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ERRATUM

Page vii, Change the next to last line to read as follows:

Blocking 2640 characters (20 records)

H-26-30
F-41-01

Manual of Petroleum Measurement Standards

Chapter 11.2.1 and 11.2.1M—Compressibility Factors for Hydrocarbons: 0–90°API Gravity and 638–1074 Kilograms per Cubic Metre Ranges

Chapter 11.2.3 and 11.2.3M—Water Calibration of Provers

Computer Tape Information and Documentation

FIRST EDITION, AUGUST 1984

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005

Manual of Petroleum Measurement Standards

Chapter 11.2.1 and 11.2.1M—Compressibility Factors for Hydrocarbons: 0–90°API Gravity and 638–1074 Kilograms per Cubic Metre Ranges
Chapter 11.2.3 and 11.2.3M—Water Calibration of Provers

Computer Tape Information and Documentation

Measurement Coordination Department

FIRST EDITION, AUGUST 1984

American
Petroleum
Institute

FOREWORD

This publication and computer tape provide tables to correct hydrocarbon volumes metered under pressure to corresponding volumes at the equilibrium pressure for the metered temperature and to calibrate volumetric provers. Tables are provided in customary and metric (SI) units.

Suggested revisions are invited and should be submitted to the director, Measurement Coordination Department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

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CONTENTS

CHAPTER 11.2.3M—WATER CALIBRATION OF VOLUMETRIC PROVERS

COMPUTER TAPE INFORMATION

The two computer tapes (ASCII or EBCDIC) contain the following tables in the order indicated.

File No. 1
Chapter 11.2.1—Table of Compressibility Factors for Hydrocarbons in the 0–90°API Gravity Range Related to API Gravity (60°F) and Metering Temperature (Degrees Fahrenheit)

File No. 2
Chapter 11.2.1M—Table of Compressibility Factors for Hydrocarbons in the 638–1074 Kilograms per Cubic Metre Range Related to Density (15°C) and Metering Temperature (Degrees Celsius)

File No. 3
Chapter 11.2.3—Table of Volume Correction Factors for Use in Water Calibration of Provers (Degrees Fahrenheit)

File No. 4
Chapter 11.2.3M—Table of Volume Correction Factors for Use in Water Calibration of Provers (Degrees Celsius)

All four tables are contained in four files on the tape. The tape is provided in one of two formats with the composite file in EBCDIC characters or ASCII characters.

The information needed to transfer the tape to your computer is as follows:

Tape contents	API tables
BPI	1600 bits per inch
Unlabeled	yes
Characters	ASCII or EBCDIC
Record	132 characters
Blocking	26400 characters (20 records)
Files	4

Chapter 11—Physical Properties Data

SECTION 2—VOLUME CORRECTION FACTORS FOR METER PROVING AND HYDROCARBON COMPRESSIBILITY FACTORS

11.2.1 Compressibility Factors for Hydrocarbons: 0–90°API Gravity Range

11.2.1.1 SCOPE

The purpose of this standard is to correct hydrocarbon volumes metered under pressure to the corresponding volumes at the equilibrium pressure for the metered temperature. This standard contains compressibility factors related to meter temperature and API gravity (60°F) of metered material. The corresponding metric version is Chapter 11.2.1M.

11.2.1.2 HISTORY AND DEVELOPMENT

The previous compressibility standard (API Standard 1101, Appendix B, Table II) for hydrocarbons in the 0–90°API gravity range was developed in 1945 by Jacobson, et al [1]. It is based on limited data obtained mostly on pure compounds and lubricating oil type materials. Also, Standard 1101 was developed without the aid of a mathematical model.

In 1981, a working group of the Committee on Static Petroleum Measurement was set up to revise the compressibility tables of Standard 1101. This group performed an extensive literature search and found only three sources of compressibility information. The resulting data base is broader than that used in the previous standard. Unfortunately, it is not large enough to cover the range of current commercial operations. When new data are available, they will be incorporated into an expanded standard. This standard now replaces the discontinued Standard 1101, Appendix B, Table II, 0–100°API gravity portion.

11.2.1.3 DATA BASE AND LIMITS OF THE STANDARD

The actual standard is the printed table. The mathematical and computer steps used to generate this standard should not be considered the standard. They can, however, be used to develop computer subroutines for various languages and machines to duplicate the results in the printed table. The tape can be used in the development of various computer subroutines.

The data base (Table 1) for this standard was obtained from Jessup [2], Downer and Gardiner [3], and Downer [4]. It consists of seven crude oils, five gasolines, and seven middle distillate-gas oils. The lubricating oil data from these sources were not included. Modeling results showed that lubricating oils are a different population than crude oils and other refined products. Their inclusion multiplies the compressibility correlation uncertainty by a factor of two. Also, lubricating oils are not normally metered under pressure and do not require the use of this standard.

The limits of the experimental data are 20 to 76°API, 32 to 302°F, and 0 to 711 pounds per square inch. As a result of a Committee on Static Petroleum Measurement (COSM) and Committee on Petroleum Measurement (COPM) survey, the actual limits of the standard are broader: 0 to 90°API, −20 to 200°F, and 0 to 1500 pounds per square inch. Hence, certain portions of the standard represent extrapolated results (Figure 1). In these extrapolated portions, the uncertainty analysis discussed in 11.2.1.5 may not be valid.

The increments of this standard are 0.5°F and 0.5°API. Interpolation to smaller increments is not recommended.

11.2.1.4 EXAMPLE USE OF THE STANDARD

In this standard, the compressibility factor (F) is used in the normal manner for volume correction (* denotes multiplication):

$$V_e = V_m/[1 - F*(P_m - P_e)]$$

Where:

V_e = volume at equilibrium (bubble point) pressure, P_e.

