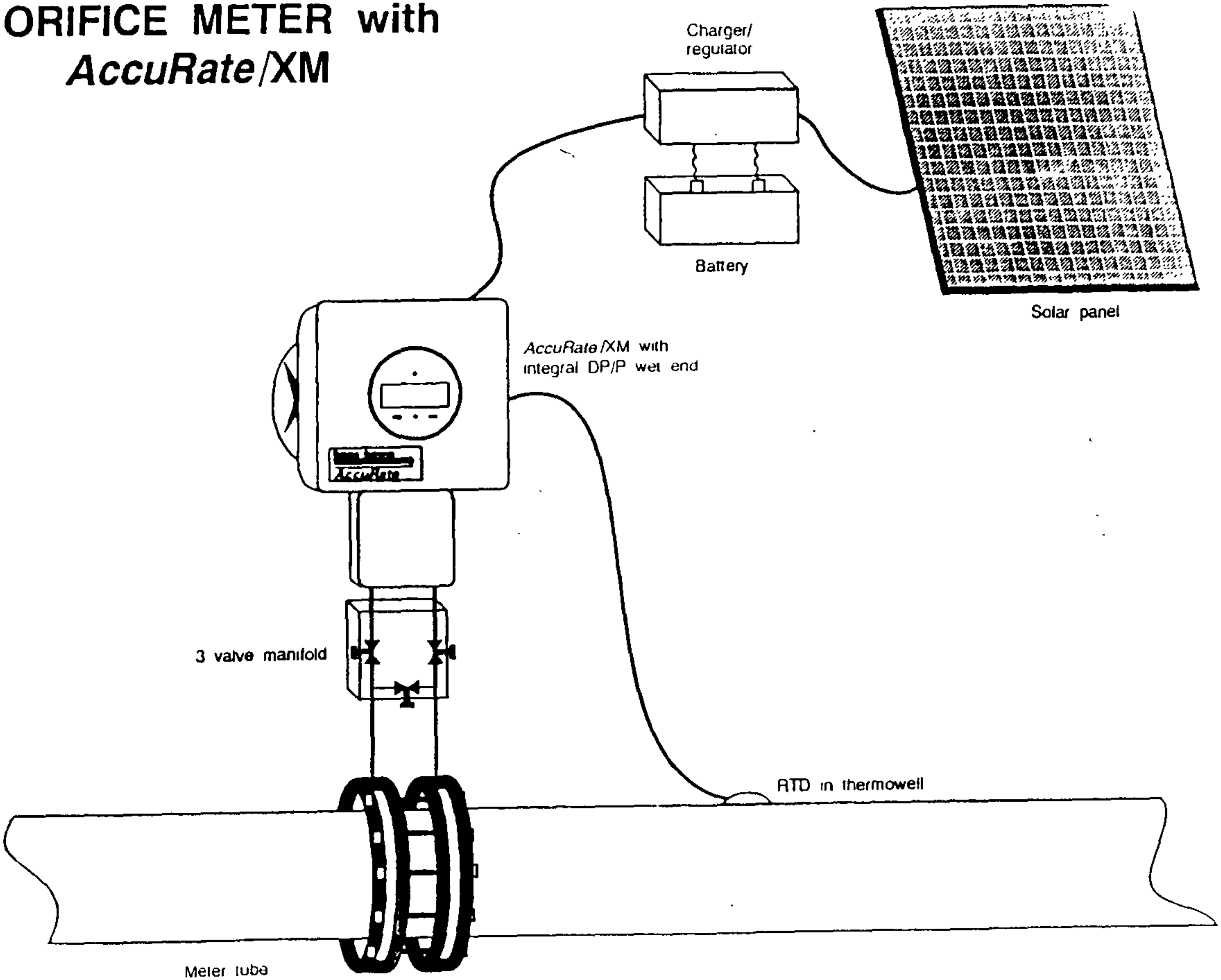
FOUR-RUN METERING AND REGULATION (M & R) STATION



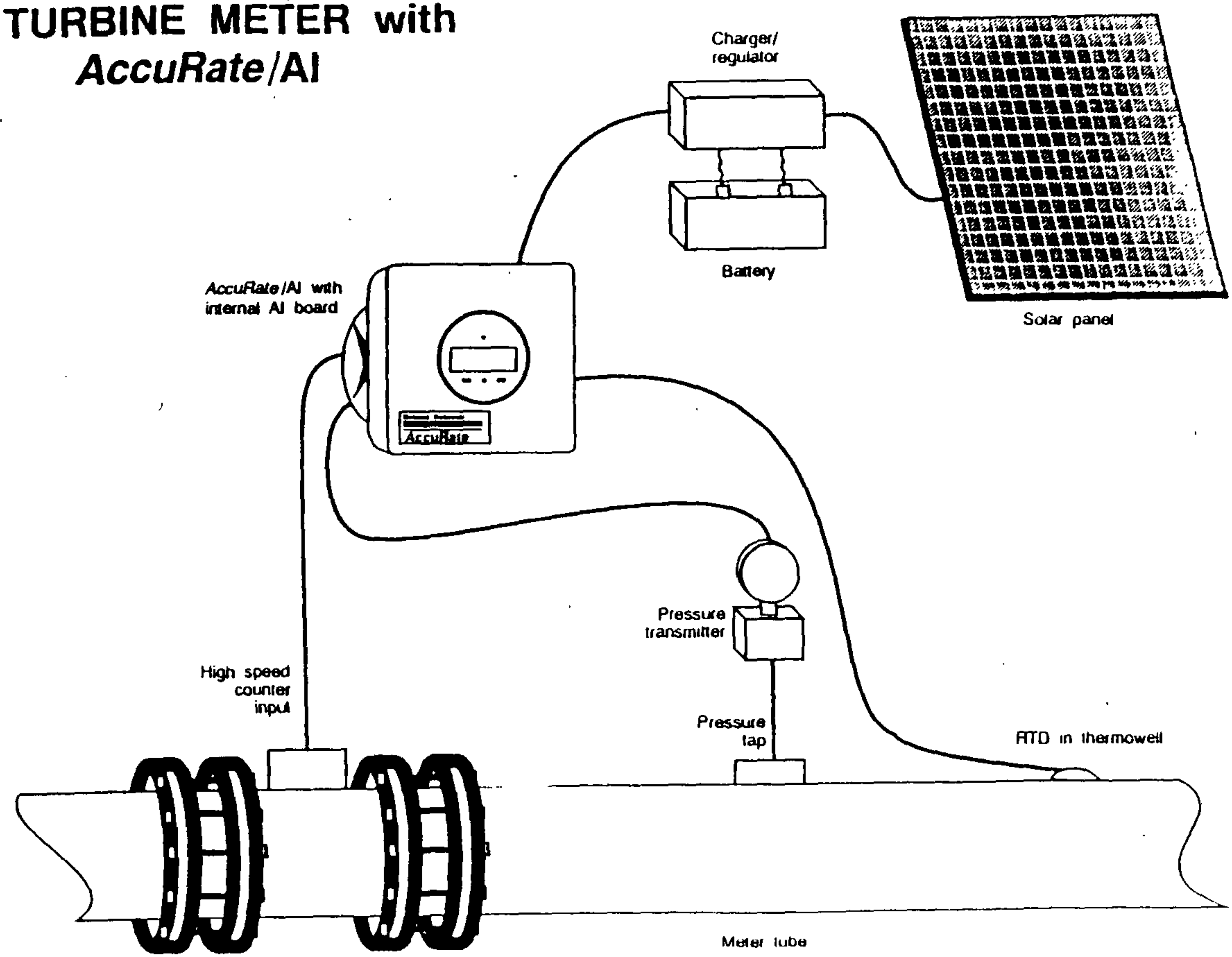
TYPICAL *AccuRate* INSTALLATION



ORIFICE METER with *AccuRate*/XM



TURBINE METER with *AccuRate*/AI



NETWORK 3000

AccuRate ADVANCED GAS FLOW COMPUTER
Model GFC 3308

The AccuRate is an advanced single-run gas flow computer that performs highly accurate calculations, performs flow/pressure control, stores extensive audit trail and historical records, and communicates on a real-time network.

Designed for low power consumption and installation in remote areas, the AccuRate provides the capabilities of Bristol's Network 3000 to gas measurement and control. Its ACCOL software and multiple communication protocols are fully compatible with our other "33XX" products such as the DPC 3330.

APPLICATIONS

The AccuRate is appropriate to any application that requires gas flow/energy calculations and flow/pressure control.

- o Production wells
- o Injection wells
- o Separation plants
- o Transmission metering stations
- o Distribution gate stations
- o Storage facilities
- o Custody transfer stations

FEATURES

- o Class I, Division I package
- o High accuracy calculations
- o AGA 3, 5, 7, 8, and NX-19
- o Programmed in ACCOL II
- o Preprogrammed, PROM-based application
- o Real time communication
- o BSAP, MODBUS, TGPL communication protocols
- o Comprehensive 35 day hourly/daily data base
- o Audit trail alarm/event data base
- o Auto selector flow/pressure controller
- o Configuration via standard IBM-compatible lap top computer
- o Operating temperature range: -40° C to 70° C

The AccuRate is available in two basic packages that allow flexibility with respect to the transducer inputs:

The "XM" version includes a smart DP/P integrated transducer and an RTD interface;

The "AI" version includes a 3 AI/1 AO interface board that accommodates external DP and P transmitters and an RTD.

OPTIONS

- o Solar power package, including solar panel, battery, charger
- o Switched network auto-dial/auto-answer modem
- o Private line modem
- o UHF radio

PRELIMINARY

Bristol Babcock

PROCESSING POWER

- Processor: 80C188
- Speed: 12 MHz
- Firmware EPROM: 256K bytes
- Application EPROM: 64K bytes
- RAM: 256K bytes
- Real time clock: DS 1287 accurate to one second per day
- RAM/clock battery back-up: 4000 hours
- 6 diagnostic LEDs
- Idle LED
- Watchdog LED visible externally
- Software selectable network address (Range: 1 to 127)

COMMUNICATION CAPABILITY

The AccuRate includes three asynchronous serial ports:

Network Port

- RS232
- Media: Multiconductor cable
- Baud Rates: 300, 1200, 2400, 4800, 9600, 19200, 38400
- Can be used with optional modem

Infrared Port for Lap Top Computer

- Modulated IR interface
- Baud Rate: 9600
- IR/RS 232 Adaptor available for Lap Top Computer

Smart DP/P Transducer Port

- TTL level interface
- Baud Rate: 1200

Optional Modems for Network Port

- Baud Rate: 300 or 1200
- Switched Network Modem allows auto-dial and auto-answer
- Private Line Modem is Bell 202

Please refer to Specification Summaries D453 SS-6 and D453 SS-7 for further information regarding the modems.

COMMUNICATION PROTOCOLS

BSAP

- Bristol Standard Asynchronous Protocol
- ISO Standard 1745/2111/2629
- Compatible with all Bristol Network 3000 Products
- Local Addressing: 127 Nodes
- Global Addressing: 32767 Nodes
- Hierarchy: 5 Levels
- Contention Scheme: Polled

MODBUS

- Standard Gould Modicon Modbus
- ASCII and Binary Versions
- Additional Daniel Chromatograph and Flow Computer Functions

TGPL

- Teledyne-Geotech with Tenneco Function Codes

ENVIRONMENTAL SUITABILITY

- Operating temperature: -40° C to 70° C
- Relative humidity: 5 to 95%, noncondensing
- RFI susceptibility: Per SAMA standard PMC 33.1-1978, using field of 10 V/Meter from 20 MHz to 500 MHz
- Vibration: 5-15 Hz: 1 mm peak-to-peak constant displacement
  15-150 Hz: 4.9 M/sec constant acceleration
- NEMA rating: NEMA 4 (certification pending)
- NEC environmental rating: Class I, Division I, Groups C and D (certification pending)
- Dimensions: please refer to diagram
- Weight:
  XM Package: TBD pounds
  AI Package: TBD pounds
  Modem/radio package: TBD pounds
- Power input: 9.0 to 15.0 VDC
- Noise and ripple: 2.0 VDC peak-to-peak
- Power requirements:
  XM package: 1.5 watts at 12.0 VDC
  AI package: 3.5 watts at 12.0 VDC
  Modem: 1.5 watts at 12.0 VDC

ANALOG INPUTS (AI version)

- 1-5 VDC/4-20 mA DC, switch selectable
- 12 bit A/D
- Conversion time: 200 µsec
- Accuracy: 0.1 % at 25 C
  0.2 % over -20° C to 70° C
  0.3 % over -40° C to 70° C
- Input filtering: single pole 50 msec time constant; 300 msec to 0.1 % of input value
- Settling time: 18 µsec to 0.01 %
- Surge protection: meets C37.90-1983
- Screw compression terminations

ANALOG OUTPUTS (AI version)

- 4-20 mA DC, switch selectable
- 12 bit A/D
- Accuracy: 0.1 % at 25 C
  0.2 % over -20° C to 70° C
  0.3 % over -40° C to 70° C

- Signal conditioning: 100 µsec time constant
- Surge protection: Meets C37 90-1983
- Screw compression terminations

HIGH SPEED COUNTER INPUTS

- 0 to 5 volt range
- Off/on threshold. 0 5/4.5 VDC
- Frequency range: 0 to 10K Hz
- Isolation: Optical isolation; 1500 volt common mode isolation
- Surge protection: meets C37.90-1983

ACCESSORIES

LAP TOP COMPUTER

- IBM-compatible with 640K RAM
- Hard disk drive and floppy disk drive required
- MS/DOS operating system required

IR CONVERTER

- Converts RS 232 to Infrared
- Bracket attaches to Accurate package

LIQUID CRYSTAL DISPLAY

- Standard, built-in accessory
- 4 line by 20 character LCD
- Backlight included

Operation of the Display:

Instead of pushbuttons, two infrared proximity sensors are used. One sensor allows the user to sequence through a list of menus while the other allows the user to sequence through individual items in a selected menu. When no operations are in effect, the display reverts to an auto-scroll of common input and flow data.

This display is read-only. The lap top computer or communication network must be used to make value changes.

SOFTWARE FUNCTIONS

The AccuRate is programmed in ACCOL II, Bristol's high-level, modular, multi-tasking measurement and control language. ACCOL II performs all calculations and data manipulation, including input sampling, scaling, flow calculations, averaging, totalizing, alarming, data storage/retrieval, mode selection, and flow/pressure control.

PERFORMANCE

Since ACCOL II is multi-tasking, the various software tasks can be performed on selected intervals. The following table relates how often the primary functions are performed. One reason for the high accuracy of the AccuRate is the execution intervals of functions such as input sampling, averaging, totalizing, and the AGA calculations.

FUNCTION	EXECUTION INTERVAL (seconds)
Input Sampling (XM)	0 2
Input Sampling (AI)	1.0
Averaging	1 0
Totalizing	1 0
AGA 3*	1.0
AGA 5	1 0
AGA 7	1.0
AGA 8	10 0
NX-19	1 0
Alarming	1 0
Flow/Pressure Control	1 0

* Note: This is the full AGA 3, including the Extension and C Prime.

AGA3 CALCULATION

Currently, the AccuRate uses the standard ACCOL II "AGAT3" module, which is exactly the same as the "AGA3" module, but with the C Prime Factors all available as signals.

At this writing, the API is testing a new orifice flow calculation intended as a revision to AGA 3. This calculation will be available as a new ACCOL module that can be selected as an alternative to the AGAT3. The API standard is scheduled to be incorporated in the AccuRate by the end of 1991.

The AGA3 Module performs the gas flow calculations specified by the American Gas Association, Report No. 3 (AGA3) ANSI/API 2530, 1985 edition. The output of this module is the rate of flow of a gas through an orifice plate in cubic feet per hour (SCFH).

The general form of the AGA3 equation is:

$$Q_h = C' \sqrt{h_w p_f} \qquad \text{Eq. 3-1}$$

where:

Q_h = Quantity rate of flow at base conditions, standard cubic feet per hour (SCFH)
C' = Orifice flow constant
h_w = Differential pressure, inches of water at 60 F
p_f = Absolute static pressure, psia

The orifice flow constant, C', is composed of various factors, some of which are fixed by the physical equipment and some that vary with the state of the flowing gas. The orifice flow constant is defined as follows.

$$C' = F_b \, F_r \, Y \, F_{pb} \, F_{tb} \, F_{tf} \, F_g \, F_{pv} \, K \qquad \text{Eq 3-2}$$

where.

- F_b = Basic orifice factor for a given orifice size and pipe diameter
- F_r = Reynolds number factor
- Y = Expansion factor
- F_{pb} = Pressure base factor
- F_{tb} = Temperature base factor
- F_{tf} = Flowing temperature factor
- F_g = Specific gravity factor
- F_{pv} = Supercompressibility factor
- K = Combined orifice constant

F_b is computed using the equations contained in Appendix B of the AGA3 report.

The term F_r, the Reynolds number correction factor, is calculated from:

$$F_r = 1 + \frac{b}{\sqrt{h_w \, p_f}} \qquad \text{Eq. 3-3}$$

where b is a constant for a given orifice size and pipe diameter. It is computed using equations in Appendix B of the AGA3 report and is combined with the linear interpolation of Table 18.

K, the combined orifice constant, is obtained from the expression:

$$K = F_m \, F_a \, F_l \qquad \text{Eq. 3-4}$$

where

- F_m = Manometer factor for mercury-type flowmeters only
- F_a = Orifice thermal expansion factor
- F_l = Gravitational correction for mercury manometer factor

Y, the expansion factor, is calculated using the equations described in the American National Standard Document, Orifice Metering of Natural Gas, Appendix B, Section 8.

These equations are broken up into two factors, one of which depends on the physical equipment, and the other which depends on the state of the gas.

The other factors are calculated as follows:

$$F_{pb} = \frac{14.73}{P_b} \qquad \text{Eq. 3-5}$$

where P_b = contract base pressure

$$F_{tb} = \frac{T_b + 459.67}{519.67} \qquad \text{Eq 3-6}$$

where T_b is the base temperature in degrees F

$$F_{tf} = \sqrt{\frac{519.67}{T_f + 459.67}} \qquad \text{Eq 3-7}$$

F_g is defined by the following expression:

$$F_g = \frac{1}{\sqrt{G}} \qquad \text{Eq 3-8}$$

where G is the specific gravity of the gas.

Combining the various expressions, the basic equation solved by the gas flow block is:

$$Q_h = KF_b \cdot \left[1 + \frac{b}{\sqrt{h_w \, P_f}}\right] \cdot Y \cdot \frac{14.73}{P_b} \cdot \frac{T_b + 459.67}{519.67} \cdot F_{pv} \cdot \sqrt{\frac{519.67}{T_f + 459.67}} \cdot \sqrt{\frac{h_w \, P_f}{G}} \qquad \text{Eq.}$$

AGA5 CALCULATION

For energy calculations, the AccuRate uses one ACCOL II AGA5 module.