V_m = volume at the meter pressure, P_m.

As an example, calculate the volume of 1000 barrels (V_m) of a 19.9°API (60°F) fuel oil metered under a pressure of 500 pounds per square inch (P_m) and 100°F. Assume a P_e value of 0 pounds per square inch. First, the gravity is rounded to the nearest 0.5°API, in this case 20.0°API. From the compressibility table, the F factor is 0.448 divided by 100,000 or 0.00000448. Then,

$$V_e = 1000/(1 - 0.00000448*500) = 1002 \text{ barrels}$$

Table 1—Data Base and Experimental Conditions for Chapter 11.2.1

Sample Name and Origin	API Gravity 60°F	Temperature °F	Pressure psi	Number of Data Points	Reference
Crude Oils					
ADMEG (Zakum) export	39.89	40.0–170.0	0–508	5	3
Barrow Island	36.97	40.0–170.0	0–508	5	3
Libyan (Tobruk) export	36.37	122.0–170.0	0–508	3	3
Iranian Light export	33.65	40.0–170.0	0–508	5	3
Kuwait export	30.98	40.0–170.0	0–508	5	3
Iranian Heavy export	30.55	40.0–170.0	0–508	5	3
Alaskan (North Slope)	27.24	60.0–170.0	0–508	4	3
Gasolines					
Light catalytic cracked	76.25	40.0–100.0	0–493	3	4
Straight run	61.12	40.0–140.0	0–493	4	4
Cracked	52.74	32.0–149.0	0–711	5	2
Fighting aviation	71.51	32.0–158.0	0–711	5	2
Fighting aviation	72.10	32.0–158.0	0–711	5	2
Kerosine and Light Fuel Oil					
Kerosine (odorless)	47.61	40.0–170.0	0–493	5	4
DERV	35.36	40.0–170.0	0–493	5	4
Gas Oils and Heavy Fuels Oils					
Gas oil	38.16	40.0–170.0	0–493	5	4
Commercial fuel oil	19.90	100.0–140.0	0–493	2	4
Los Angeles basin gas oil	30.42	32.0–302.0	0–711	3	2
Oklahoma gas oil	29.08	32.0–302.0	0–711	3	2
Midcontinent gas oil	28.66	32.0–302.0	0–711	3	2

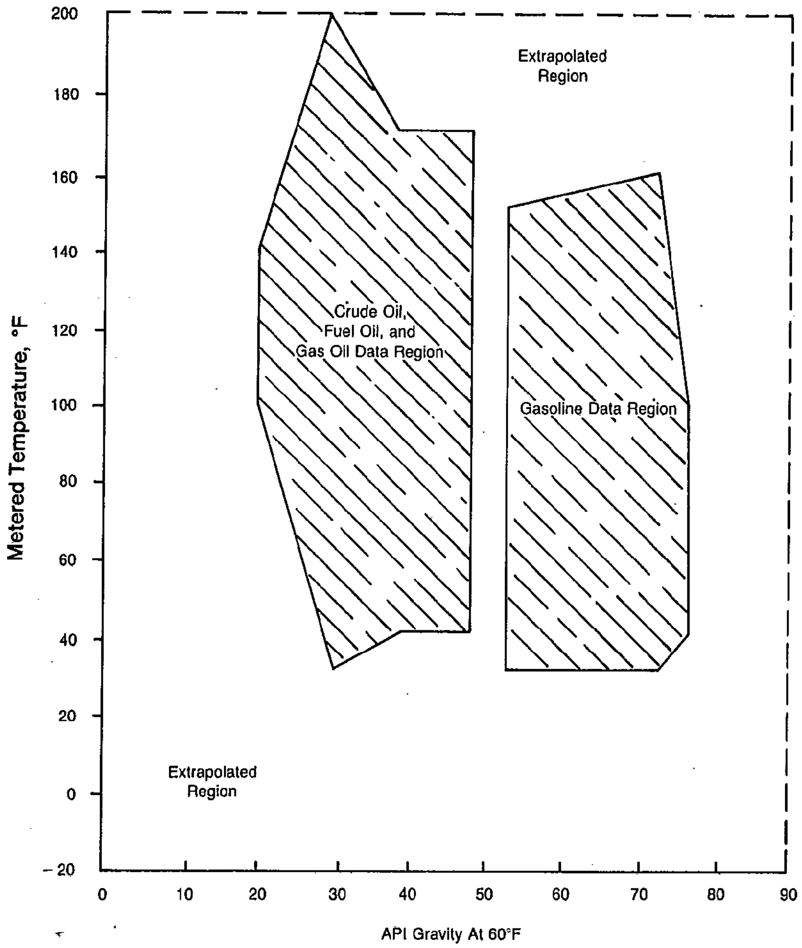

Figure 1—Comparison of Data Base and Extrapolated Regions for Chapter 11.2.1

For more examples and details, see *Manual of Petroleum Measurement Standards,* Chapter 12.2.

11.2.1.5 MATHEMATICAL MODEL FOR THE STANDARD

11.2.1.5.1 Basic Model and Uncertainty Analysis

The basic mathematical model, used to develop this standard, relates the compressibility factor exponentially (EXP) to temperature and the square of molecular volume. That is,

$$F = \text{EXP}(A + B*T + C/\text{RHO}^2 + D*T/\text{RHO}^2)$$

Where:

A, B, C, and D = constants.
T = temperature, in °F.
RHO = density, in grams per cubic centimeter at 60°F. 1/RHO is proportional to molecular volume.
RHO = (141.5*0.999012)/(131.5 + °API at 60°F).