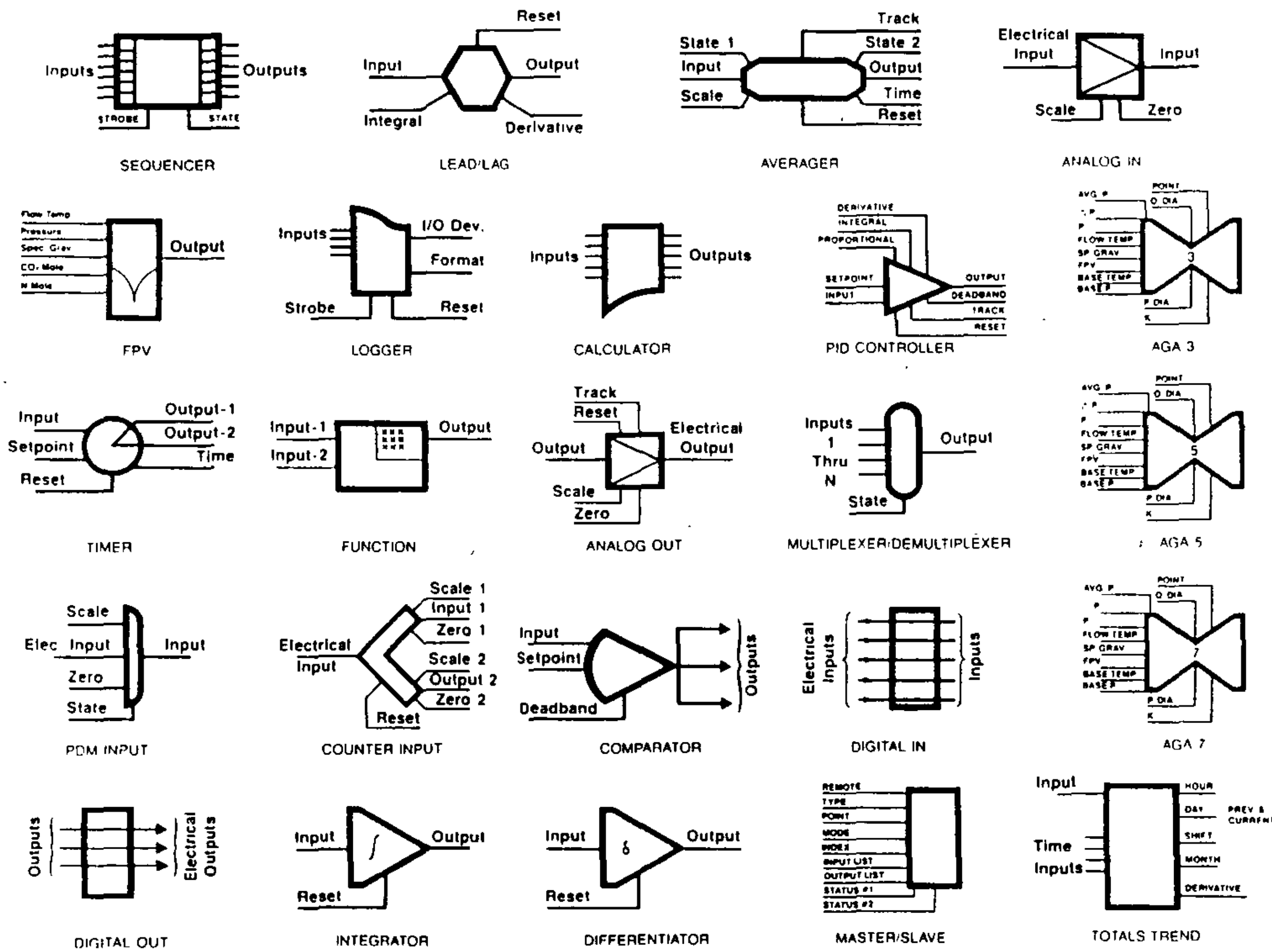
The AGA5 Module performs AGA5 calculations for conversion of computed gas volume to energy equivalents as described in the American Gas Association Report No. 5, reference Catalog No. XQ0776. The equation implemented by this module is taken from Section II of AGA Report No. 5. This particular equation dovetails the requirements of the orifice metering approach and the volume metering approach. As such, several of the factors are not required for the orifice metered volume to energy conversions. This module is only used when a calorimeter signal is not available. It performs the following equation for gas volume-to-energy conversio..

$$U_e = U_v \cdot E_v \cdot F_w \cdot F_{ws} \qquad \text{Eq 3-13}$$

ACCO . ™ Network 3000™ Software

ACCOL II is the most advanced control language available for process controllers. It is a set of forty preprogrammed software modules (software algorithms) that perform process control functions. They provide powerful computational and arithmetic functions as well as control functions.

ACCOL II is essentially a symbolic language easily understood and implemented by the process engineer. It can handle control chores ranging from simple sequencing and control interlocks, to performance calculations and state evaluation in real-time. Through the power of ACCOL II, process modeling, simulation and optimization can be accomplished on even the smallest control system budget. Below is a sample of these ACCOL II blocks. In addition to those shown are high speed counter, encoder, command, scheduler, stepper, storage, PDO, low level input, AGA 8, audit trail, keyboard, and custom protocol communication.



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Fax 44 26 43 73

GENESIS™ Network 3000™ Software

Features

- Runs on IBM AT and PS/2 or compatible computers
- DOS compatible
- ICON-driven graphic display builder
- Graphic animation
- Easy-to-use database builder
- Comprehensive alarm reporting
- Alarm, event, and report logging
- Historic data archive and replay
- Realtime and historic trending
- LOTUS 1-2-3 compatible
- On-line file transfer utility
- Password protection
- SPC/SQC
- Networking software
- Report generation

Introduction

GENESIS is a powerful operator interface software package for Network 3000 products including DPC 3330, DPC 3335, RDC 3350, and UCS 3380 Distributed Process Controllers. In process control, industrial automation, and SCADA applications, GENESIS provides data acquisition, operator graphics, trending, alarm logging, data logging, historical replay, report generation, and SPC/SQC functions.

GENESIS consists of two main parts: the system configurator which runs under DOS and the run-time system which is a real-time multi-tasking operating system that is co-resident with DOS. The system configurator is a CAD-like system development environment which includes the database builder and the graphics builder. The run-time system executes the data collection system and provides a graphical operator interface.

Database Builder

GENESIS includes a utility which extracts all database signals from the ACCOL II™ program files and automatically generates an interface file for each Network 3000 process controller. Signals are then selected for inclusion into the database by simple selection with the click of the mouse. Also, using the mouse you can select from a library of acquistion, mathematical, logic, and calculation functions, position them on the screen and connect them to database signals.

Graphic Display Builder

The graphic display builder also uses ICON selection via mouse interaction. These ICONS allow drawing of lines, boxes, bars, circles, ellipses, arcs, area fill, and text.

Object oriented editing functions include move, copy, change color, change size and rotate.

Once a symbol, such as a valve motor or faceplate, is created it can be stored in a symbol library for later use.

Run-Time System

The run-time system provides real-time and historical data acquisition for color graphic display, trending, and reporting functions. Data entry fields allow setpoint changes, on-off status changes, and manual override of signal values.

GENESIS provides outstanding display capability with graphic animation, multiple dynamic color changes, dynamic messages, and on-screen trend windows.

Alarm System

Network 3000 Distributed Process Controllers provide a unique alarm system whereby alarms are detected and time stamped in the process controller at the time of occurrence and transmitted to GENESIS.

Data Logging

GENESIS provides two different data logging models with the standard package: the Event-Driven Historian and the Shift Historian. Both models produce delimited ASCII files designed to be directly imported by LOTUS 1-2-3. You can select one of the models according to the needs of your application. These files can be replayed in a tabular or graphical trend format. During historical replay, the system maintains full operation including data logging and short term trending.

System Trend Display

System trending is a dedicated display with an internal data storage buffer. It allows up to 20 variables to be trended simultaneously. System trending also provides a trend "SNAPSHOT" allowing the operator to instantly capture any number of trend curves for later replay.

Optional Packages

Host Communication Package

Provides automatic or demand file transfers to a host computer using the industry standard KERMIT file transfer protocol. All file transfers are accomplished concurrently with full GENESIS run-time functions.

Remote Supervisory Station

The Remote Supervisory Station (RSS) is a full network product allowing a master GENESIS system to be accessed by up to eight remote stations for monitoring and supervisory control. Each of the remote stations function as a full operator console allowing access to live data, operator graphics, trend charts, historical files, and statistical data results. In addition, each of the remote stations have the ability to modify set points, select and modify operating limits, totals, and other parameters influencing overall system operation. The physical interface supports ARCNET running at 2.5m baud between stations.

SPC/SQC

The Statistical Process Control option for GENESIS is an independent module allowing on-line calculation and storage of statistical information vital to the process. GEN-SPC provides automatic or manual sampling of process data, calculates averages, X-bar, standard deviation, S, and range, R. The statistical option generates multiple types of alarms based on whether the upper or lower control limits for the X-bar, R or S are exceeded.

Hardware Requirements

- IBM AT, PS/2, or compatible
- 286 or 386 CPU
- 640 Kb memory minimum
- 10 Mb fixed disk minimum
- Floppy disk
- Math coprocessor
- EGA or VGA card with 256K memory
- EGA or VGA color monitor
- 1 serial port
- 1 parallel port
- Mouse (three button recommended) required for configuration only

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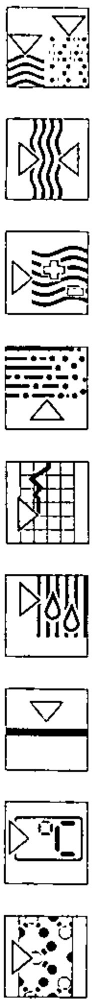
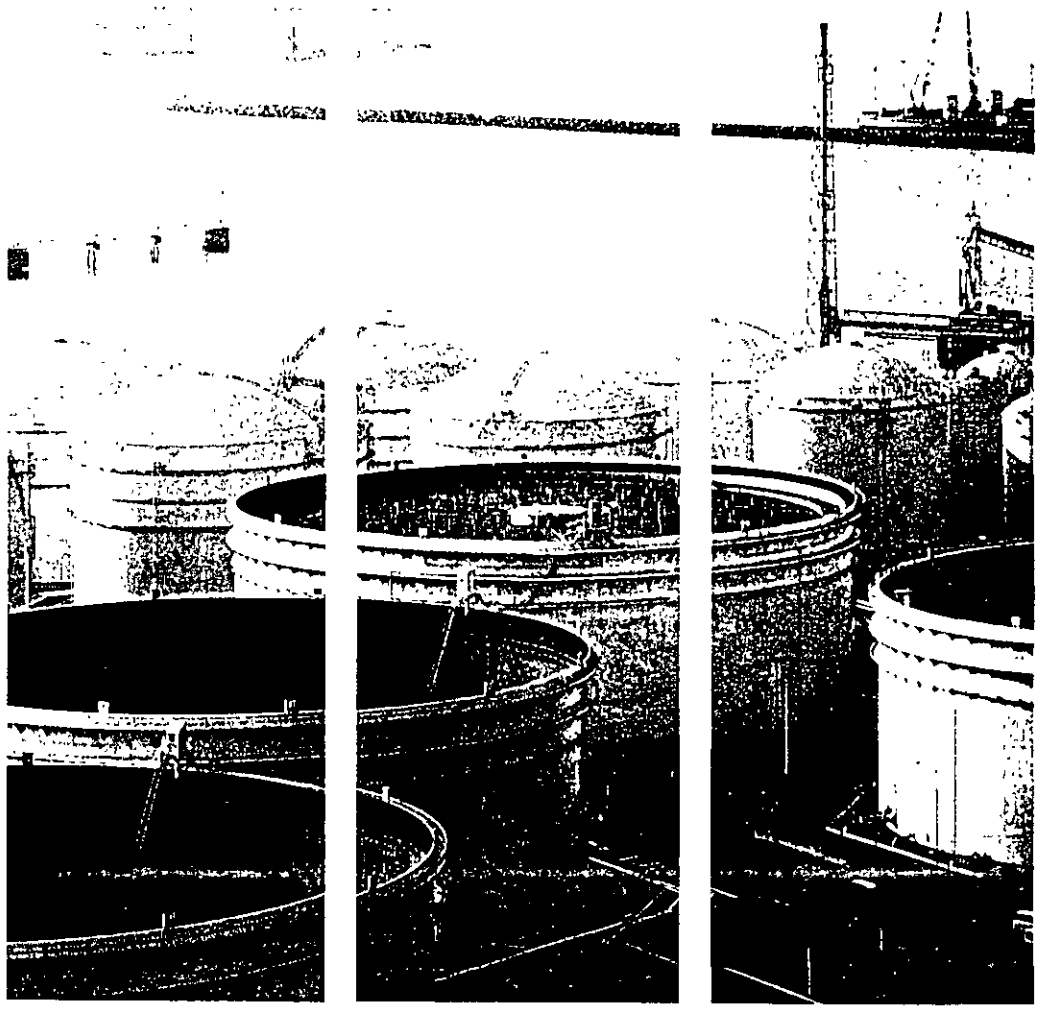
GS-100 A

System-
Information
SI001N/08/ae/9.93

Tank Level Gauging

Inventory Management





Endress+Hauser
Nothing beats know-how

Sakura Endress
Member of the International E+H Group

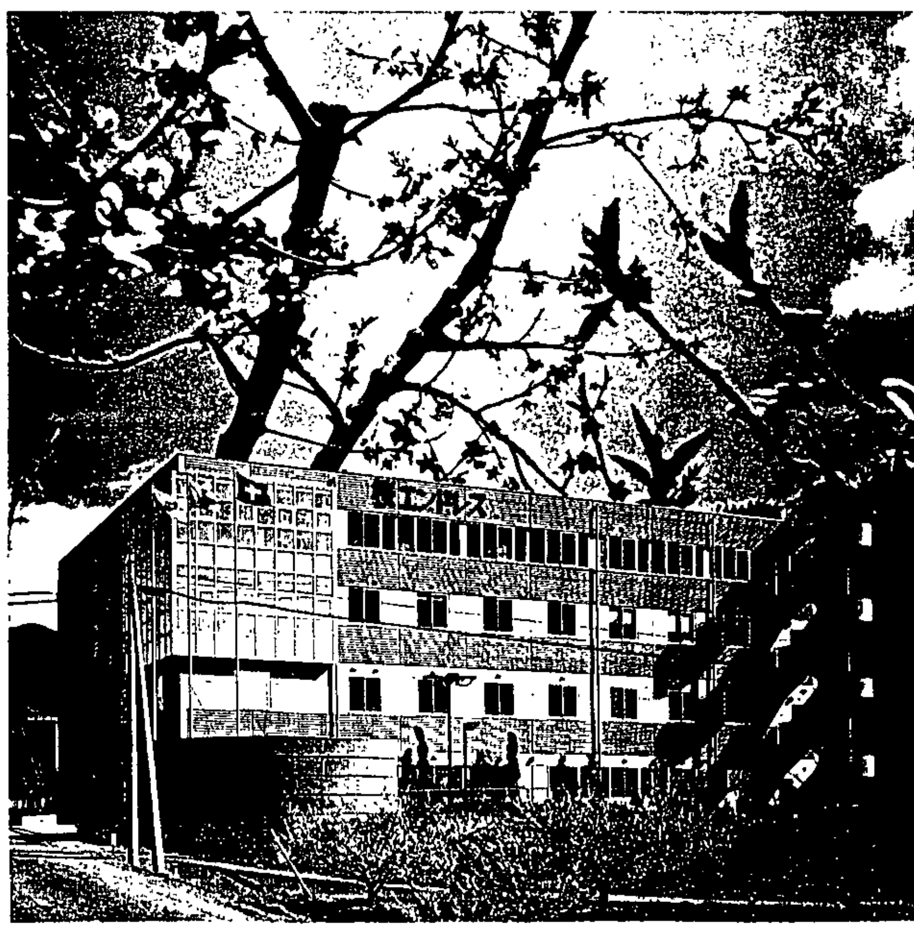
The International E+H Group

The Group employs more than 4500 people working in 13 production centres and 15 sales centres on 5 continents. The Group manufactures a broad range of process control instrumentation including the following:
Measurement of levels – liquid and solid; flow – liquids and solids; temperature; density; pressure, moisture; analysis and tank level gauging.
Endress+Hauser tank level gauging and inventory control systems are designed and manufactured by Endress+Hauser in Tokyo, Japan. The tank inventory systems are sold and serviced worldwide by the international Endress+Hauser network.

The Sakura Endress Program:

1. Servo balanced tank level gauges
2. Data communication instruments
3. Temperature gauges
4. Float tank level gauges
5. Remote and on-site indicators, limit switches

All Endress+Hauser instruments are certified worldwide.
The Endress+Hauser factory, established in 1955, is located near Tokyo, Japan.
The new production facilities, surrounded by cherry trees (Sakura), house the think tank for a dedicated and well trained staff of technicians and engineers.
Endress+Hauser inventory systems are found worldwide in refineries, chemical and foodstuffs tank farms.



The dedicated staff is proud of its newest tank level gauge: the TGM 4000.

Intelligent Tank Level Gauging

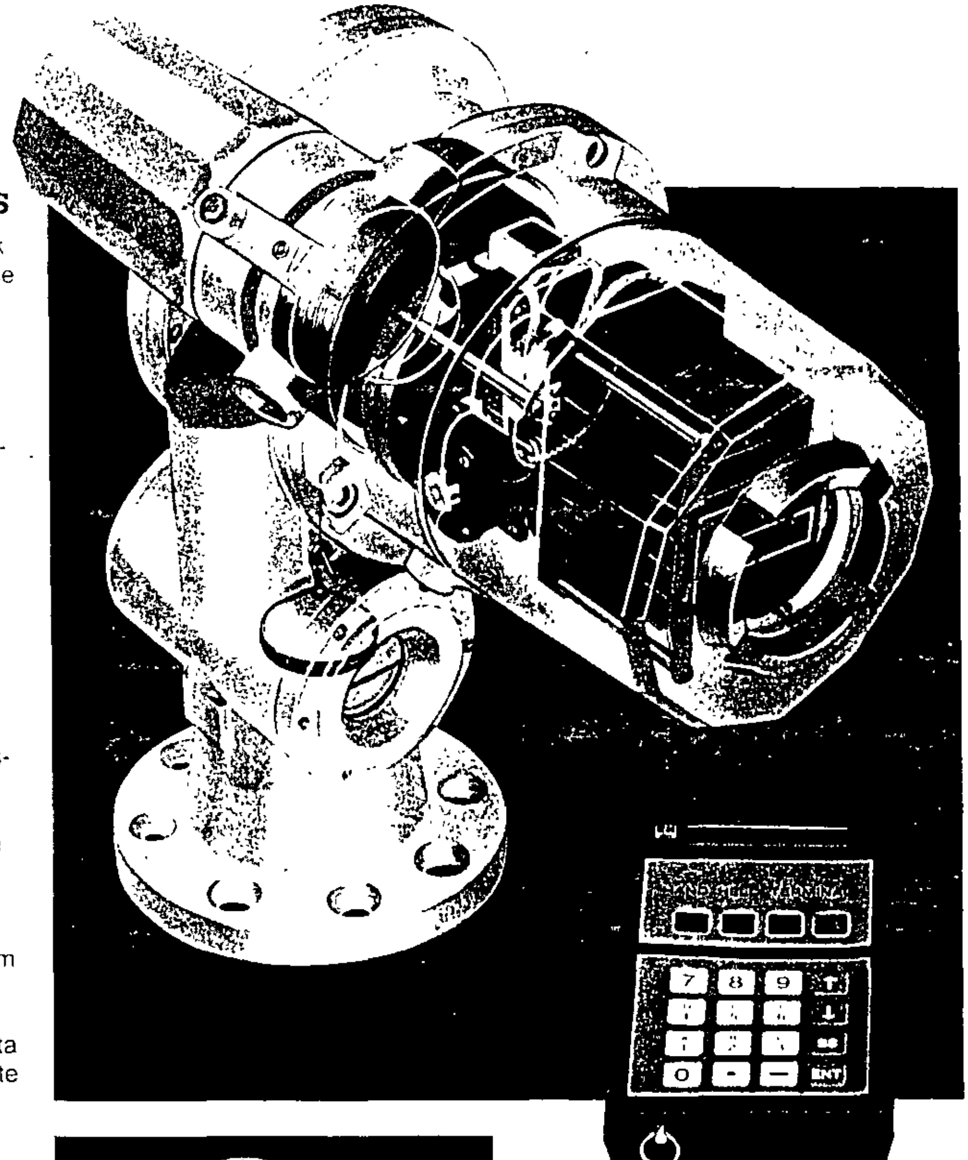
Intelligent Tank Gauges

The TGM 4000 series of intelligent tank gauges, working with the servo-balance displacer system, features an integrated calibration chamber for ease of handling. The self-diagnosing unit employs direct torque detection with coupling magnets (Hall effect). The TGM 4000 has an operating range of 27 meters in tanks pressurised up to 25 bar The compact tank gauge is highly accurate (0.9 mm) and can be upgraded to provide measurement of

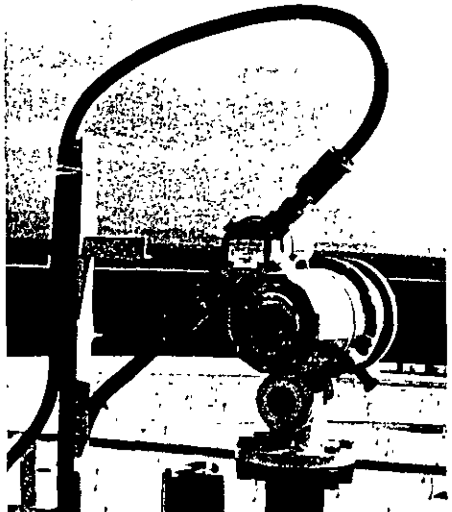
- volume
- specific gravity
- interface

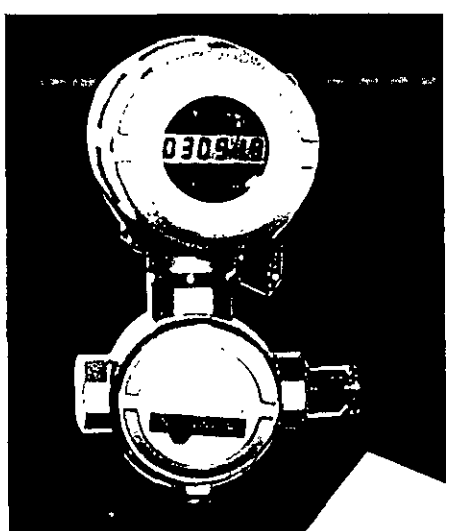
Modular Program

Endress + Hauser inventory control systems provide tank gauging for 1 tank, 1 .. 20 tanks, 1 ... 140 tanks Signal transmission is by low-cost, 2-wire line or 1 core optical cable on which external field instrument signals are also transmitted.
The complete Endress+Hauser program includes an encompassing process control system from straightforward level switches to complete data transmission networks (with appropriate software)

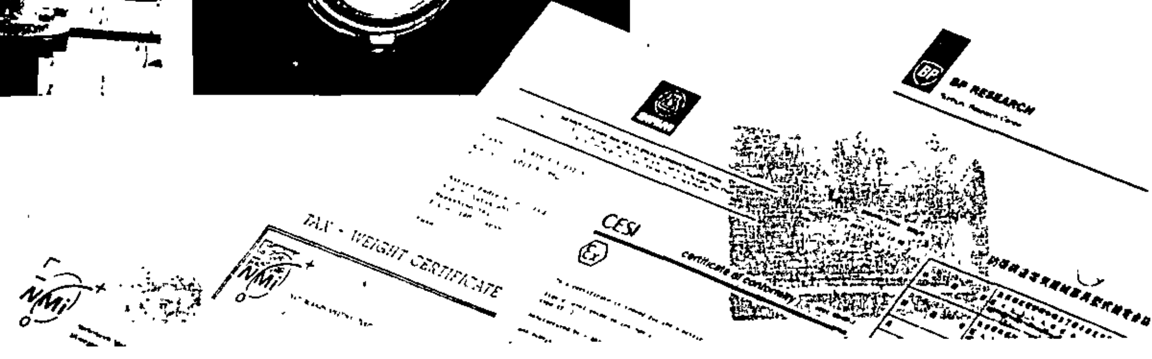


The TGM 4000 can be accessed, programmed, monitored and read by hand-held terminal HHT



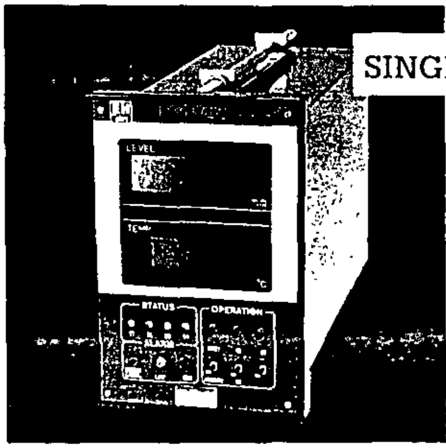


Tank side Monitor - DRM 9700E is a flame-proof, remote indicator. The tank side monitor features an integrated display of both level and temperature values. A magnetic key allows DRM display to be changed externally.



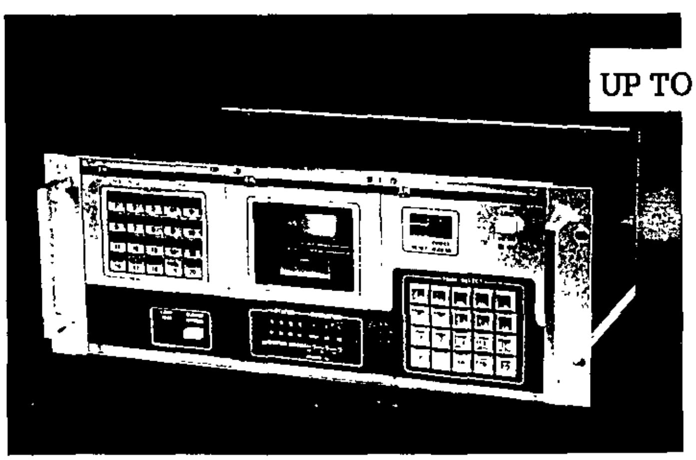
Certification
TGM tank level gauges are certified by important institutions for hazardous and tax and weight applications

MIC 1000
with TGM or LT+TMD

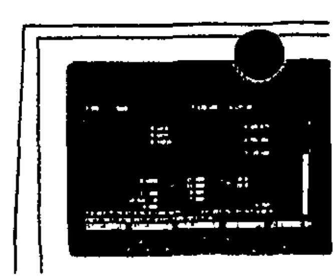


The single tank monitoring unit MIC 1000 is designed for standardized control panel installation.
The unit offers:
• indication of level • temperature
• alarm signal • operation switch.

BBB 1000
with TGM or LT+TMD



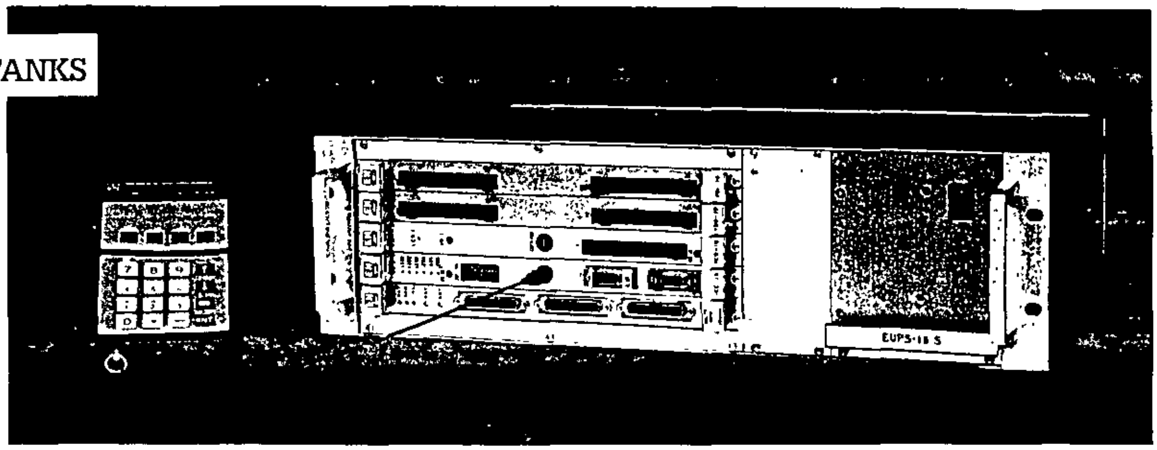
The BBB receiver, together with TGM 4000 or LT+TMD is designed for tank farms with a maximum of 20 tanks. The BBB receiver is available for panel mounting or desk top installation.
The unit indicates:
tank level • temperature • 40 alarm signals. Connection to the tank is by serial digital communication.

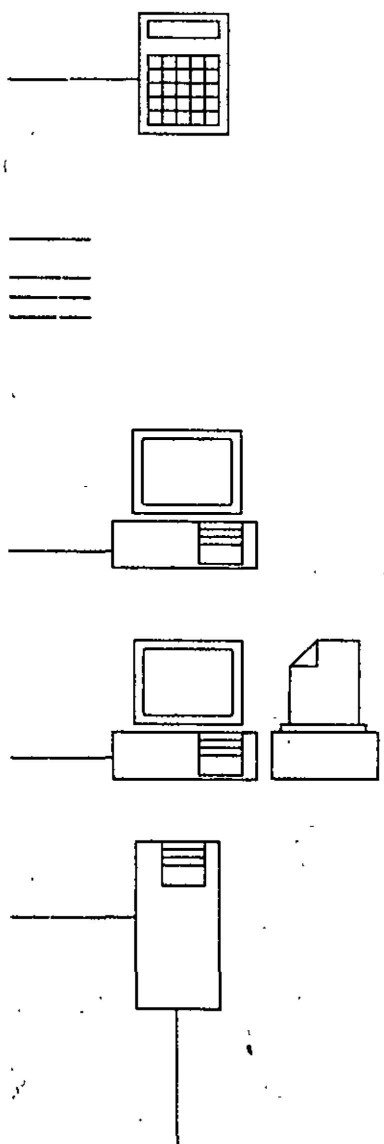


Tank Inventory Management

MDP II I/F V1 with TGM or LT+TMD

UP TO **140** TANKS





The personal computer based MDP II I/F V1 system is designed to display the latest information of up to 140 tanks (standard) on a colour screen A variety of tank information is obtained by continuous scanning of the field sensors. The field data is collected and processed with an interface unit and displayed and operated on a computer screen.

The Data includes:

• Menu • System menu • Level • Temperature • Product identification • Gross volume • Standard volume (converted at 15°C or 60°F in compliance with ASTM table) • Specific gravity • Level and temperature alarm status • Options

MDP-II Multiprocessing System

This receiver system is based on the most advanced microcomputer/microprocessor technology MDP systems consist of control/interface and display unit with keyboard. The control/interface unit processes data signals of surface and interface,-level, temperature, specific gravity and alarm signals from the field gauges The tank data is indicated on the associated colour screen in various display and format pages and can be modified by simple keyboard operation

All the available data are accepted directly by hand-held terminal The MDP II is a highly flexible system with auxiliary data processing and communication units, e.g. data logger, sub-receiver and host-computer connections.

Operator Capabilities

1. Tank Detail
Continuous data provided by the system includes – real time check, tank number, product identification, level, temperature, alarm, gross volume, specific gravity, interface and surface level.

2. Large Character Display
Tank number, level, temperature, gross and standard volume of a single tank are displayed in large characters. Convenient for remote monitoring of tanks in operation.

3. Automatic Volume Calculation
Gross volume of product in any tank, calculated automatically from the tank strapping data in the memory and the actual value The system will correct gross volume using the temperature data and specific gravity entered by the operator to the corrected volume (ASTM standard).

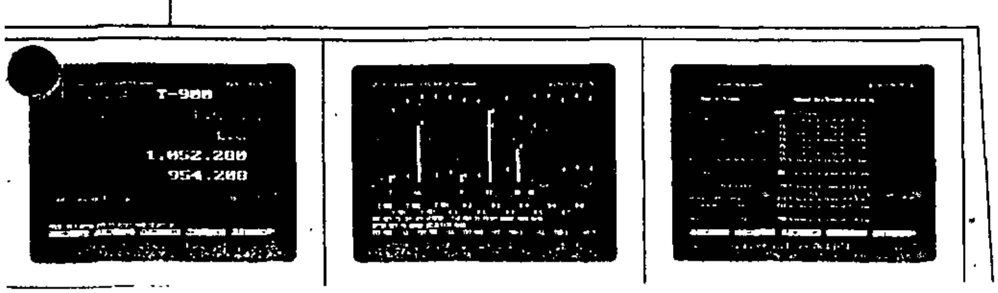
4. Alarm Message
Display at 4 points level and 2 points temperature on all pages. The annunciator continuously sounds and the alarm message flashes until acknowledged.

5. LAN Communication
(ETHERNET)

6. Operation Data Set
Screen operation can correct conditions

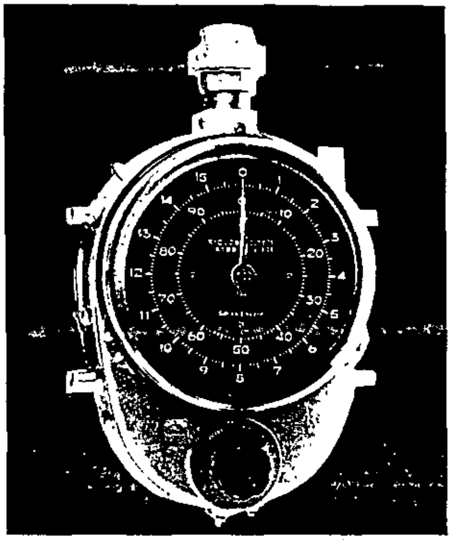
7. Tank History Data
For one month

8. Transfer Expectations



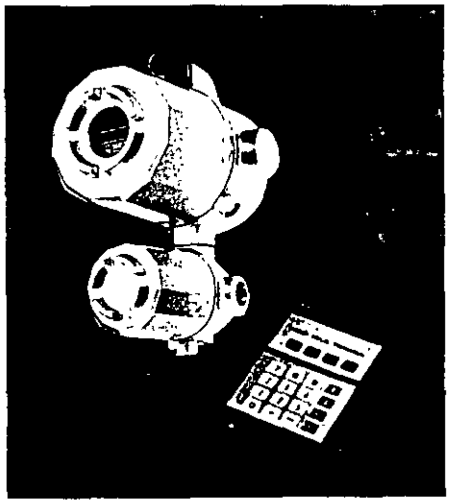
Float Gauges LT Series
Transmitter TMD/AT Series

Float Gauges

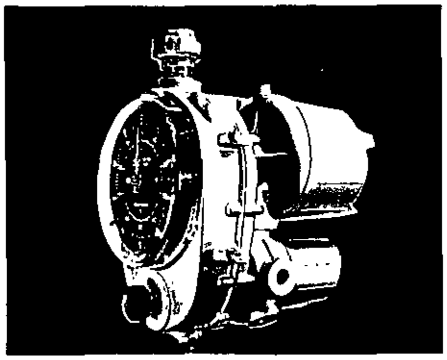


Some tank level applications require purely mechanical, float operated tank gauges.
Endress+Hauser float gauges, LT 1000 series, are used widely in the measurement of petroleum products and all other types of liquids where a maximum of reliability and accuracy is required. Float gauges are installed on different tank constructions: cylindrical, spherical, floating roof, etc.

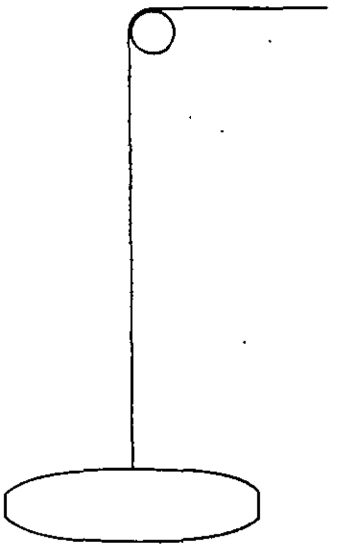
Digital Technology (tank gauge LT 1000+TMD transmitter)
The instrument range contains the float tank gauge LT 1000 series, featuring a measuring range of 40 meters The instruments work in conjunction with TMD digital transmitters
Flexible pipe configurations make the system adaptable to a great variety of tank constructions.