Hence, compressibility is the result of the interaction of two molecular volumes and temperature. The above equation is consistent with the development of API Standard 2540 (*Manual of Petroleum Measurement Standards,* Chapter 11.1) for the thermal expansion of hydrocarbons. The use of higher powers of T and RHO does not yield further significant minimization of compressibility factor uncertainty.

Using the above equation and data base, maximum compressibility factor uncertainty is ±6.5 percent at the 95 percent confidence level. Hence at worst, one should expect that the real compressibility factor for a given material could be either 6.5 percent higher or 6.5 percent lower than the value in the standard. This statement is only true within the limits of the data base. It may not be true for the extrapolated portions of the standard.

To assess the possible uncertainty in the calculated volume at equilibrium pressure using the above data base and equation, two approaches were taken. First, it was assumed that only the correlation uncertainty in mean compressibility of ±6.5 percent was significant. With this approach, volumetric uncertainties should be in the range of 0.02 to 0.10 percent, depending on operating conditions (Table 2, Basis A). These uncertainties are in agreement with the maximum error of 0.10 percent recommended by a COSM and COPM survey.

The first volumetric uncertainty analysis assumes that mean compressibility is not a function of pressure. For low pressures, this assumption is adequate. For higher pressures, mean compressibility will decrease with increasing pressure. At what pressure this effect becomes significant for the materials of this standard is not definitely known. However, analysis of the Jessup [2] data indicates that mean compressibility could possibly decrease by about 0.005 percent per pound per square inch with increasing pressure. Incorporating both the compressibility correlation uncertainty and the potential pressure uncertainty yields volumetric uncertainties in the range of 0.03 to 0.21 percent (Table 2, Basis A + B). Hence, the use of this standard with operating pressures greater than the experimental limit of 711 pounds per square inch could double the uncertainty in calculated volume over the uncertainty based on available data.

11.2.1.5.2 Calculation Procedure

This procedure is recommended for computers with 6 to 7 floating point digits of precision or greater.

Step 1: Initialize temperature and gravity.

T = XXX.X °F: $-20.0 \leq T \leq 200.0$, rounded to nearest 0.5°F.

API = XX.X: $0.0 \leq$ °API ≤ 90.0, rounded to the nearest 0.5 degree by

Table 2—Volumetric Uncertainty Analysis for Chapter 11.2.1

Mean Compressibility psi^{-1}	Percent Uncertainty in Volume for Various Pressures, psi					
	Correlation Uncertainty Only Basis A			Correlation + Pressure Uncertainty Basis A + B		
	500	1000	1500	500	1000	1500
$1.0 * 10^{-5}$ (Note 1)	0.03	0.07	0.10	0.05	0.12	0.21
$0.6 * 10^{-5}$ (Note 2)	0.02	0.04	0.06	0.03	0.08	0.13

BASIS: A. 6.5 percent correlation uncertainty in mean compressibility prediction.
B. 0.005 percent/psi uncertainty in mean compressibility due to effect of pressure [2].

NOTES:
1. Typical compressibility value for 65°API gasoline at 100°F or 45°API fuel oil at 200°F.
2. Typical compressibility value for 60°API gasoline at 20°F or 35°API crude oil at 100°F.

X is either a temperature or gravity value.
$TX = \text{INT}(X)$: i.e., truncation.
$\text{DIFF} = X - TX$.
If $\text{DIFF} \geq 0$ then $\text{SIGN} = 1.0$ else $\text{SIGN} = -1.0$.
$\text{DIFF} = \text{ABS}(\text{DIFF})$: i.e., absolute value.
If $\text{DIFF} < 0.25$ then $X = TX$.
If $\text{DIFF} \geq 0.75$ then $X = TX + 1.0 * \text{SIGN}$.
Else $X = TX + 0.5 * \text{SIGN}$.

Step 2: Calculate the density in grams per cubic centimeter and the square of density.

$\text{RHO} = 141.36/(\text{API} + 131.50) = \text{X.XXXXX}$, rounded to the nearest 0.00001 by
$\text{RHO} = \text{INT}(\text{RHO}*100000.0 + 0.5)*0.00001$.
$\text{RHOSQR} = \text{RHO}*\text{RHO} = \text{X.XXXXX}$, rounded to the nearest 0.00001 by
$\text{RHOSQR} = \text{INT}(\text{RHOSQR}*100000.0 + 0.5) *0.00001$.

Step 3: Calculate the compressibility factor.

$F = \text{EXP}\ (-1.99470 + 0.00013427*T + 0.79392/\text{RHOSQR} + 0.0023260*T/\text{RHOSQR})$
by rounding each term to the nearest 0.00001 as follows:
If $T < 0$ then $\text{SIGN} = -1.0$ else $\text{SIGN} = 1.0$.
$\text{TERM1} = -1.99470$.
$\text{TERM2} = \text{INT}(13.427 * T + 0.5 * \text{SIGN}) * 0.00001$.
$\text{TERM3} = \text{INT}(79392.0/\text{RHOSQR} + 0.5) * 0.00001$.
$\text{TERM4} = \text{INT}(232.60 * T/\text{RHOSQR} + 0.5 * \text{SIGN}) * 0.00001$.
$F = \text{EXP}(\text{TERM1} + \text{TERM2} + \text{TERM3} + \text{TERM4}) = \text{X.XXXX}$.
Then round F to the nearest 0.001 by
$F = \text{INT}(F * 1000.0 + 0.5) * 0.001 = \text{X.XXX}$.
F is now the table value.

The INT intrinsic function returns an integer by truncating all digits to the right of the decimal point. The exponential intrinsic EXP must return a result accurate to the nearest 0.0001.