TMD
This is a digital transmitter used in conjunction with LT tank gauges. 12 module card technology allows for changes of input/output transmission, temperature, alarm, status and valve control



Analogue Technology
Tank Gauge LT 1000 series with transmitter AT 1000 is a simple, trouble-free, analogue instrument The Ex-proof gauge with up to 6 alarm outputs has voltage, current and resistance outputs



Temperature Measuring Bulb RCV/RCS Series

Temperature Measurement in Inventory Control

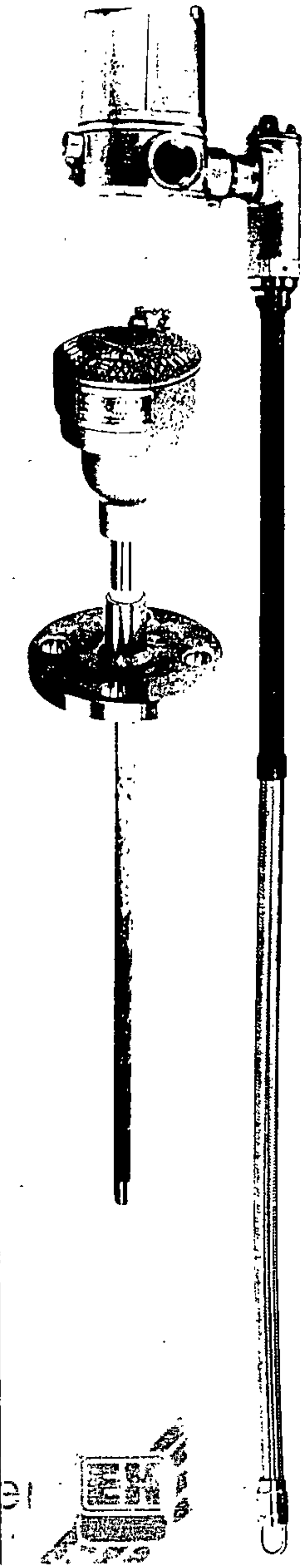
Product temperature significantly influences the volume in tank inventory management. As the mean product temperature in large tanks varies greatly from top to bottom, the temperature of the product within the entire tank must be measured and averaged with great accuracy.

RCV Average Temperature Bulb

The RCV temperature bulb detects a maximum of 10 points (optionally more). Highly corrosion resistant platinum elements measure temperature to an accuracy of ± 0 25°C to meet custody transfer requirements. The temperature signal is picked up by the switching circuit in the TGM tank gauge or TMD transmitter. The RCV unit accurately measures over a flexible tube with vertically arranged sensing elements (Pt.100). Individual temperature segments within the tank can also be averaged to exclude temperature variations in phases, e g oil/water.

RCS Spot Temperature Bulb

The RCS temperature bulb employs a Pt 100 sensing element encased in the thermowell to measure the spot temperature of liquid in the tank. The signal is converted into digital values for remote transmission by TGM tank gauge or TMD transmitter.



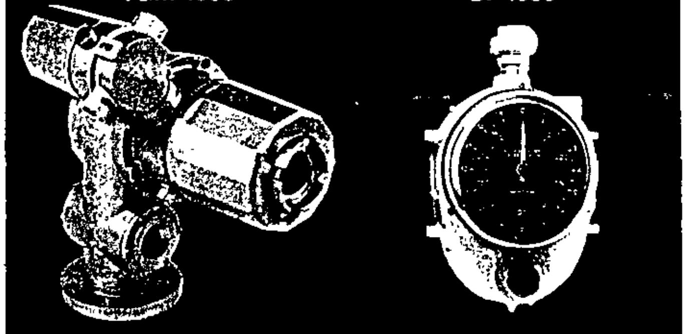
Level Limit Switches – Overspill Protection

Liquiphant
Level limit switch for all liquids. Approved overspill protection for flammable and water polluting liquids. Instruments in the Liquiphant range are distinguished by a constant switchpoint featuring greatest accuracy without the need for calibration.
Certificates:
for hazardous applications and overspill protection.

Float type Level Switch – CS series
Compact construction for upper and lower limit alarms. Range features explosion proof models.

Displacer type magnetic Level Switch MPC series
This displacement switch provides 1 to 4 output contacts. This reliable limit switch can be mounted vertically or horizontally on a variety of liquid tanks.

Tank Level Gauging Instrument Line up

Tank Level Gauge	TGM 4000		LT 1000	
				
Transmitter	integrated		TMD 1000	AT 1000 AT 5000
Temperature Probe	RCS, RCV, field instruments connectable			
Receiver Interface	MDP	BBB	MIC	
Supervising	PC/Host	PC (RS 232) optional		

Instrument line up	Model	Working Press. Max. (kg/cm²)	Measuring Range Max.	Accuracy
Servo Gauge Built in micro-processor universally applicable for higher demands **Remarks:** Wire employed, built-in transmitter	Series TGM 4100	0 5	27 m	± 0.9 mm
	Series TGM 4400	6	27 m	± 0.9 mm
	Series TGM 4600	25	27 m	± 0 9 mm
Float Gauge Spring balance, universally applicable **Remarks:** Tape employed, separate transmitter connectable	Series LT 1100/1200	0.2	30 m	± 2 0 mm
	Series LT 1600	25	30 m	± 2.0 mm

For detailed technical information on E+H tank gauging equipment, please contact
Sakura Endress Co., Ltd.
3-4-22 Naka-Machi
Musashino-Shi
Tokyo 180
Tel. (04 22) 54 06 11
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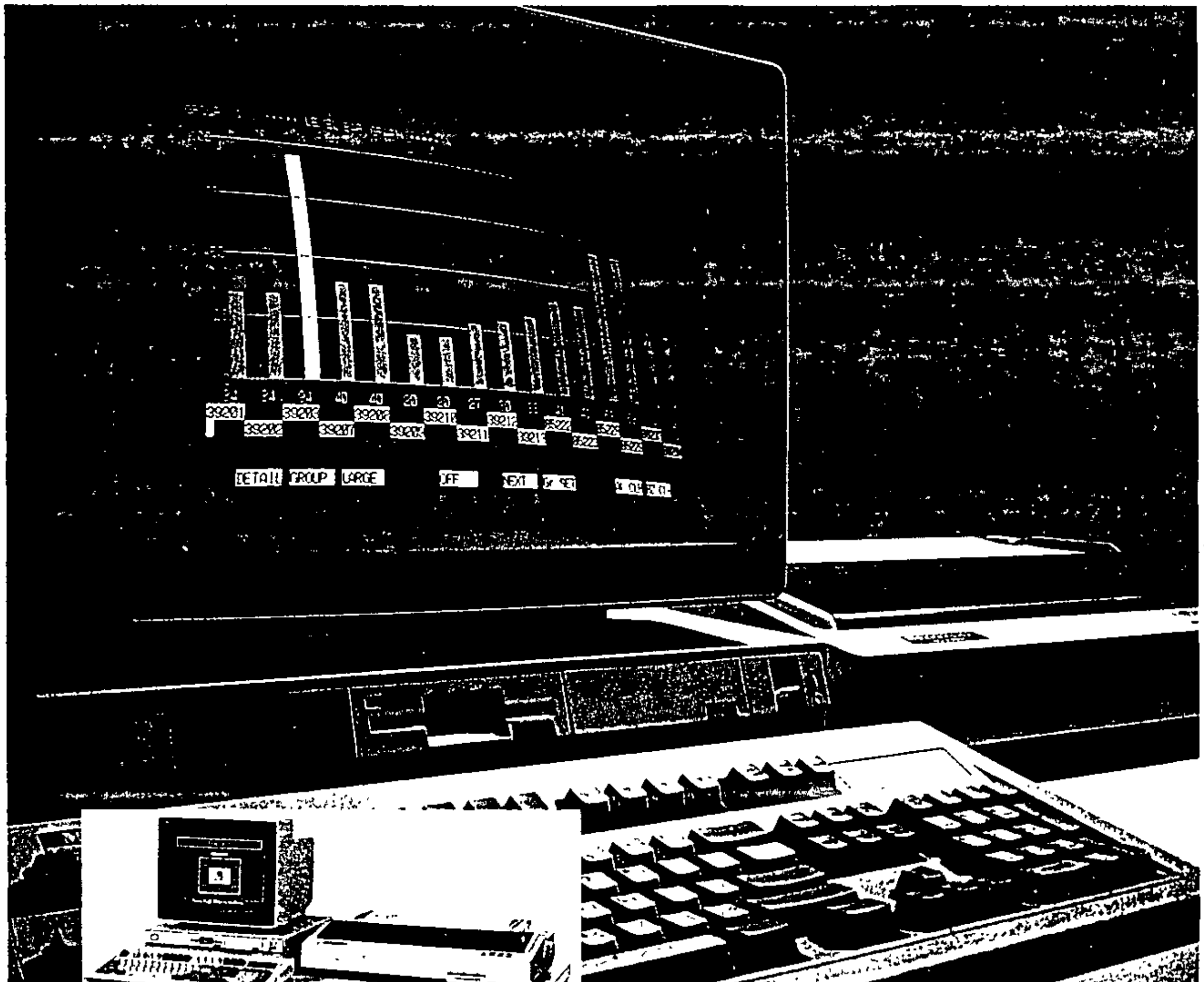
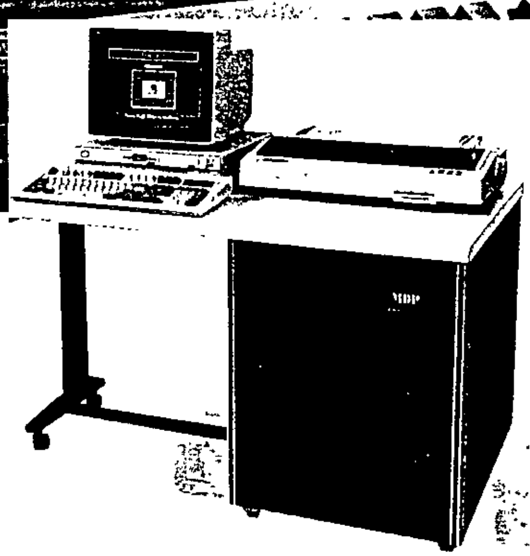
Telex 028-22 615

Sakura Endress+Hauser
Nothing beats know-how

MDP-II-PC

Remote Tank Gauging
& Inventory Control System





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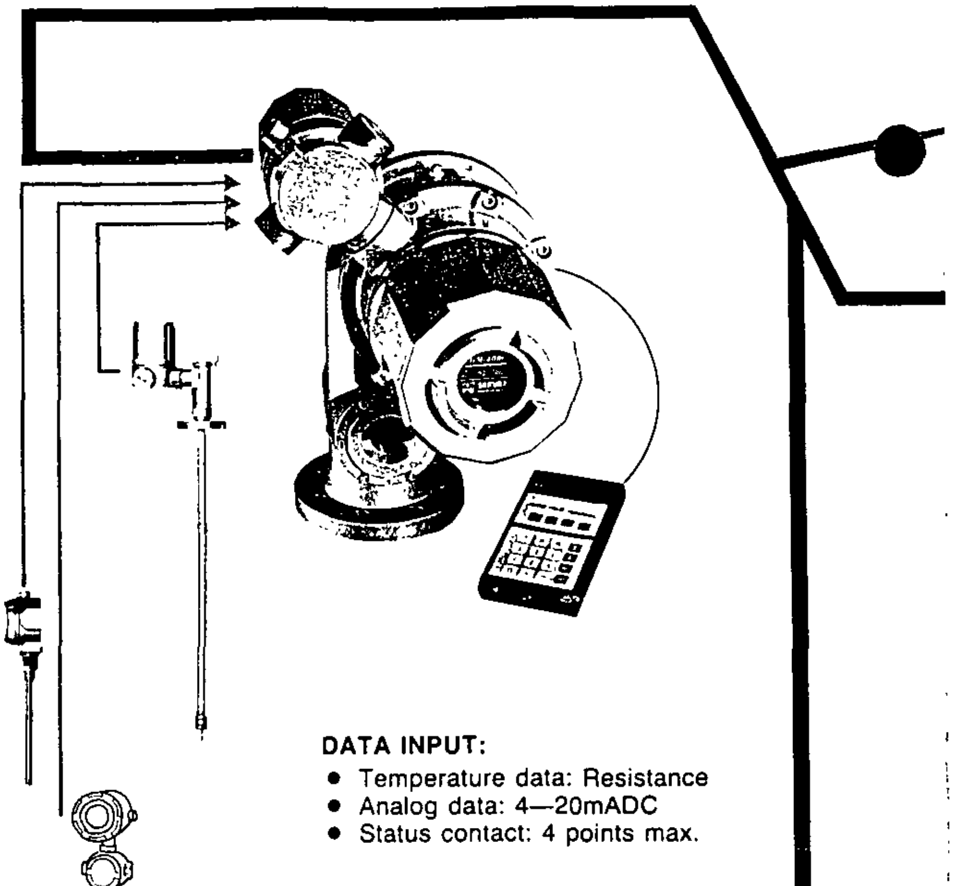
Sakura Endress Co., Ltd.

GENERAL
MDP-II MULTI-DATA-PROCESSING SYSTEM

Receiver system for tank inventory management based on the most advanced microprocessor/microcomputer technology. The system has a capability to meet a variety of user's demand with SAKURA's unique software acquired as an essence of references based on more than 150 installations over the world since 1970.
The system consists of Interface Unit and Personal Computer. Interface Unit processes signals of level, temperature and alarm from tank gauges and the processed tank data are indicated on the display of Personal Computer in various display format/pages. User's tank data and basic data registration for computation can be performed or modified through simple keyboard operation. And it is very flexible with auxiliary data processing units, e.g. printer, data logger, subreceiver and host computer.

- Module units prepared for optional choice permits low cost tank remote gauging system.
- 2-way 2-wire data communication system employed permits hoist-up of the displacer and repeatability check remotely from a control room in addition to valve control at the tank field.
- Self-diagnosis function for the entire tank gauging system enables highly reliable inventory management.
- Microprocessor adopted to equip the small receiver with a variety of functions.
- Clearly visible indication with the Liquid Crystal Display (LCD).
- Receive dimension in accordance with IEC standard to facilitate panel mounting on 19 inch rack mounting.
- CPU interface, other modules are prepared for optional choice according to application modes of the receiver.
- Lightning arrester provided as standard.

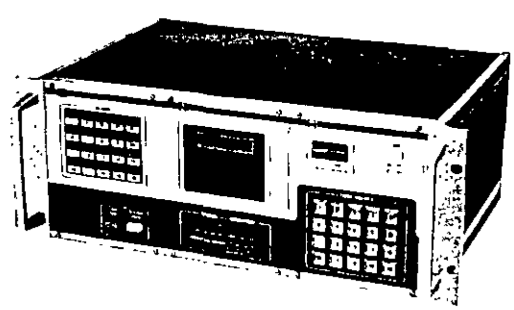
TGM SERVO TANK GAUGE

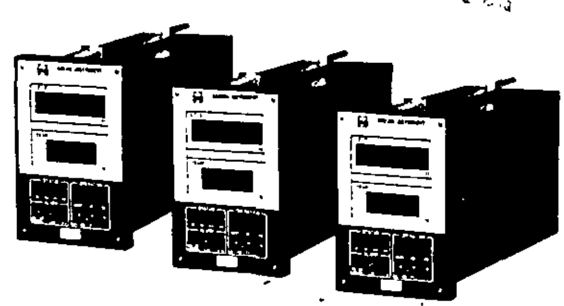


DATA INPUT:
- Temperature data: Resistance
- Analog data: 4—20mADC
- Status contact: 4 points max.

LOCAL EQUIPMENTS:
: Hand held terminal (HHT-1)
: Local indicator (DRM-9700E)
: Average, multi point temperature (RCV)
: Spot temperature (RCS)

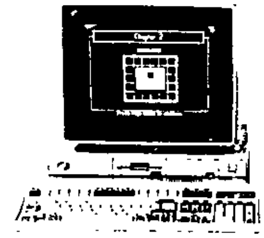
BBB series modular receiver
Max. 20 tank monitoring at control panel





MIC single receiver
Tank data monitoring at control panel

DATA OUTPUT:
- 2-way 2-wire serial
  Digital pulse:
- DC 4—20mA
- 2-way 1-wire optical
  All the tank data:
  Level, Alarm, Sp.Gr., Temperature
  Interface Level, Pressure Data,
  Status, etc.



Personal C
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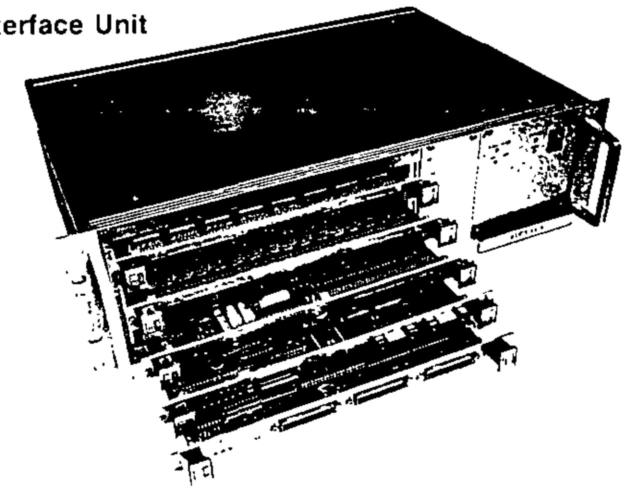
MDP-Multi Data Processor Interface Unit



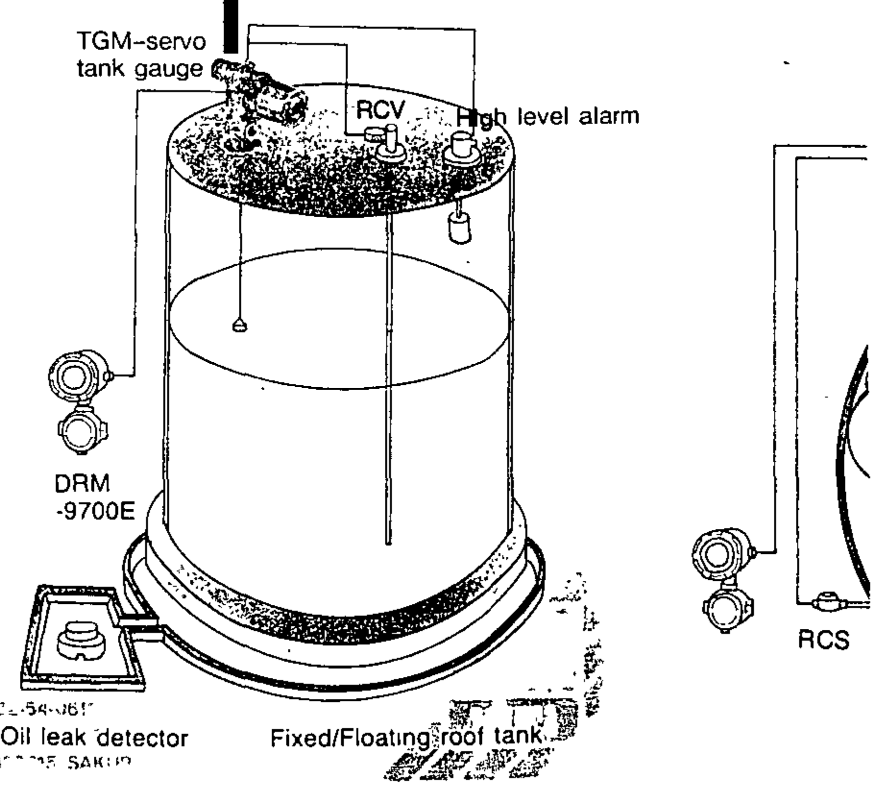
MDP-II Multi-Data-Processor

The system consists of an interface unit personal computer system with keyboard. The interface unit processes data signals of level, temperature and alarm from the gauges. The processed tank data is indicated on the associated CRT-Display in various display format/pages. Customer's tank data and basic data registration for computation can be performed or modified through simple keyboard operation. MDP-II-System is very flexible with auxiliary data processing and communication units, e.g. data logger, sub-receiver and host computer.