11.2.1.6 REFERENCES

1. Jacobson, E. W., Ambrosius, E. E., Dashiell, J. W., and Crawford, C. L., "Second Progress Report on Study of Existing Data on Compressibility of Liquid Hydrocarbons," Report of the Central Committee on Pipe-Line Transportation, Vol. 2 (IV), p. 39–45, American Petroleum Institute, Washington, D.C., 1945.
2. Jessup, R. S, "Compressibility and Thermal Expansion of Petroleum Oils in the Range 0° to 300°C," *Bureau of Standards Journal of Research,* Vol. 5, July to December 1930, p. 985–1039, National Bureau of Standards, Washington, D.C.
3. Downer, L., and Gardiner, K. E. S., "Bulk Oil Measurement Compressibility Measurements on Crude Oils Deviations from API Standard 1101," BP Research Centre Report No. 20 587/M (8 pages), October 28, 1970.
4. Downer, L. "Bulk Oil Measurement Compressibility Data on Crude Oils and Petroleum Products Viewed as a Basis for Revised International Tables (API Standard 1101 Tables)," BP Research Centre Report No. 20 639 (21 pages), January 17, 1972.

11.2.1M Compressibility Factors for Hydrocarbons: 638–1074 Kilograms per Cubic Metre Range

11.2.1.1M SCOPE

The purpose of this standard is to correct hydrocarbon volumes metered under pressure to the corresponding volumes at the equilibrium pressure for the metered temperature. This standard contains compressibility factors related to meter temperature and density (15°C) of metered material. The corresponding version in customary units is Chapter 11.2.1.

11.2.1.2M HISTORY AND DEVELOPMENT

The previous compressibility standard (API Standard 1101, Appendix B, Table II) for hydrocarbons in the 0–90°API gravity range was developed in 1945 by Jacobson, et al [1]. It is based on limited data obtained mostly on pure compounds and lubricating oil type materials. Also, Standard 1101 was developed without the aid of a mathematical model.

In 1981, a working group of the Committee on Static Petroleum Measurement was set up to revise the compressibility tables of Standard 1101. This group performed an extensive literature search and found only three sources of compressibility information. The resulting data base is broader than that used in the previous standard. Unfortunately, it is not large enough to cover the range of current commercial operations. When new data are available, they will be incorporated into an expanded standard. This standard now replaces the discontinued Standard 1101, Appendix B, Table II, 0–100°API gravity portion.

11.2.1.3M DATA BASE AND LIMITS OF THE STANDARD

The actual standard is the printed table. The mathematical model and computer steps used to generate this standard should not be considered the standard. They can be used to develop computer subroutines for various languages and machines to duplicate the results in the printed table. The tape can be used in the development of various computer subroutines.

The data base (Table 1) for this standard was obtained from Jessup [2], Downer and Gardiner [3], and Downer [4]. It consists of seven crude oils, five gasolines, and seven middle distillate-gas oils. The lubricating oil data from these sources were not included. Modeling results showed that lubricating oils are a different population than crude oils and other refined products. Their inclusion increases the compressibility correlation uncertainty by a factor of two. Also, lubricating oils are not normally metered under pressure and do not require the use of this standard.

The limits of the experimental data are 681 to 934 kilograms per cubic metre, 0 to 150°C, and 0 to 4902 kilopascals. As a result of a Committee on Static Petroleum Measurement (COSM) and Committee on Petroleum Measurement (COPM) survey, the actual limits of the standard are broader: 638 to 1074 kilograms per cubic metre, -30 to 90°C, and 0 to 10300 kilopascals. Hence, certain portions of the standard represent extrapolated results (Figure 1). In these extrapolated portions, the uncertainty analysis discussed in 11.2.1.5M may not be valid.

The increments of this standard are 0.25°C and 2 kilograms per cubic metre. Interpolation to smaller increments is not recommended.

11.2.1.4M EXAMPLE USE OF THE STANDARD

In this standard, the compressibility factor (F) is used in the normal manner for volume correction (* denotes multiplication):

$$V_e = V_m / [1 - F*(P_m - P_e)]$$

Where:

V_e = volume at equilibrium (bubble point) pressure, P_e.

V_m = volume at the meter pressure, P_m.

As an example, calculate the volume of 1000 cubic metres (V_m) of a 933.6 kilograms per cubic metre (15°C) fuel oil metered under a pressure of 3450 kilopascals (P_m) and 37.85°C. Assume a P_e value of 0 kilopascals. First, the density and temperature are rounded to the nearest 2 kilograms per cubic metre and 0.25°C, in this case 934 kilograms per cubic metre and 37.75°C. From the compressibility table, the F factor is 0.643 divided by 1,000,000 or 0.000000643. Then,

$$V_e = 1000/(1 - 0.000000643*3450) = 1002.2 \text{ cubic metres}$$

For additional examples and more details, see *Manual of Petroleum Measurement Standards,* Chapter 12.2.

11.2.1.5M MATHEMATICAL MODEL FOR THE STANDARD

11.2.1.5.1M Basic Model and Uncertainty Analysis

The basic mathematical model, used to develop this standard, relates the compressibility factor exponentially (EXP) to temperature and the square of molecular volume. That is,

$$F = \text{EXP}\ (A + B*T + C/\text{RHO}^2 + D*T/\text{RHO}^2)$$

Where:

A, B, C, and D = constants.

T = temperature, in °C.

RHO = density, in grams per cubic centimetre at 15°C. 1/RHO is proportional to molecular volume.

Hence, compressibility is the result of the interaction of two molecular volumes and temperature. The above equation is consistent with the development of API Standard 2450 (*Manual of Petroleum Measurement Standards,* Chapter 11.1) for the thermal expansion of hydrocarbons. The use of higher powers of T and RHO does not yield further significant minimization of compressibility factor uncertainty.