- Registered data is stored in a mini-floppy discs, eliminating the necessity of a back-up power supply against power failure.
- Test program and monitor program are built in the system for speedy trouble shooting.
- A variety of optional functions are prepared to make the system applicable to numerous fields.

Operation Capabilities

- Standardization has realized the compact design and low price.
- Tank data is acquired and computed incessantly for displaying accurate data at any time desired. Inventory and conditional variations can therefore be managed easily and accurately.
- The CRT display provides legible lists of data in numerous tanks, facilitating centralized control.
- Data acquisitions and basic data registration for computation can be performed by simple operations on a keyboard. Therefore, the microprocessor/receiver system permits modifying types of measuring liquids and alarm settings as well as data registration for additional tanks in a short time.
- The system automatically detects and displays troubles in transmitters and transmission cable, providing highly reliable data.



TECHNICAL SPECIFICATIONS

Item	Field Communication unit
Housing	Standard cabinet rack mounting
Capacity	Tank selecting capacity 140 tanks (Standard package)
Data	Tank-level: 0 to 99999mm Temperature: −50 to + 199.9°C Alarm 4 points
Accuracy	Tank level ±0.9mm (option ±0.5mm) Temperature. 0.1 C
Communica-ation	One twisted-pair max. connection to MDP-II serial card with RS-232C I/F for 5 channels 600 ~ 9600 BPS
Control-unit card	VCC-11 main card; VCD-10 (2-way 2-wire transmission) — Standard VME master card; VDI status input card: 64 bit; VDO alarm annunciator card: 64 bit — Option
Connector	Optical ring connector P1 VME bus DIN 96 pin P2 Sakura bus DIN 64 pin RS-232C D-sub 9 pin: 2 RS-232C D-sub 25 pin. 3
Research-function	Watch dog timer
Power voltage	DC 5V ± 5%
Signal-transnission	2-way 2-wire serial digital pulse linkage 2-way 1-wire optical optical data linkage
Connect-cont'l unit	Multi point: pull ring form
Transmission -code	V_1 transmission 7 bit ASCII
Allowable transmission way	Max. 0.3 μF capacitance 120 ohm per line wire resistance
Signal voltage	DC ± 6V ± 23V (trimmer adjustable)
Signal	V_1 transmission: command pulse (current pulse) V_1 transmission: response pulse (valtage pulse)
Optional status alarm	64 point/per card (VDO)
Transmitter applicable	TGM 4000 series, TMD1000 series
Data collec-tion mode	Free scan of all tanks at all times 180 ms/per tank
Power supply	100V 110V 120V 200V 220VAC (±10%), 50/60 Hz
Power-consumption	Approx-500 VA

Item	Processing display unit
Micro processor	IBM P.C. or compatible (386 or 486 type)
Memory-capacity	ROM: 2MB Floppy disk memory: 1.4 MB Hard disk memory: 20 MB
CRT display	14" color CRT × 25 lines (Standerd)
Key board	Alpha numeric keyboard, key arrangement according to IBM-P.C. / U.S. English type

Real-time clock arrangements	Clock with calendar (battery back-up)
Power supply	100V ~ 120V 200V ~ 220VAC 50/60 Hz
Printer	High-performance 24-wire letter quality printer

Item	Display function by CRT screen
Display function	Menu 1 page Index of registered tank No.(Index). 2 page Tank data set (table): 140 page max. make tanks table for 80 points Operation data set (OP set): 140 pages max System data set (sys set). 1 page Tank group set (gr. set): 99 groups/13 pages max. Tank detail data (Detail). 1 page Large character (Large): 1 page Tank group date list. 15 tank/page − 99 pages max. Transfer expectation (Expect): 1 page Tank historical (Histo): 1 page CRT off (off): 1 page
CRT data display	All registered data Month, day, o'clock and minute Product: registered name in 8 digits max. Tank No.: registered name in 8 digits max. Level measured value 5 digits max. Temp measured value 4 digits max. SP. Gr measured value and registered value 5 digits max Net volume at 15 C computed value in 9 digits (ℓ) Gross volume. computed value in 9 digits (ℓ) Alarm message Tank No. & type of alarm in 4 characters (red color)
Alarm	Level alarm displayed on CRT with annunciator Sound and optical annunciator Programmable level alarm set by keyboard Upper-upper, upper, lower, lower-lower limits : 4 points status-level alarm (2 points) Temp alarm, high temp., Low temp. by keyboard Computed based on measured level and registered alarm setting Setting of data collection mode. registered by key-board operation and by HHT-1
Alarm (message contents) Message	All kinds of alarm and Error displayed on CRT Annunciator sounds with Error code Status in all tanks and Registration in maintenance busy condition displayed on CRT
Computation function	Computed from measured level and tank table with 80 strapping points applicable
Gross volume Net volume	Volume converted at 15°C according to ASTM table Computed based on gross volume, temperature registed Sp. Gr. weight of floating roof Conversion of Sp Gr. according to ASTM table
Print out (Logging time)	Set the continuous print out Determines the printing format with time in the 1.Daily report 2.All group data report 3.Special group data report 4.One tank data report

Sakura Endress Co., Ltd.

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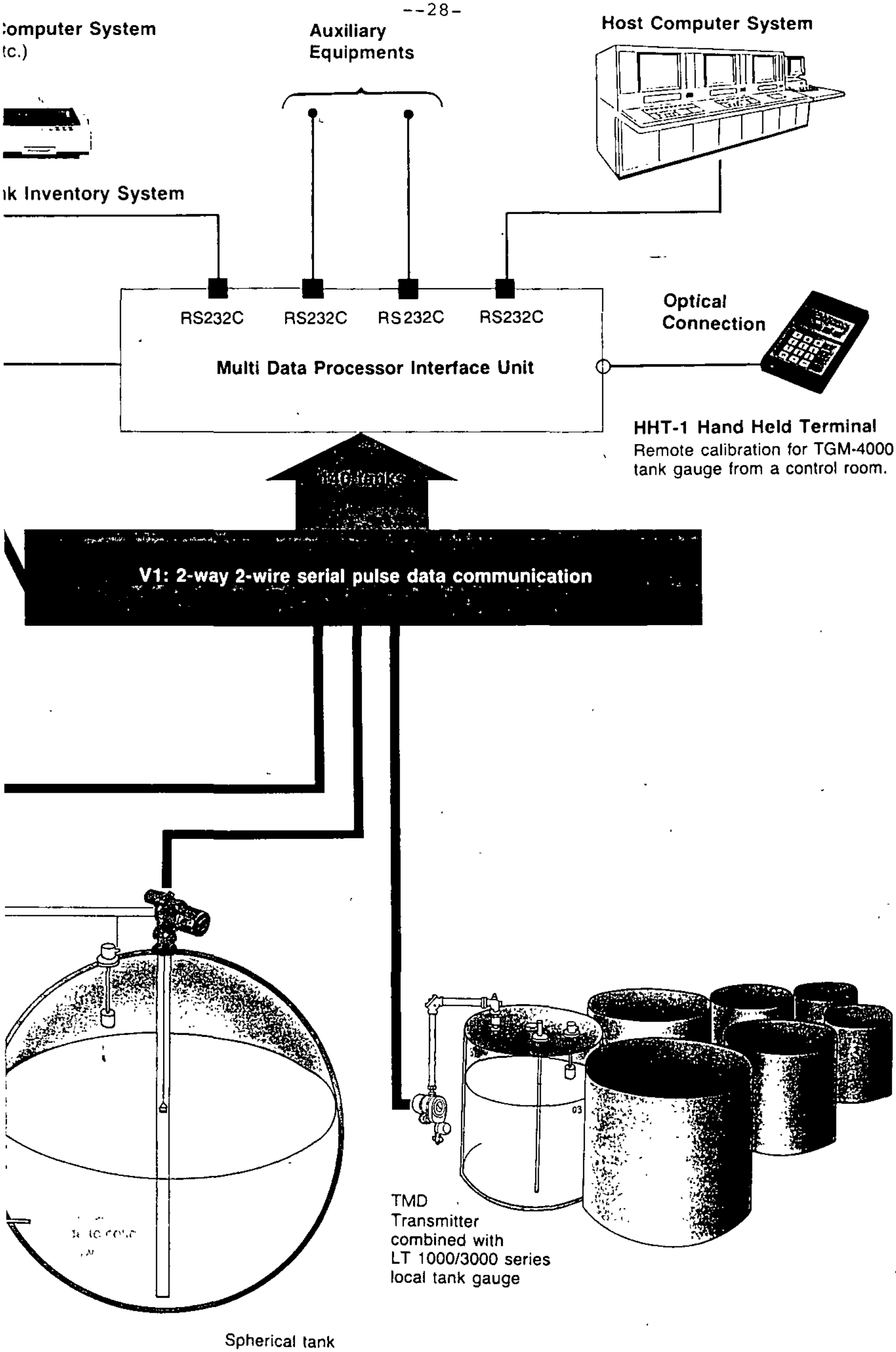

:omputer System
tc.)
Auxiliary
Equipments
Host Computer System
ık Inventory System
RS232C
RS232C
RS232C
RS232C
Multi Data Processor Interface Unit
Optical
Connection
HHT-1 Hand Held Terminal
Remote calibration for TGM-4000
tank gauge from a control room.
V1: 2-way 2-wire serial pulse data communication
TMD
Transmitter
combined with
LT 1000/3000 series
local tank gauge
Spherical tank

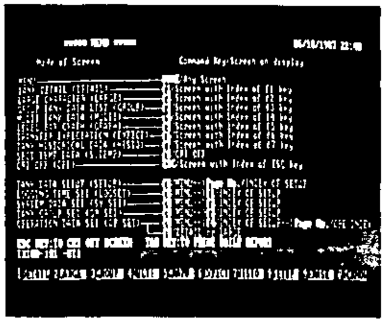
CRT DISPLAY MODE

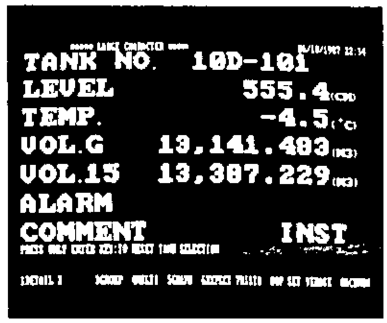
- MENU (Mode of screen)
- Tank detail (product tank data)
- Large character for a single tank
- Group tank data list (Daily report page)
- Multi tank data
- Product tank level bargraph
- Transfer expectation (movement/h or m)
- Tank historical data per tank
- Index of registered tank No.
- Tank data set-up
- Tank table data set-up
- Logging time set
- System data set
- Operation data set
- Tank group set
- Alarm display for all tanks, etc.
- Printer print-out function

Others on request

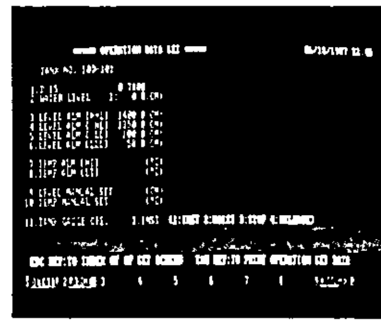
- Percentage bargraph
- Volume, Temp. bargraph
- Product weekly movement

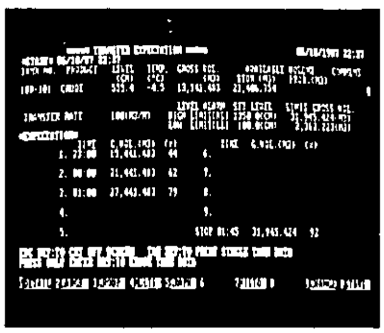
TYPICAL DATA DISPLAY FORMAT

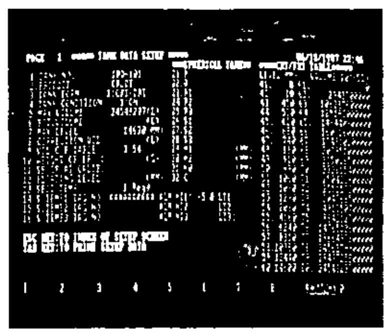

Menu page

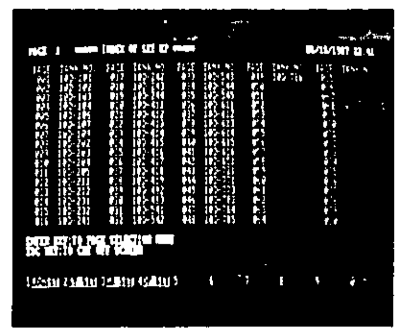


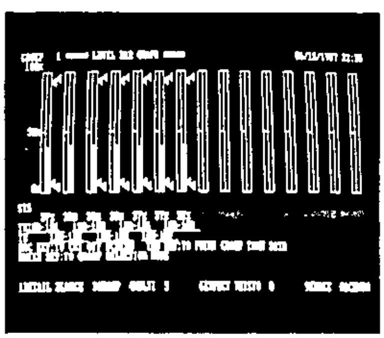
Large character page

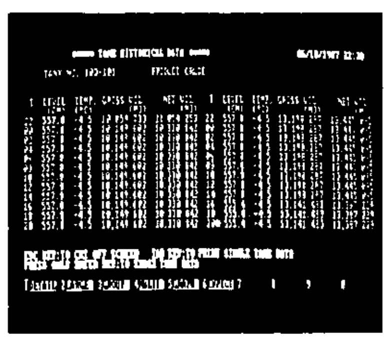

Operation data page

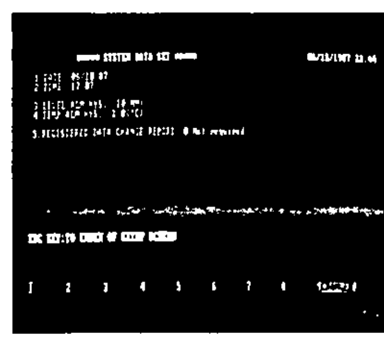

Transfer expectation data page


Tank data set-up page


Index of set-up page


Tank level bargraph page


Tank historical data page


System data set page

BRIEF SYSTEM REVIEW

The personal computer-based MDP-II system is designed to display the latest information up to 140 tanks on a color CRT screen. A variety of tank information can be obtained by continuous scanning of the outputs of field transmitters installed tank-side to collect data in a real-time mode showing the current status of individual tank.

The data to be collected includes:
1) Level
2) Temperature
3) Product identification
4) Gross volume
5) Net volume (converted at 15°C in compliance with ASTM TABLE)
6) Specific gravity
7) Level and temperature alarm status and error alarm
8) Flow rate
9) Others (option)

INTRODUCCION

"¿Puedo usar un capacitor de 0.22 uF en lugar de uno de 0.01 uF?".

"¿Es correcto sustituir un resistor de 10 000 ohms por uno de 12 000?".

Esta sección contestará esas preguntas comunes y muchas otras. Domínelas y estará bien preparado para comprender los circuitos que se explican en este libro.

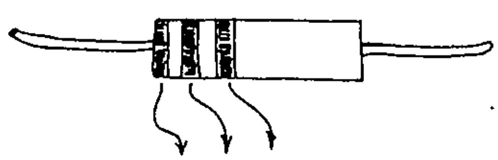
RESISTORES

Los resistores limitan el flujo de la corriente eléctrica. Un resistor tiene una resistencia (R) de 1 ohm, si una corriente (I) de 1 ampere fluye por ella cuando se aplica en sus extremos una diferencia de potencial (E) de 1 volt. En otras palabras:

$$R = \frac{E}{I} \quad ó \quad I = \frac{E}{R} \quad ó \quad E = IR$$

Estas fórmulas útiles expresan la ley de Ohm. Memorícelas, ya que tendrá que usarlas con frecuencia.

Los resistores se identifican por un código de colores:



COLOR	1	2	3 (Multiplicador)
NEGRO	0	0	1
MARRON	1	1	10
ROJO	2	2	100
ANARANJADO	3	3	1 000
AMARILLO	4	4	10 000
VERDE	5	5	100 000
AZUL	6	6	1 000 000
VIOLETA	7	7	10 000 000
GRIS	8	8	100 000 000
BLANCO	9	9	(ninguno)

Puede estar presente una cuarta banda de color que especifica la tolerancia del resistor. El color dorado indica ± 5%, el plateado ± 10% y la ausencia de la cuarta banda de color indica ± 20%.

Puesto que ningún resistor tiene una tolerancia perfecta, con frecuencia se sustituyen. Por ejemplo, casi siempre se puede emplear un resistor de 1.8 K en lugar de uno de 2 K; únicamente trate de mantenerse entre el 10 y el 20% del valor especificado.

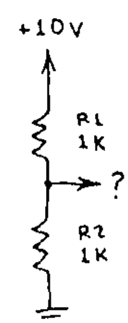
¿Qué significa la K? Es la abreviatura de 1 000. 20 K significa 20 x 1 000 ó 20 000 ohms. M es la abreviatura de megaohm ó 1 000 000 ohms; así, un resistor de 2.2 M tiene una resistencia de 2 200 000 ohms.

Los resistores que soportan mucha corriente deben poder disipar el calor producido. Utilice siempre resistores con la capacidad de disipación especificada. ¿No se especifica la disipación? Entonces úselos de 1/4 ó de 1/2 watt.

Casi todos los circuitos electrónicos utilizan resistores. A continuación se indican tres de los usos más importantes:

1. Para limitar la corriente de los diodos emisores de la luz (LED), transistores, altavoces, etc.

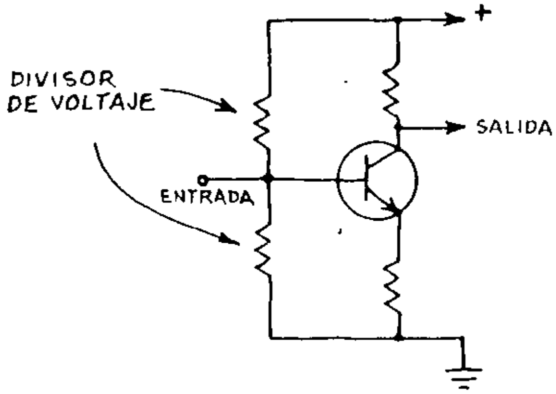
2. Dividen el voltaje; por ejemplo:



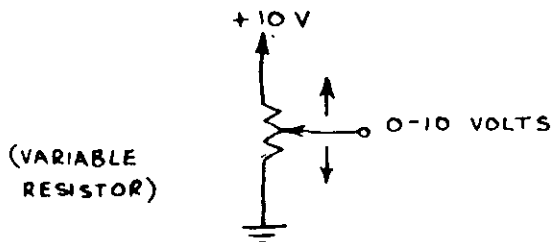
El voltaje en ¿ es I x R2. I expresa la corriente a través de R1 y R2, de modo que I= 10/(R1 + R2) ó 0.005 amperes. Por consecuencia ?= (0.005) x (1000) ó 5 volts.