Using the above equation and data base, maximum compressibility factor uncertainty is ± 6.5 percent at the 95 percent confidence level. Hence at worst, one should expect that the real compressibility factor for a given material could be either 6.5 percent higher or 6.5 percent lower than the value in the standard. This statement is only true within the limits of the data base. It may not be true for the extrapolated portions of the standard.

To assess the possible uncertainty in the calculated volume at equilibrium pressure using the above data base and equation, two approaches were taken. First, it was assumed that only the correlation uncertainty in mean compressibility of ± 6.5 percent was significant. With this approach, volumetric uncertainties should be in the range of 0.02 to 0.10 percent, depending on operating conditions (Table 2, Basis A). These uncertainties are in agreement with the maximum error of 0.10 percent recommended by a COSM and COPM survey.

The first volumetric uncertainty analysis assumes that mean compressibility is not a function of pressure. For low pressures this assumption is adequate. For higher pressures, mean compressibility will decrease with increasing pressure. At what pressure this effect becomes significant for the materials of this standard is not definitely known. However, analysis of the Jessup [2] data indicates that mean compressibility could possibly decrease by about 0.00073 percent per kilopascal with

Table 1—Data Base and Experimental Conditions for Chapter 11.2.1M

Sample Name and Origin	Density kg/m³ at 15°C	Temperature °C	Pressure kPa	Number of Data Points	Reference
Crude Oils					
ADMEG (Zakum) export	825.2	4.44–76.67	0–3503	5	3
Barrow Island	839.5	4.44–76.67	0–3503	5	3
Libyan (Tobruk) export	842.5	37.78–76.67	0–3503	3	3
Iranian Light export	856.4	4.44–76.67	0–3503	5	3
Kuwait export	870.4	4.44–76.67	0–3503	5	3
Iranian Heavy export	872.7	4.44–76.67	0–3503	5	3
Alaskan (North Slope)	890.9	15.56–76.67	0–3503	4	3
Gasolines					
Light catalytic cracked	680.9	4.44–37.78	0–3399	3	4
Straight run	734.4	4.44–60.0	0–3399	4	4
Cracked	768.0	0.0–65.0	0–4902	5	2
Fighting aviation	697.0	0.0–70.0	0–4902	5	2
Fighting aviation	695.0	0.0–70.0	0–4902	5	2
Kerosine and Light Fuel Oil					
Kerosine (odorless)	789.7	4.44–76.67	0–3399	5	4
DERV	847.6	4.44–76.67	0–3399	5	4
Gas Oils and Heavy Fuels Oils					
Gas oil	833.6	4.44–76.67	0–3399	5	4
Commercial fuel oil	934.1	37.78–60.0	0–3399	2	4
Los Angeles basin gas oil	873.4	0.0–150.0	0–4902	3	2
Oklahoma gas oil	880.7	0.0–150.0	0–4902	3	2
Midcontinent gas oil	883.0	0.0–150.0	0–4902	3	2

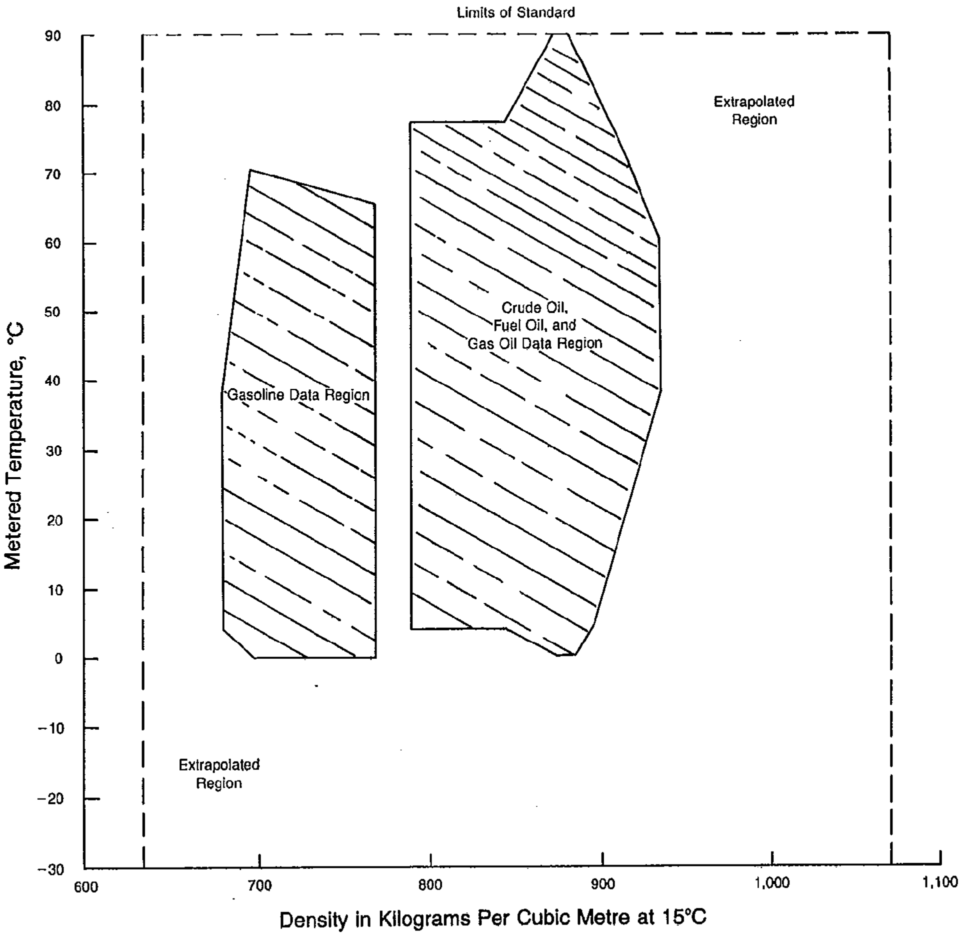

Figure 1—Comparison of Data Base and Extrapolated Regions for Chapter 11.2.1M

increasing pressure. Incorporating both the compressibility correlation uncertainty and the potential pressure uncertainty yields volumetric uncertainties in the range of 0.03 to 0.21 percent (Table 2, Basis A + B). Hence, the use of this standard with operating pressures greater than the experimental limit of 4902 kilopascals could double the uncertainty in calculated volume over the uncertainty based on available data.