Observe que la resistencia total de R1 y R2 es simplemente R1 + R2. Esta regla proporciona un medio útil para hacer resistencias a la medida.

Los divisores de voltaje se usan para polarizar transistores:



También son una fuente conveniente de voltaje variable.



Y también son útiles en circuitos sensores de voltaje. Véanse los circuitos comparadores en este cuaderno.

3. Controlan el tiempo de carga de los capacitores. Siga leyendo...

CAPACITORES

Los capacitores almacenan energía eléctrica e impiden el flujo de la corriente directa, dejando pasar la corriente alterna. La capacitancia se especifica en farads. Un farad representa una capacitancia inmensa, de modo que la mayoría de los capacitores tienen valores de pequeñas fracciones de un farad.

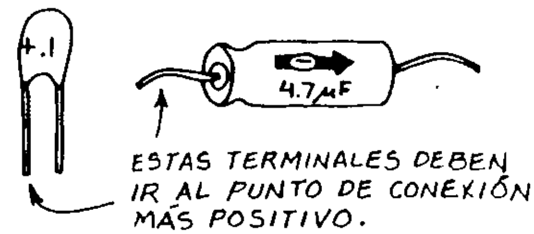
1 microfarad (uF) = 10^{-6} farad

1 picofarad (pF) = 10^{-12} farad

6
1 uF = 1 000 000 pF

El valor de un capacitor por lo general está impreso sobre el componente. Las designaciones uF y pF pueden no estar presente. Los pequeños marcados de 1 a 1000, están especificados en pF; los más grandes, marcados de .001 a 1 000, están especificados en uF.

Los capacitores electrolíticos proporcionan alta capacidad en espacio reducido. Sus terminales están polarizadas y deben conectarse en el circuito en la dirección apropiada.



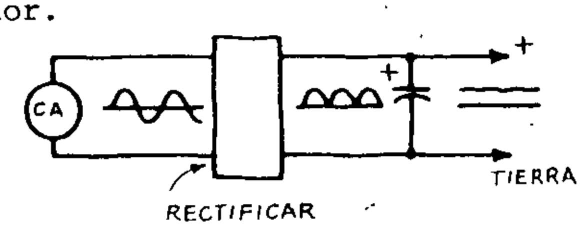
Los capacitores tienen especificación de voltaje, impresa generalmente bajo el valor de la capacitancia. La especificación de voltaje debe ser mayor que el máximo voltaje esperado (usualmente el voltaje de la fuente de alimentación).

Precaución: un capacitor puede almacenar carga por tiempo considerable después de desconectar la energía. ¡Esta carga puede ser peligrosa! Un capacitor electrolítico grande, cargado sólo a 5 ó 10 volts puede fundir la punta de un destornillador colocado entre sus terminales. ¡Los capacitores de alto voltaje pueden almacenar cargas letales! Descargue un capacitor conectando cuidadosamente un resistor a sus terminales 1 K o más; use la ley de Ohm. Use sólo una mano para evitar tocar ambas terminales del capacitor.

Aplicaciones importantes de los capacitores:

1. Eliminan los transitorios de la fuente de alimentación (Conecte un capacitor de 0.01 a 0.1 uF a las patas de la fuente de alimentación en los CI digitales; esto evita el disparo en falso.)

2. Suavizan el voltaje alterno rectificado, convirtiéndolo en voltaje directo (Conecte de 100 a 10 000 uF a la salida del rectificador.

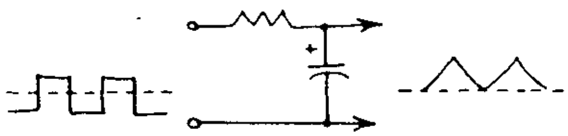


3. Bloquean la señal de CC y dejan pasar la señal de

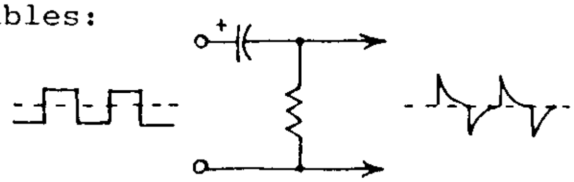
4. Dejan pasar la señal de alrededor de un circuito o a tierra.

5. Filtran las componentes no deseadas de una señal variable.

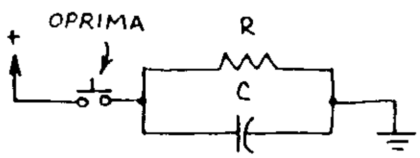
6. Se emplean con resistores para integrar señales variables.



7. O para diferenciar señales variables:



8. Realizan funciones de temporización:



C se carga rápidamente... después se descarga lentamente a través de R.

9. Almacenan carga para mantener un transistor en corte o en conducción.

10. Almacenan carga para vaciarla a través de un tubo de destello o un LED, como un pulso rápido y potente.

¿Puede usted sustituir capacitores? En la mayor parte de los casos, el cambiar el valor de un capacitor en 10% o aún en 100% no causará fallas, pero puede afectar al funcionamiento del circuito. En un circuito temporizador, por ejemplo, el aumento de valor del capacitor de temporización alargará el período de temporización. El cambio de los capacitores en un filtro, alterará la respuesta en frecuencia del filtro. Asegúrese de usar la especificación adecuada de voltaje y no se preocupe por la diferencia entre 0.47 y 0.5 uF.

SEMICONDUCTORES

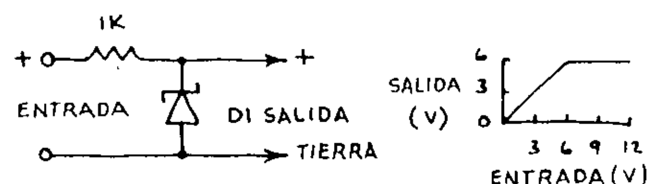
Generalmente se fabrican de silicio. Asegúrese de observar todas las restricciones de operación. He aquí unas breves descripciones de dispositivos semiconductores importantes:

DIODOS

Permiten el flujo de corriente en una sola dirección (polarización directa). Se usan para rectificar, permiten que la corriente fluya hacia un circuito pero bloquean su retorno, etc.

DIODOS ZENER

El diodo zener es un regulador de voltaje. En este circuito típico, el voltaje que excede al voltaje de disrupción del diodo se deriva a tierra:



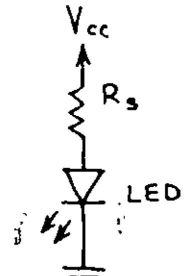
D1 = DIODO ZENER DE 6 VOLTS

Los diodos zener también pueden proteger los componentes sensibles al voltaje y proporcionar voltajes de referencia convenientes.

DIODOS EMISORES DE LUZ (LED)

Los LED emiten luz verde, amarilla, roja o infrarroja cuando están polarizados directamente. Debe emplearse un resistor en serie para limitar la corriente a menos de la máxima permitida:

$$R_S = \frac{V_{CC} - V_{LED}}{I_{LED}}$$



Ejemplo: V_{LED} de un LED rojo es 1.7 volts. Para una corriente en sentido directo (I_{LED}) de 20 mA a V = 5 volts, R = 165 ohms. ¡No exceda la I_{LED}!

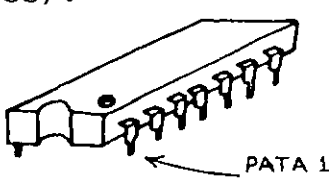
Los LED infrarrojos son mucho más potentes que los visibles, pero su radiación es totalmente invisible. Uselos para detectores de objetos y para comunicadores.

TRANSISTORES

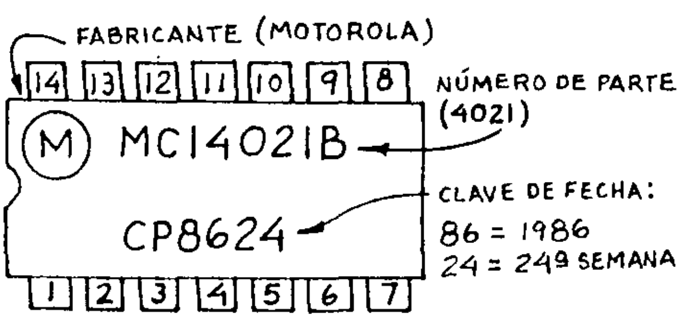
En estos apuntes los transistores se utilizan como simples amplificadores e interruptores que encienden los LED. Esto se logra con cualquier transistor de conmutación de propósito general.

CIRCUITOS INTEGRADOS

Puesto que un CI es un circuito completo en una pastilla de silicio, se deben observar todas las restricciones de operación. La polaridad invertida, el voltaje excesivo de alimentación y suministrar o extraer mucha corriente pueden destruir un CI. Asegúrese de prestar mucha atención a la ubicación de las patas de la fuente de alimentación. La mayoría de los CI están encapsulados en plástico de 8, 14 ó 16 patas (DIP o Duan In-line Packages).



Cuando el CI está de cara hacia arriba, la pata 1 se encuentra en el extremo inferior izquierdo:



A propósito, la clave de fecha puede no estar presente, pero otros números sí... y la clave de fecha no siempre está debajo del número de dispositivo:

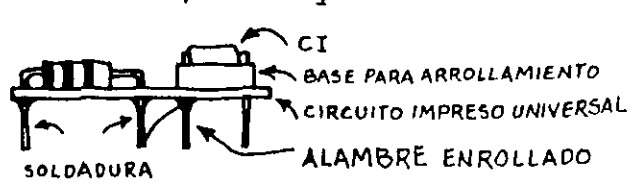
Almacene los CI en un gabinete de plástico, si puede conseguir uno, o bien insértelos en una bandeja de espuma de plástico (como las que se emplean para la carne en las tiendas de autoservicio). PRECAUCION: nunca guarde los CI MOS/CMOS en plástico ordinario no conductivo.

CONSTRUCCION DE CIRCUITOS

Construya sus circuitos en una tablilla de las que no requieren soldadura, para hacer cambios y encontrar errores; después haga versiones permanentes. Son ideales las tablillas modulares de plástico, Radio Shack (276-173, etc.) Incluyen dos filas de contactos para las fuentes de alimentación y rieles de sujeción para unir las tablillas. Los componentes y alambres pueden insertarse directamente en los agujeros de la base.

En el caso de los circuitos permanentes, utilice circuitos impresos Radio Shack; los que tienen números de catálogo 276-024 y 276-151 son ideales para proyectos simples con CI. Para proyectos más complejos utilice circuitos impresos universales mayores (276-152 y 276-157). Puede cortarlos en secciones más pequeñas con una segueta.

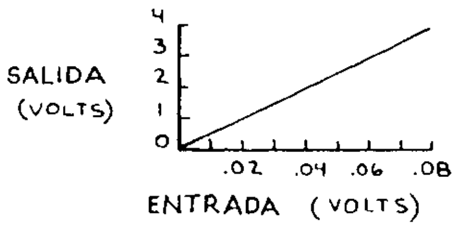
Yo prefiero usar alambre enrollado para los proyectos con CI. Inserte las bases para arrollamiento en el circuito impreso y efectúe las conexiones con una herramienta enrolladora de alambre (como la 276-1570). Aplique este alambre directamente a las terminales de los transistores, resistores, etc. y súldelo.



CIRCUITOS INTEGRADOS LINEALES

INTRODUCCIÓN

LA SALIDA DE UN CI LINEAL ES PROPORCIONAL A LA SEÑAL EN SU ENTRADA. EL CI LINEAL CLÁSICO ES EL AMPLIFICADOR OPERACIONAL. LA GRÁFICA MUESTRA LA RELACIÓN LINEAL ENTRE LA SALIDA Y LA ENTRADA DE UN CIRCUITO TÍPICO CON AMPLIFICADOR OPERACIONAL:



MUCHOS CI NO DIGITALES, ENTRE ELLOS LOS AMPLIFICADORES OPERACIONALES, PUEDEN USARSE TANTO EN EL MODO LINEAL COMO EN EL NO LINEAL. A VECES SE LLAMAN CI ANALÓGICOS.

LOS CI LINEALES GENERALMENTE REQUIEREN MÁS COMPONENTES EXTERNAS QUE LOS CI DIGITALES, LO QUE AUMENTA SU SUSCEPTIBILIDAD AL RUIDO EXTERNO Y HACE QUE SU USO REQUIERA MÁS CUIDADO. POR OTRA PARTE, ALGUNOS CI LINEALES PUEDEN HACER ESENCIALMENTE LO MISMO QUE TODA UNA RED DE CI DIGITALES.

HE AQUÍ UNA BREVE DESCRIPCIÓN DE LOS CI LINEALES INCLUIDOS EN ESTA SECCIÓN.

REGULADORES DE VOLTAJE

PROPORCIONA UN VOLTAJE ESTABLE, YA SEA FIJO O AJUSTABLE, AL QUE NO AFECTAN LOS CAMBIOS EN EL VOLTAJE DE ALIMENTACIÓN, MIENTRAS QUE SE MANTENGA POR ARRIBA DEL VOLTAJE DESEADO DE SALIDA.

AMPLIFICADORES OPERACIONALES

ES CASI EL AMPLIFICADOR IDEAL. ALTA GANANCIA E IMPEDANCIA DE ENTRADA. LA GANANCIA SE CONTROLA FÁCILMENTE CON UN SOLO RESISTOR DE RETROALIMENTACIÓN. LOS AMPLIFICADORES OPERACIONALES DE ENTRADA POR FET (BIFETS) TIENEN UNA RESPUESTA EN FRECUENCIA MUY AMPLIA. GENERALMENTE PUEDEN SUSTITUIRSE LOS AMPLIFICADORES OPERACIONALES CUANDO LA ALIMENTACIÓN NORMAL DE AMBOS SE REALIZA CON FUENTE BIPOLAR (½ LF353 POR UN 741C, ETC.)... PERO EL DESEMPEÑO SERÁ MEJOR O PEOR DE ACUERDO CON LAS ESPECIFICACIONES DEL NUEVO AMPLIFICADOR.

COMPARADOR

ES LO MISMO QUE UN AMPLIFICADOR OPERACIONAL SIN RESISTOR DE RETROALIMENTACIÓN. TIENE GANANCIA ULTRA ALTA QUE DA UNA RESPUESTA DE TIPO ESCALÓN AL VOLTAJE APLICADO A UNA ENTRADA, CUANDO EXCEDE AL VOLTAJE DE REFERENCIA QUE SE APLICA A UNA SEGUNDA ENTRADA.

TEMPORIZADORES

ÚSELOS SOLOS O CON OTROS CI PARA NUMEROSAS APLICACIONES DE TEMPORIZACIÓN DE PULSOS.

CI PARA LED

LOS MÁS IMPORTANTES SON UN CI DESTELLADOR Y UN CONVERTIDOR ANALÓGICO DIGITAL PARA UNA PANTALLA DE PUNTOS Y BARRAS. SON FÁCILES DE USAR.

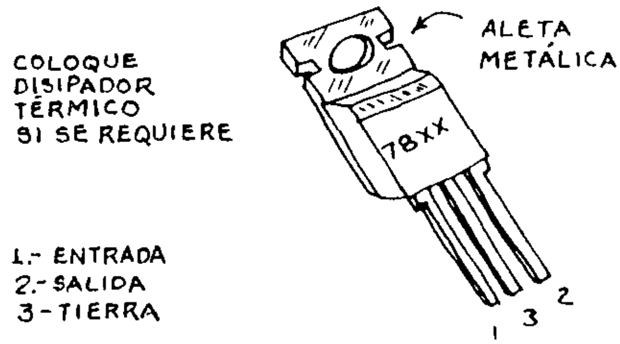
OSCILADORES

UN OSCILADOR CONTROLADO POR VOLTAJE Y UN CONVERTIDOR COMBINADO DE VOLTAJE A FRECUENCIA Y DE FRECUENCIA A VOLTAJE. SE INCLUYE TAMBIÉN UN DECODIFICADOR DE TONO QUE PUEDE USARSE PARA INDICAR UNA FRECUENCIA ESPECÍFICA.

AMPLIFICADORES DE AUDIO

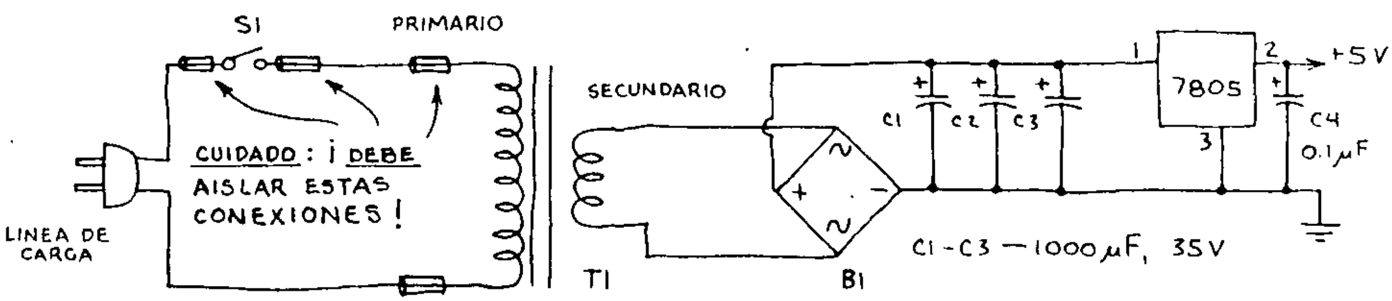
ESTA SECCIÓN INCLUYE VARIOS AMPLIFICADORES DE POTENCIA DE USO FÁCIL, QUE SON IDEALES PARA QUE UNO MISMO CONSTRUYA ESTÉREOS, SISTEMAS DE SONIDO, INTERCOMUNICADORES Y OTRAS APLICACIONES DE AUDIO.

REGULADORES DE VOLTAJE
7805 (5- VOLTS)
7812 (12- VOLTS)
7815 (15- VOLTS)



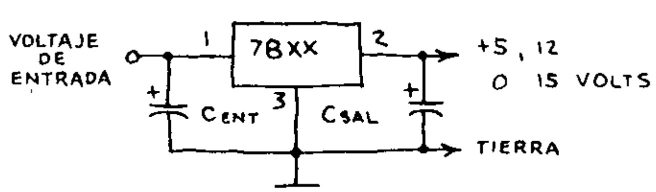
REGULADORES DE VOLTAJE FIJO. SON IDEALES PARA FUENTES DE ALIMENTACIÓN AUTÓNOMAS, REGULADORES SOBRE TABLILLAS, PROYECTOS PARA AUTOMÓVILES CON ALIMENTACIÓN DE BATERÍA, ETC. TIENEN SALIDAS HASTA DE 1.5 AMPERES SI SE TIENE DISIPACIÓN TÉRMICA ADECUADA Y SUFICIENTE CORRIENTE DE ENTRADA. UN CIRCUITO DE CORTE TÉRMICO APAGA EL REGULADOR SI EL DISIPADOR ES MUY PEQUEÑO.