11.2.1.5.2M Calculation Procedure

This procedure is recommended for computers with 6 to 7 floating point digits of precision or greater.

```
Step 1: Initialize temperature in °C.
    $T = XX.XX:\ -30.00 \le T \le 90.00$, rounded to nearest 0.25°C by
    $TT = INT(T)$: i.e., truncation.
    $DIFF = T - TT$.
    If $DIFF \ge 0$ then $SIGN = 1.0$ else $SIGN = -1.0$.
    $DIFF = ABS(DIFF)$: i.e., absolute value.
    If $DIFF < 0.125$ then $T = TT$.
    If $0.125 \le DIFF < 0.375$ then
        $T = TT + 0.25 * SIGN$.
    If $0.375 \le DIFF < 0.625$ then
        $T = TT + 0.50 * SIGN$.
    If $0.625 \le DIFF < 0.875$ then
        $T = TT + 0.75 * SIGN$.
    If $DIFF \ge 0.875$ then $T = TT + 1.00 * SIGN$

Step 2: Initialize the density in kilograms per cubic metre.
    $RHO = XXXX:\ 638 \le RHO \le 1074$, rounded to the nearest 2 by
    $RHOH = INT(RHO/2.0)$.
    $DIFF = RHO - 2 * RHOH$.
    If $DIFF \ge 1.0$ then $RHO = 2 + 2 * RHOH$.
    Else $RHO = 2 * RHOH$.

Step 3: Calculate density in grams per cubic centimetre and the square of density.
    $RHO = RHO * 0.001$.
    $RHOSQR = RHO*RHO = X.XXXXX$, rounded to the nearest 0.00001 by
    $RHOSQR = INT(RHOSQR * 100000.0 + 0.5) * 0.00001$.

Step 4: Calculate the compressibility factor.
    $F = EXP(-1.62080 + 0.00021592*T + 0.87096/RHOSQR + 0.0042092*T/RHOSQR)$
    by rounding each term to the nearest 0.00001 as follows:
    If $T < 0$ then $SIGN = -1.0$ else $SIGN = 1.0$.
    $TERM1 = -1.62080$.
    $TERM2 = INT(21.592 * T + 0.5 * SIGN) * 0.00001$.
    $TERM3 = INT(87096.0/RHOSQR + 0.5) * 0.00001$.
    $TERM4 = INT(420.92 * T/RHOSQR + 0.5 * SIGN) * 0.00001$.
    $F = EXP(TERM1 + TERM2 + TERM3 + TERM4) = X.XXXX$.
    Then round $F$ to the nearest 0.001 by
    $F = INT(F * 1000.0 + 0.5) * 0.001 = X.XXX$.
    $F$ is now the table value.
```

The INT intrinsic function returns an integer by truncating all digits to the right of the decimal point. The exponential intrinsic EXP must return a result accurate to the nearest 0.0001.

11.2.1.6 REFERENCES

1. Jacobson, E. W., Ambrosius, E. E., Dashiell, J. W., and Crawford, C. L., "Second Progress Report on Study of Existing Data on Compressibility of Liquid Hydrocarbons," Report of the Central Committee on Pipe-Line Transportation, Vol. 2 (IV), p. 39–45, American Petroleum Institute, Washington, D.C., 1945.
2. Jessup, R. S., "Compressibility and Thermal Expansion of Petroleum Oils in the Range 0° to 300°C," *Bureau of Standards Journal of Research,* Vol. 5, July to December 1930, p. 985–1039, National Bureau of Standards, Washington, D.C.
3. Downer, L., and Gardiner, K. E. S., "Bulk Oil

Table 2—Volumetric Uncertainty Analysis for Chapter 11.2.1M

Mean Compressibility kPa^{-1}	Percent Uncertainty in Volume for Various Pressures, kPa					
	Correlation Uncertainty Only Basis A			Correlation + Pressure Uncertainty Basis A + B		
	3447	6895	10342	3447	6895	10342
$1.45 * 10^{-6}$ (Note 1)	0.03	0.07	0.10	0.05	0.12	0.21
$0.87 * 10^{-6}$ (Note 2)	0.02	0.04	0.06	0.03	0.08	0.13

BASIS: A. 6.5 percent correlation uncertainty in mean compressibility prediction.
B. 0.00073 percent/kPa uncertainty in mean compressibility due to effect of pressure [2].

NOTES:
1. Typical compressibility value for 720 kg/m³ (15°C) gasoline at 38°C or 800 kg/m³ fuel oil at 93°C.
2. Typical compressibility value for 738 kg/m³ gasoline at −7°C or 850 kg/m³ crude oil at 38°C.

Measurement Compressibility Measurements on Crude Oils Deviations from API Standard 1101," BP Research Centre Report No. 20 587/M (8 pages), October 28, 1970.
4. Downer, L. "Bulk Oil Measurement Compressibility Data on Crude Oils and Petroleum Products Viewed as a Basis for Revised International Tables (API Standard 1101 Tables)," BP Research Centre Report No. 20 639 (21 pages), January 17, 1972.