FUENTE DE ALIMENTACIÓN DE 5 VOLTS TTL/LS CONECTADA A LA LÍNEA



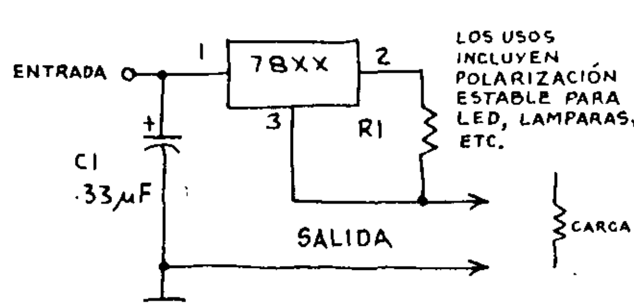
T1 - TRANSFORMADOR DE 117 A 12.6 V, 1.2 ó 3 A (273-1505 o 273-1511)
B1 - RECTIFICADOR DE ONDA COMPLETA 1 A 4 A (276-1161, 276-1151 o 276-1171)
(ENTRE PARÉNTESIS LOS NÚMEROS DE CATÁLOGO RADIO SHACK)

REGULADOR DE VOLTAJE



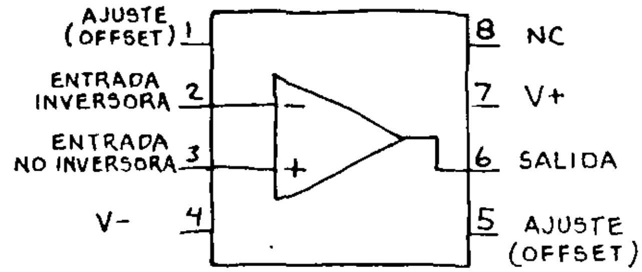
CENT - OPCIONAL; USE 0.33 µF O UN VALOR SEMEJANTE SI EL REGULADOR ESTÁ LEJOS DE LA FUENTE DE ALIMENTACIÓN.
CSAL - OPCIONAL; USE 0.1 µF O MÁS PARA ELIMINAR PICOS QUE AFECTEN A LOS CI LÓGICOS

REGULADOR DE CORRIENTE



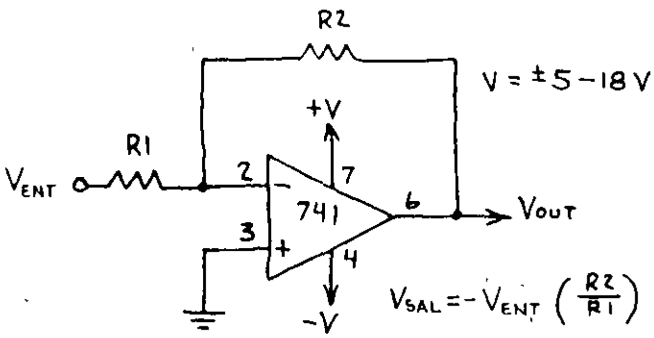
$$\text{CORRIENTE DE SALIDA} = \frac{\text{VOLTAJE DEL REGULADOR}}{\text{R1}}$$

AMPLIFICADOR OPERACIONAL 741C

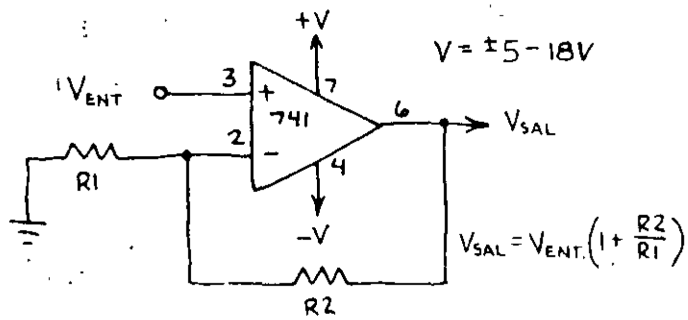


ES EL AMPLIFICADOR OPERACIONAL MÁS POPULAR. ÚSELO EN TODAS LAS APLICACIONES DE PROPÓSITO GENERAL. (PARA OPERACIÓN CON UNA SOLA FUENTE Y MUY ALTA IMPEDANCIA DE ENTRADA UTILICE OTROS AMPLIFICADORES OPERACIONALES INCLUIDOS EN ESTE CUADERNO.)

AMPLIFICADOR INVERSOR

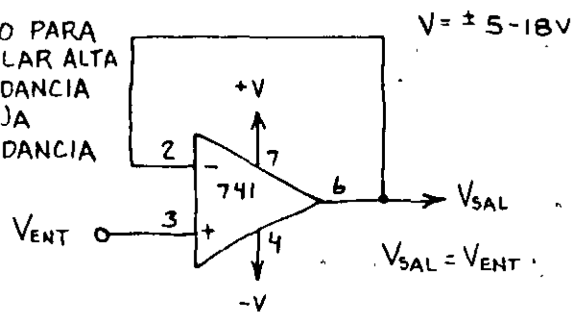


AMPLIFICADOR NO INVERSOR

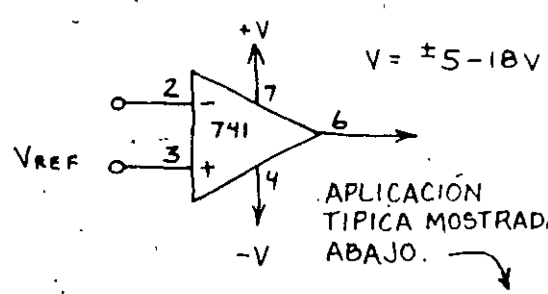


SEGUIDOR DE VOLTAJE DE GANANCIA UNITARIA

ÚSELO PARA ACOPLAR ALTA IMPEDANCIA A BAJA IMPEDANCIA

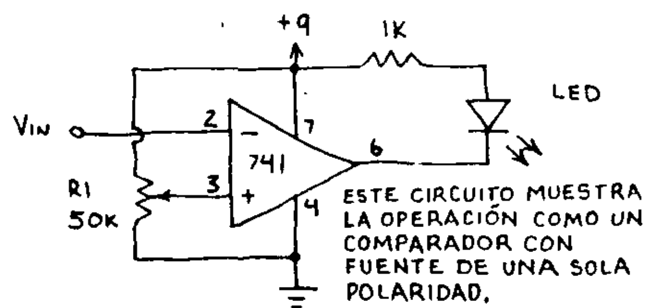


COMPARADOR



APLICACIÓN TÍPICA MOSTRADA ABAJO.

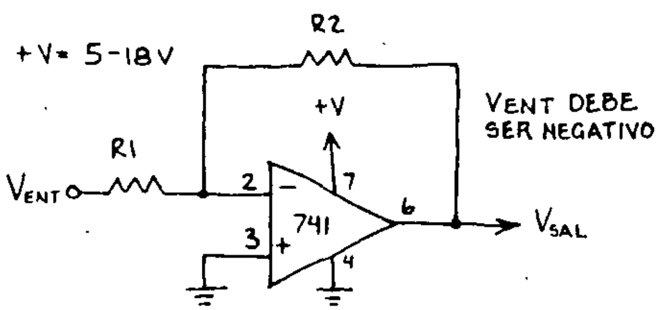
DETECTOR DE NIVEL



ESTE CIRCUITO MUESTRA LA OPERACIÓN COMO UN COMPARADOR CON FUENTE DE UNA SOLA POLARIDAD.

R1 AJUSTA EL UMBRAL DE DETECCIÓN DE VOLTAJE (HASTA + 9V). CUANDO V_{ENT} EXCEDE AL UMBRAL (TAMBIÉN LLAMADO REFERENCIA), EL LED SE ENCIENDE.

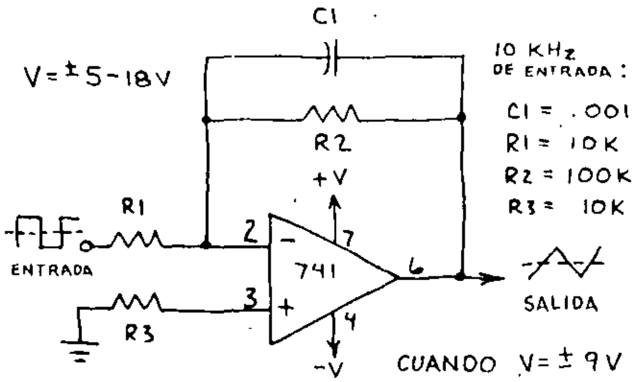
FUENTE DE UNA SOLA POLARIDAD



USOS TÍPICOS: AMPLIFICACIÓN DE VOLTAJE CC Y PULSOS.

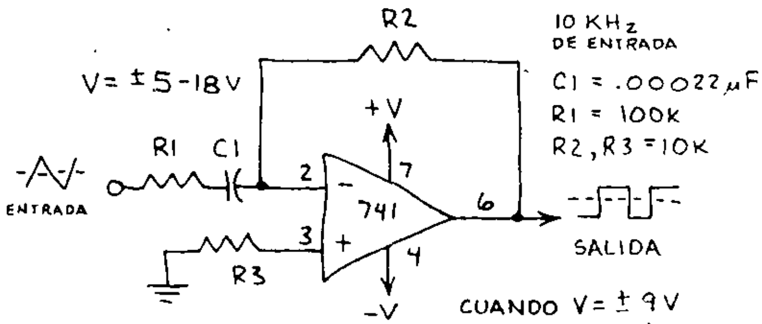
AMPLIFICADOR OPERACIONAL (CONTINUACIÓN)
741C

INTEGRADOR BÁSICO



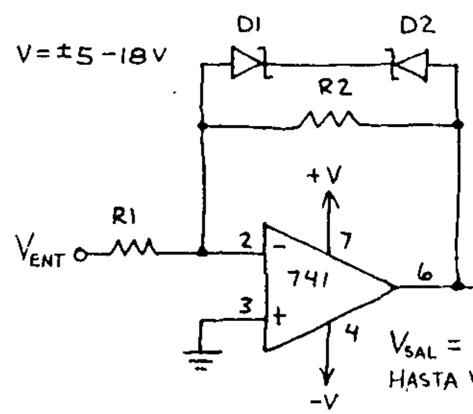
CUANDO V = ± 9V
Y LA ENTRADA = ± .25 V,
SALIDA = ± 1 V

DIFERENCIADOR BÁSICO



CUANDO V = ± 9 V
Y LA ENTRADA = ± .25 V,
SALIDA = ± .25 V

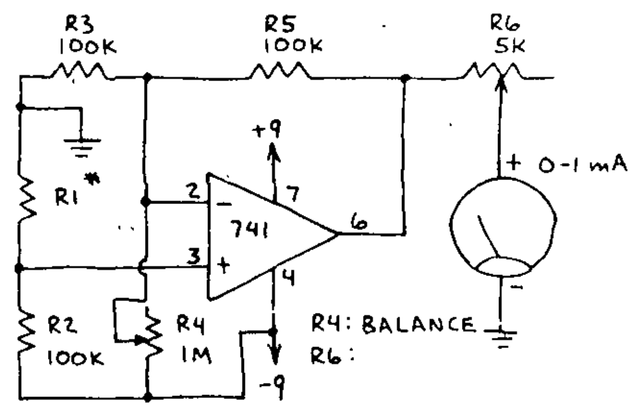
AMPLIFICADOR RECORTADOR



D1 Y D2 = DIODOS ZENER.
SI $V_Z = 6V$, ENTONCES LA SALIDA NO PUEDE EXCEDER DE ± 6.7 V.

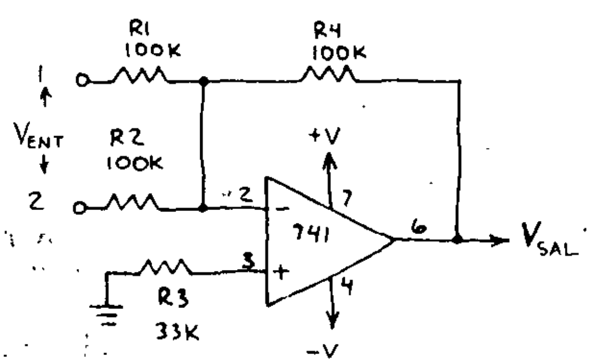
$V_{SAL} = V_{ENT}\left(\frac{R2}{R1}\right)$... HASTA $V_Z + 0.7V$

AMPLIFICADOR DE PUENTE



R1 ES UN RESISTOR DE VALOR DESCONOCIDO. USE UNA CELDA DE CdS EN LUGAR DE R1 PARA HACER UN MEDIDOR DE LUZ MUY SENSIBLE.

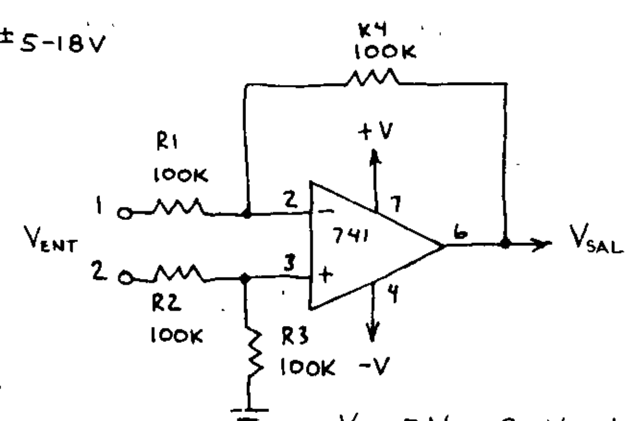
AMPLIFICADOR SUMADOR



$-V_{SAL} = -(V_{ENT}1 + V_{ENT}2)$

AMPLIFICADOR DE DIFERENCIA

V = ±5-18V



NOTA: V_{SAL} NO PUEDE EXCEDER DE ± V

$V_{SAL} = V_{ENT}2 - V_{ENT}1$

CIRCUITOS INTEGRADOS DIGITALES

INTRODUCCIÓN

LOS CI DIGITALES SON DISPOSITIVOS DE DOS ESTADOS. UN ESTADO ESTÁ CERCANO A 0 VOLT. O TIERRA (BAJO O L) Y EL OTRO ESTÁ CERCANO AL VOLTAJE DE ALIMENTACIÓN DEL CI (ALTO Ó H). SUBSTITUYENDO L POR O Y H POR 1, LOS CI DIGITALES PUEDEN PROCESAR DÍGITOS BINARIOS (BITS) O PALABRAS DE MÚLTIPLES BITS. UNA PALABRA DE 4 BITS SE LLAMA <u>NIBBLE</u> Y UNA DE 8 BITS SE LLAMA <u>BYTE</u>.

EL SISTEMA BINARIO

ES DE GRAN AYUDA SABER LOS PRIMEROS 16 NÚMEROS BINARIOS: SI O = L Y 1 = H, ESTOS NÚMEROS SON:

0 - L L L L	8 - H L L L
1 - L L L H	9 - H L L H
2 - L L H L	10 - H L H L
3 - L L H H	11 - H L H H
4 - L H L L	12 - H H L L
5 - L H L H	13 - H H L H
6 - L H H L	14 - H H H L
7 - L H H H	15 - H H H H

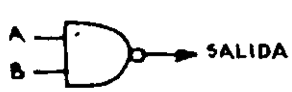
NÓTESE QUE LLLL(O) ES UN NÚMERO IGUAL QUE CUALQUIER OTRO.

COMPUERTAS LÓGICAS

LOS CIRCUITOS LÓGICOS SE FORMAN INTERCONECTANDO DOS O MÁS DE ESTAS COMPUERTAS LÓGICAS BÁSICAS:

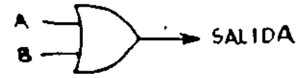
AND

A	B	SALIDA
L	L	L
L	H	L
H	L	L
H	H	H



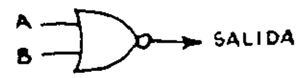
NAND

A	B	SALIDA
L	L	H
L	H	H
H	L	H
H	H	L



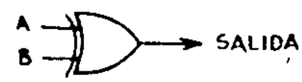
OR

A	B	SALIDA
L	L	L
L	H	H
H	L	H
H	H	H



NOR

A	B	SALIDA
L	L	H
L	H	L
H	L	L
H	H	L



OR EXCLUSIVO

A	B	SALIDA
L	L	L
L	H	H
H	L	H
H	H	L

NOR-EXCLUSIVO

A	B	SALIDA
L	L	H
L	H	L
H	L	L
H	H	H

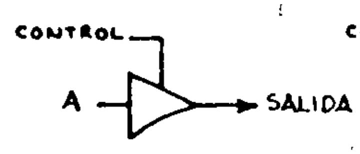
SEPARADOR (BUFFER)

A	SALIDA
L	L
H	H

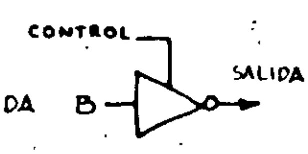
INVERSOR

A	SALIDA
L	H
H	L

LÓGICA DE 3 ESTADOS



CONTROL	A	SALIDA
L	L	L
L	H	H
H	X	Z-ALTA

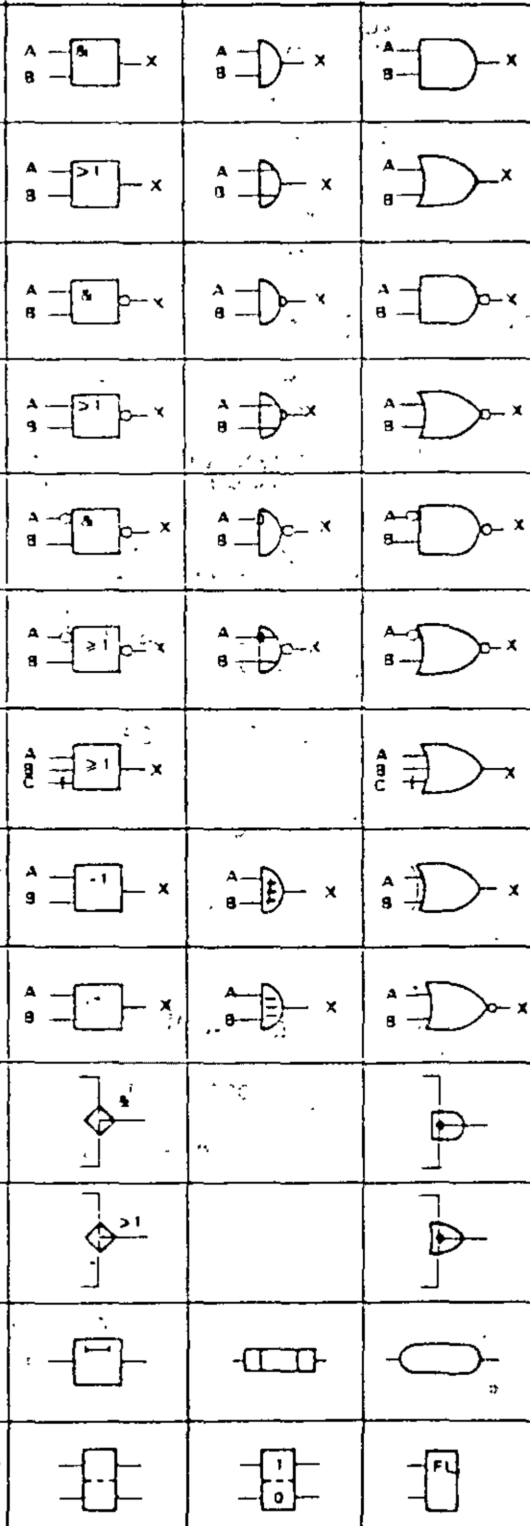


CONTROL	A	SALIDA
L	L	H
L	H	L
H	X	Z-ALTA

Z-ALTA: SALIDA EN ESTADO DE ALTA IMPEDANCIA.