11.2.3 Water Calibration of Volumetric Provers

11.2.3.1 SCOPE

This standard is for use in the water calibration of volumetric provers. It contains volume correction factors related to prover temperature and the difference in temperature between the prover and a certified test measure. The corresponding metric (SI) version is Chapter 11.2.3M.

11.2.3.2 HISTORY AND DEVELOPMENT

The previous standard (API Standard 1101, Appendix B, Table I) was based on water density data from the Smithsonian Institution. The old standard was developed without the aid of a mathematical model and was limited in temperature increments and number of decimal digits.

In 1981, a working group of the Committee on Static Petroleum Measurement was set up to revise this standard. They decided to use the internationally accepted water density versus temperature equation of H. Wagenbreth and H. Blanke [1]. This equation is currently used by the National Bureau of Standards to calibrate test measures. The National Bureau of Standards, however, plans to switch to the equation developed by G. S. Kell [2]. Evaluation of these two equations showed that calculated water densities can differ by two parts in a million, for example, 999.012 versus 999.014 kilograms per cubic meter, respectively, for the density of water at 60°F. However, the volumetric correction factors (density ratios) presented in this standard are essentially invariant of either equation for the temperature range of the standard.

11.2.3.3 TYPE AND LIMITS OF THE STANDARD

The actual standard is the printed table. The mathematical equation used to generate this table should not be considered the standard. The equation, however, can be used to develop subroutines to duplicate the results in the printed table. Such an effort will require a computer with a minimum floating point precision of eleven digits. The computer tape can be employed in the development of various subroutines.

The table consists of two parts. In both parts, the limits are 35 to 105°F in prover temperature and 32.1 to 105°F in measure temperature. This range is essentially the same as that of the Wagenbreth equation. Hence, extrapolation outside this range is not recommended. All volumetric correction factors (water density ratios) are recorded to six decimal figures, and volume correction factors are given for measure temperatures lower than and higher than prover temperatures.

In the first part of the table, the increments in prover temperatures are 0.1°F. Likewise, the increments between the prover and measure temperatures are 0.1°F with a maximum difference of 3.0°F.

In the second part of the table, increments of prover temperature and prover-measure difference temperatures are 1.0°F. Maximum prover-measure temperature difference in this part is 10.0°F. This part of the table is for use in nontypical operations where the difference between prover and measure temperatures exceeds 3.0°F. If interpolation in this part becomes necessary, use of the Wagenbreth equation is recommended in a computer procedure that duplicates the first part of the table. Linear interpolation of the second part of the table is not recommended. Also, temperature increments of 0.1°F and larger only are recommended.

11.2.3.4 EXAMPLE USE OF THE STANDARD

In this standard, the volume correction factors will be used in the normal manner (* denotes multiplication):

$$V_p = V_m * C_{tdw}$$

Where:

V_p = prover volume.
V_m = measure volume.
C_{tdw} = volume correction factor.

As an example, assume a measure volume of 49.985 gallons and prover and measure temperatures of 80.7 and 83.0°F, respectively. For a measure temperature 2.3°F higher than the prover temperature (83.0 − 80.7), the C_{tdw} from the table is 0.999639. Hence,

$$V_p = 49.985 * 0.999639 = 49.967 \text{ gallons}$$

For additional examples and ore details, see *Manual of Petroleum Measurement Standards,* Chapter 12.2.

11.2.3.5 MATHEMATICAL MODEL FOR THE STANDARD

The Wagenbreth equation used to develop this standard is:

$$\begin{aligned}\text{RHO} = {} & 999.8395639 + 0.06798299989*T \\ & - 0.009106025564*T^2 \\ & + 0.0001005272999*T^3 \\ & - 0.000001126713526*T^4 \\ & + 0.000000006591795606*T^5\end{aligned}$$

Where:

RHO = water density, in kilograms per cubic meter.

T = temperature, in °C and equals (temperature °F − 32.0)/1.8.

The volume correction factor in this standard is the ratio of two water densities, that is:

$$C_{tdw} = \text{RHO}_{TM}/\text{RHO}_{TP} = V_p/V_m$$

Where:

TM = measure temperature.

TP = prover temperature.

In developing this standard, a 48-bit word size computer was used with full floating point precision. In each step of the calculations, the returned number contained eleven significant digits after exponential scaling. In the last step of the computation, the C_{tdw} was rounded to six significant digits to the right of the decimal point. In the development of other computer subroutines, equal or greater accuracy will have to be employed to exactly duplicate the printed table, which is the standard.

11.2.3.6 UNCERTAINTY ANALYSIS

Using the Wagenbreth equation yields a maximum uncertainty in any C_{tdw} value of ± 0.000007. As mentioned previously, the use of the Wagenbreth versus the Kell equation essentially does not yield any differences in C_{tdw} values. That is, C_{tdw} values via the two equations will differ by less than 0.0000005 within the temperature range of the standard. However, on rounding to six decimal places, less than 9 percent of equivalent table entries could differ by ± 0.000001. Therefore, it is not recommended that the Kell equation be used to duplicate the standard. However, the Kell equation is suggested for calculating C_{tdw} values for temperatures above the maximum of the standard.

11.2.3.7 REFERENCES

1. Wagenbreth, H., and Blanke, H., "The Density of Water in the International System of Units and in the International Practical Temperature Scale of 1968," *Mitteilungen der Physikalish-Technischen Budnesanstalt (PTB-Mitt)*, p. 412–415, June 1971.

2. Kell, G. S., "Density, Thermal Expansion, and Compressibility of Liquid Water from 0° to 150°C: Correlations and Tables for Atmospheric Pressure and Saturation Reviewed and Expressed in 1968 Temperature Scale," *Journal of Chemical and Engineering Data*, Vol. 20, p. 97–105, 1975.

11.2.3M Water Calibration of Volumetric Provers

11.2.3.1M SCOPE

This standard is for use in the water calibration of volumetric provers. It contains volume correction factors related to prover temperature and the difference in temperature between the prover and a certified test measure. The corresponding version in customary units is MPMS 12.2.3.

11.2.3.2M HISTORY AND DEVELOPMENT

The previous standard (API Standard 1101, Appendix B, Table I) was based on water density data from the Smithsonian Institution. The old standard was developed without the aid of a mathematical model and was limited in temperature increments and number of decimal digits.

In 1981, a working group of the Committee on Static Petroleum Measurement was set up to revise the water calibration tables of Standard 1101. They decided to use the internationally accepted water density versus temperature equation of H. Wagenbreth and H. Blanke [1]. This equation is currently used by the National Bureau of Standards to calibrate test measures. The National Bureau of Standards, however, plans to switch to the equation developed by G. S. Kell [2]. Evaluation of these two equations showed that calculated water densities can differ by two parts in a million, for example, 999.012 versus 999.014 kilograms per cubic metre, respectively, for the density of water at 15.56°C. However, the volumetric correction factors (density ratios) presented in this standard are essentially invariant of either equation for the temperature range of the standard.

11.2.3.3M TYPE AND LIMITS OF THE STANDARD

The actual standard is the printed table. The mathematical equation used to generate this table should not be considered the standard. The equation, however, can be used to develop subroutines to duplicate the results in the printed table. Such an effort will require a computer with a minimum floating point precision of eleven digits. The computer tape can be employed in the development of various subroutines.

The table consists of two parts. In both parts, the limits are 2 to 40°C in prover temperature and 0.05 to 40°C in measure temperature. This range is essentially the same as that of the Wagenbreth equation. Hence, extrapolation outside this range is not recommended. All volumetric correction factors (water density ratios) are recorded to six decimal figures, and, volume correction factors are given for measure temperatures lower than and higher than prover temperatures.

In the first part of the table, the increments in prover temperatures are 0.05°C. Likewise, the increments between prover and measure temperatures are 0.05°C with a maximum difference of 2.00°C.

In the second part of the table, increments of prover temperature and prover-measure difference temperatures are 0.5°C. Maximum prover-measure temperature difference in this part is 5.0°C. This part of the table is for use in nontypical operations where the difference between prover and measure temperatures exceeds 2.0°C. If interpolation in this part becomes necessary, use of the Wagenbreth equation is recommended in a computer procedure that duplicates the first part of the table. Linear interpolation of the second part of the table is not recommended. Also, temperature increments of 0.05°C and larger only are recommended.

11.2.3.4M EXAMPLE USE OF THE STANDARD

In this standard, the volume correction factors will be used in the normal manner (* denotes multiplication):

$$V_p = V_m * C_{tdw}$$

Where:

V_p = prover volume.
V_m = measure volume.
C_{tdw} = volume correction factor.

As an example, assume a measure volume of 1.7615 cubic metres and prover and measure temperatures of 27.05 and 28.35°C, respectively. For a measure temperature 1.30°C higher than the prover temperature (28.35 − 27.05), the C_{tdw} from the table is 0.999633. Hence,

$$V_p = 1.7615 * 0.999633 = 1.7609 \text{ cubic metres}$$

For additional examples and more details, see *Manual of Petroleum Measurement Standards,* Chapter 12.2.

11.2.3.5M MATHEMATICAL MODEL FOR THE STANDARD

The Wagenbreth equation used to develop this standard is:

$$\begin{aligned} \text{RHO} = {} & 999.8395639 + 0.06798299989 * T \\ & - 0.009106025564 * T^2 \\ & + 0.0001005272999 * T^3 \\ & - 0.000001126713526 * T^4 \\ & + 0.000000006591795606 * T^5 \end{aligned}$$

Where:

RHO = water density, in kilograms per cubic metre.
T = temperature, in °C.

The volume correction factor in this standard is the ratio of two water densities, that is:

$$C_{tdw} = \text{RHO}_{TM}/\text{RHO}_{TP} = V_p/V_m$$

Where:

TM = measure temperature.
TP = prover temperature.

In developing this standard, a 48-bit word size computer was used with full floating point precision. In each step of the calculations, the returned number contained eleven significant digits after exponential scaling. In the last step of the computation, the C_{tdw} was rounded to six significant digits to the right of the decimal point. In the development of other computer subroutines, equal or greater accuracy will have to be employed to exactly duplicate the printed table, which is the standard.

11.2.3.6M UNCERTAINTY ANALYSIS

Using the Wagenbreth equation yields a maximum uncertainty in any C_{tdw} value of ± 0.000007. As mentioned previously, the use of the Wagenbreth versus the Kell equation essentially does not yield any differences in C_{tdw} values. That is, C_{tdw} values via the two equations will differ by less than 0.0000005 within the temperature range of the standard. However, on rounding to six decimal places, less than 9 percent of equivalent table entries could differ by ± 0.000001. Therefore, it is not recommended that the Kell equation be used to duplicate this standard. However, the Kell equation is suggested for calculating C_{tdw} values for temperatures above the maximum of this standard.

11.2.3.7M REFERENCES

1. Wagenbreth, H., and Blanke, H., "The Density of Water in the International System of Units and in the International Practical Temperature Scale of 1968,"

Mitteilungen der Physikalish-Technischen Budnesanstalt (PTB-Mitt), p. 412–415, June 1971.

2. Kell, G. S., "Density, Thermal Expansion, and Compressibility of Liquid Water from 0° to 150°C: Correlations and Tables for Atmospheric Pressure and Saturation Reviewed and Expressed in 1968 Temperature Scale," *Journal of Chemical and Engineering Data,* Vol. 20, p. 97–105, 1975.