TABLE 3.1 Standard Symbols for Logic Elements

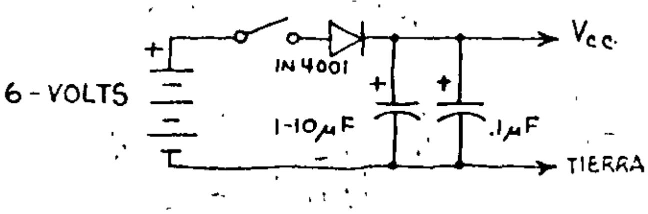
Circuit	IEC norm	DIN norm, 40700	American standard	Boolean function
AND				$X = AB$
OR				$X = A + B$
NAND				$X = \overline{AB}$
NOR				$X = \overline{A + B}$
NAND with one inverting input				$X = \overline{\bar{A}B}$
NOR with one inverting input				$X = \overline{\bar{A} + B}$
Inhibit gate				$X = (A + B)\bar{C}$
Exclusive OR				$X = A\bar{B} + \bar{A}B$ $A \oplus B$
Comparator				$X = AB + \bar{A}\bar{B}$ $A \equiv B$
Distributed AND				
Distributed OR				
Delay				
Flip-flop				



CIRCUITOS INTEGRADOS TTL/LS

INTRODUCCIÓN

LA FAMILIA TTL ES LA MEJOR ESTABLECIDA Y MÁS DIVERSIFICADA DE LOS CIRCUITOS INTEGRADOS. LA FAMILIA LS ES FUNCIONALMENTE IDÉNTICA A TTL, PERO ES UN POCO MÁS RÁPIDA Y CONSUME 80% MENOS POTENCIA. LOS CIRCUITOS INTEGRADOS TTL/LS REQUIEREN UNA FUENTE DE VOLTAJE REGULADA DE 4.75 A 5.25 VOLTS. HE AQUÍ UNA FUENTE SIMPLE CON BATERÍA:



EL DIODO REDUCE EL VOLTAJE DE LA BATERÍA A UN NIVEL SEGURO. AMBOS CAPACITORES DEBEN INSTALARSE EN LA TABLILLA DEL CIRCUITO TTL/LS. LOS CIRCUITOS CON MUCHOS CIRCUITOS INTEGRADOS DE TTL/LS PUEDEN CONSUMIR MUCHA CORRIENTE. USE UNA FUENTE DE ALIMENTACIÓN COMERCIAL DE 5 VOLTS CONECTADA A LA LÍNEA PARA AHORRAR BATERÍAS, O CONSTRUYA LA SUYA PROPIA (VEA EL 7805 EN LA PAGINA 86).

REQUERIMIENTOS DE OPERACIÓN

1. Vcc NO DEBE EXCEDER DE 5.25 VOLTS.

2. LAS SEÑALES DE ENTRADA NUNCA DEBEN EXCEDER A Vcc NI SER INFERIORES AL NIVEL DE TIERRA.

3. LAS ENTRADAS TTL/LS NO CONECTADAS POR LO GENERAL TOMAN EL ESTADO H... ¡PERO NO CUENTE CON ELLO! SI UNA ENTRADA DEBE ESTAR FIJA EN H, CONÉCTELA A Vcc.

4. SI UNA ENTRADA DEBE ESTAR FIJA EN L, CONÉCTELA A TIERRA.

5. CONECTE LAS ENTRADAS NO USADAS DE AND/NAND/OR A UNA ENTRADA USADA DEL MISMO CI.

6. OBLÍGUE A LAS SALIDAS DE COMPUERTAS NO USADAS A ESTAR EN NIVEL H PARA AHORRAR CORRIENTE (NAND- UNA ENTRADA H; NOR-TODAS LAS ENTRADAS L).

7. USE AL MENOS UN CAPACITOR DE DESACOPLAMIENTO (0.01-0.1µF) POR CADA 5 A 10 PAQUETES DE COMPUERTAS, UNO POR CADA 2 A 5 CONTADORES Y REGISTROS Y UNO POR CADA MONOESTABLE. LOS CAPACITORES DE DESACOPLAMIENTO NEUTRALIZAN LOS PICOS DE VOLTAJE DE LA FUENTE DE ALIMENTACIÓN QUE OCURREN CUANDO UNA SALIDA TTL/LS CAMBIA DE ESTADO. LOS CAPACITORES DEBEN TENER TERMINALES CORTAS Y CONECTARSE ENTRE Vcc Y TIERRA LO MÁS CERCA POSIBLE DE LOS CI TTL/LS.

8. EVITE LOS CABLES LARGOS DENTRO DE LOS CIRCUITOS.

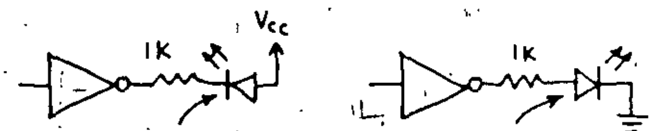
9. SI LA FUENTE DE ALIMENTACIÓN NO ESTÁ SOBRE LA TABLILLA DEL CIRCUITO, CONECTE UN CAPACITOR DE 1 A 10µF A LAS TERMINALES DE LA FUENTE DE ALIMENTACIÓN A SU LLEGADA A LA TABLILLA.

INTERCONEXIÓN DE TTL/LS

1. UNA SALIDA TTL PUEDE ALIMENTAR HASTA 10 ENTRADAS TTL O 20 LS.

2. UNA SALIDA LS PUEDE ALIMENTAR HASTA 5 ENTRADAS TTL O 10 LS.

3. EXCITADORES DE LED CON TTL/LS.



ENCIENDE CUANDO L   ENCIENDE CUANDO H

LOCALIZACIÓN DE FALLAS EN TTL/LS

1. ¿VAN TODAS LAS ENTRADAS A ALGUNA PARTE?

2. ¿ESTÁN TODAS LAS PATAS DEL CI INSERTADAS EN LA TABLILLA O EN SU BASE?

3. ¿CUMPLE EL CIRCUITO CON TODOS LOS REQUERIMENTOS DE OPERACIÓN DE TTL/LS?

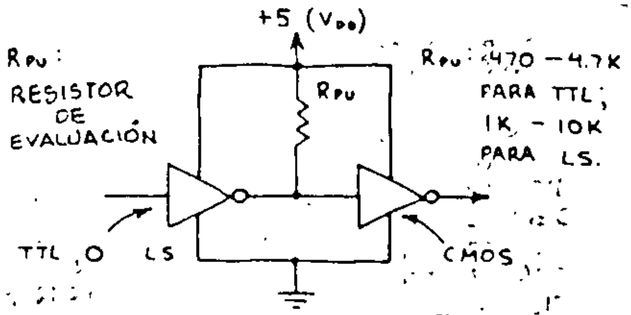
4. ¿NO OLVIDÓ ALGUNA CONEXIÓN?

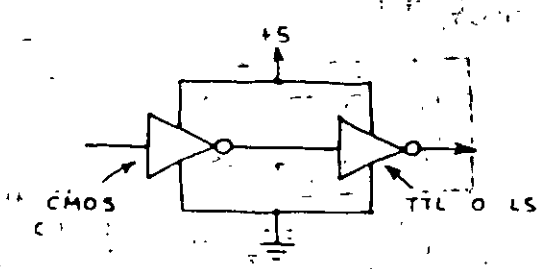
5. ¿USÓ SUFICIENTES CAPACITORES DE DESACOPLAMIENTO? ¿SON CORTAS SUS TERMINALES?

6. ¿ESTÁ Vcc DENTRO DE LOS LÍMITES EN CADA CI?

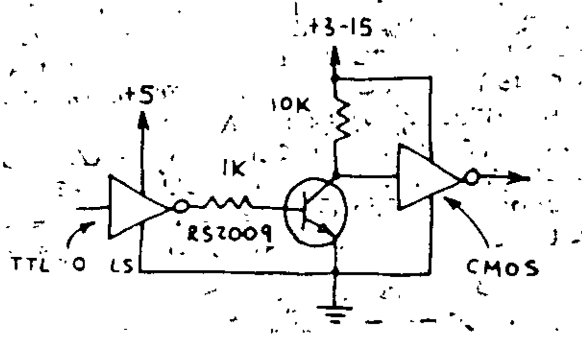
INTERCONEXION DE CMOS

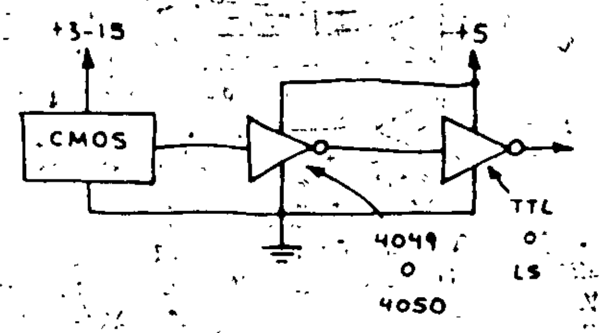
1. SI LOS VOLTAJES DE ALIMENTACIÓN SON IGUALES:





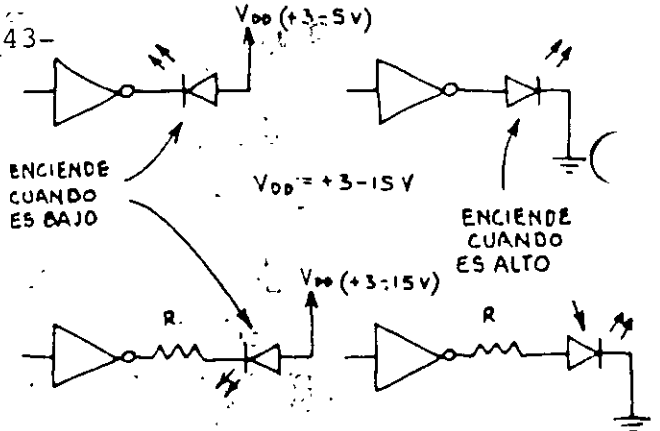
2. VOLTAJES DE ALIMENTACIÓN DIFERENTES.





OBSÉRVESE QUE LOS CIRCUITOS CMOS DEBEN ALIMENTARSE POR LO MENOS CON 5 VOLTS CUANDO SE INTERCONECTAN CON CIRCUITOS T.T.L. DE OTRA MANERA LA ENTRADA AL CMOS EXCEDERÍA A V_{DD}

3. EXCITADORES DE LED CON CMOS.

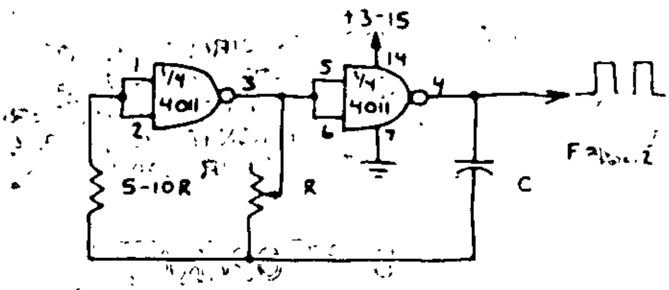


$$R = \frac{V_{DD} - 1.7}{.01}$$ PARA CORRIENTE DE LED DE 10 mA

USE 1000 OHMS PARA LA MAYORÍA DE APLICACIONES.

RELOJ LÓGICO CON CMOS

MUCHOS CIRCUITOS DE ESTA SECCIÓN REQUIEREN UNA FUENTE DE PULSOS. HE AQUÍ UN RELOJ SIMPLE CON CMOS.



VALORES TÍPICOS: R = 100 K, C = 0.01 - 0.1 uF

SE PUEDE USAR EL 4049 ... PERO CONSUMIRÁ UNA CORRIENTE MUCHO MAYOR.

LOCALIZACIÓN DE FALLAS EN CMOS

1. ¿ VAN A ALGUNA PARTE TODAS LAS ENTRADAS ?

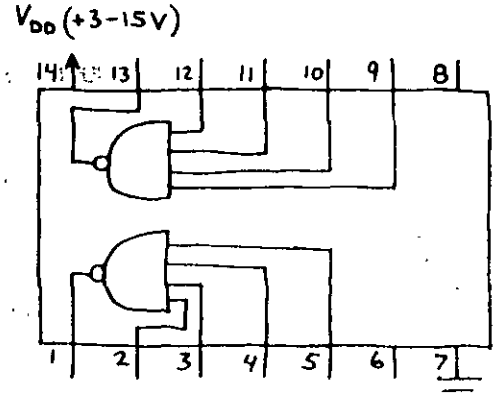
2. ¿ ESTÁN TODAS LAS PARTES DEL CI INSERTADAS EN LA TABLILLA O EN LA BASE ?

3. ¿ ESTÁ CALIENTE EL CI ? SI ES ASÍ, VEA LOS NÚMEROS 1 Y 2 ANTERIORES Y ASEGÚRESE DE QUE LA SALIDA NO ESTÉ SOBRECARGADA.

4. ¿ CUMPLE EL CIRCUITO TODOS LOS REQUISITOS DE OPERACIÓN PARA CMOS ?

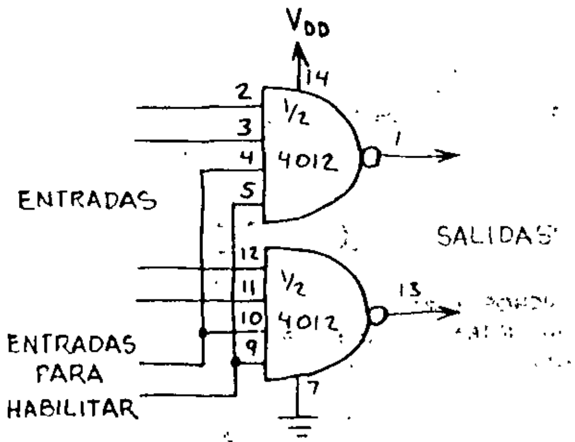
5. ¿ OLVIDÓ ALGUNA CONEXIÓN ?

COMPUERTA NAND DE 4 ENTRADAS DOBLE 4012

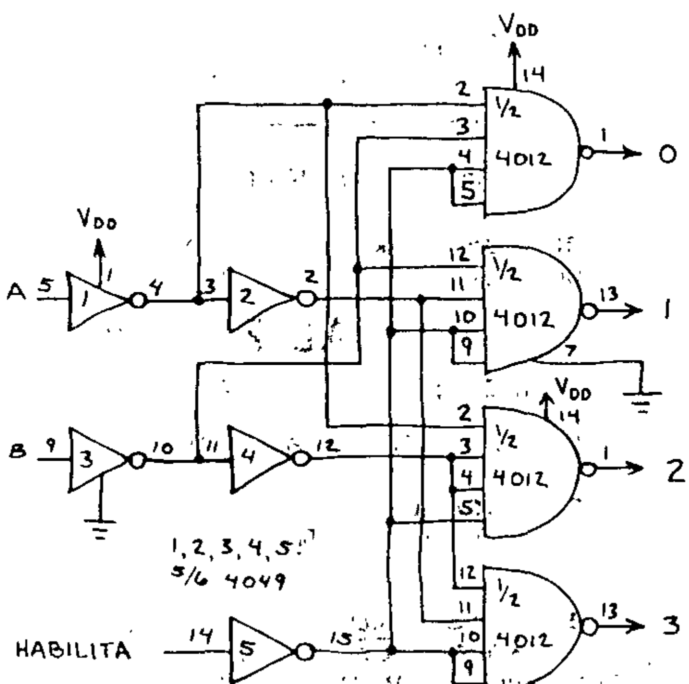


MUY ÚTIL PARA CONSTRUIR DECODIFICADORES. TAMBIÉN PUEDE USARSE PARA AÑADIR UNA O MÁS ENTRADAS DE HABILITACIÓN A VARIOS CIRCUITOS.

HABILITADOR DE ENTRADAS



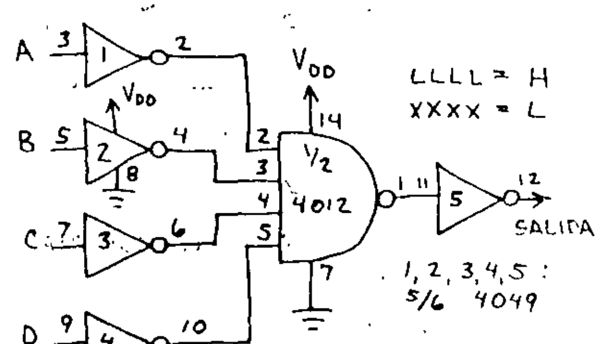
DECODIFICADOR 1 DE 4



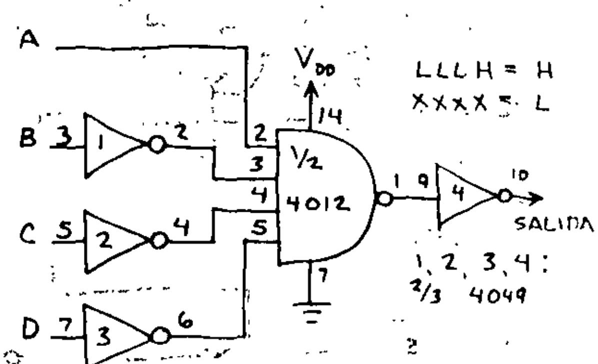
CUANDO "HABILITA" ES L, LA SALIDA CORRESPONDIENTE AL NÚMERO BINARIO BA SE HACE BAJA. TODAS LAS DEMÁS SALIDAS SE TORNAN ALTAS CUANDO "HABILITA" ES H.

DECODIFICADORES BCD

0 DECIMAL



1 DECIMAL



9 DECIMAL