Manual of Petroleum Measurement Standards Chapter 12—Calculation of Petroleum Quantities

Section 2—Calculation of Petroleum Quantities Using Dynamic Measurement Methods and Volumetric Correction Factors

Part 1—Introduction

SECOND EDITION, MAY 1995

REAFFIRMED, MARCH 2014

AMERICAN PETROLEUM INSTITUTE

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FOREWORD

This five-part publication consolidates and presents standard calculations for metering petroleum liquids using turbine or displacement meters. Units of measure in this publication are in International System (SI) and United States Customary (USC) units consistent with North American industry practices.

This standard has been developed through the cooperative efforts of many individuals from industry under the sponsorship of the American Petroleum Institute and the Gas Processors Association.

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Suggested revisions to this publication are invited and should be submitted to the Measurement Coordinator, Exploration and Production Department, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005.

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PART 1—INTRODUCTION

1.1 Purpose

When most of the older standards were written, mechanical desk calculators were widely used for calculating measurement documentation, and tabulated values were used more widely than is the case today. Rules for rounding and the choice of how many figures to enter in each calculation step were often made on the spot. As a result, different operators obtained different results from the same data.

This five-part publication consolidates and standardizes calculations pertaining to metering petroleum liquids using turbine or displacement meters and clarifies terms and expressions by eliminating local variations of such terms. The purpose of standardizing calculations is to produce the same unbiased answer from the given data. So that different operators can obtain identical results from the same data, the rules for sequence, rounding, and discrimination of figures (or decimal places) have been defined.

1.2 Scope

This document provides standardized calculation methods for the quantification of liquids and the determination of base prover volumes under defined conditions, regardless of the point of origin or destination or the units of measure required by governmental customs or statute. The criteria contained in this document allow different entities using various computer languages on different computer hardware (or manual calculations) to arrive at identical results using the same standardized input data.

The publication rigorously specifies the equations for computing correction factors, rules for rounding, calculational sequence, and discrimination levels to be employed in the calculations. No deviations from these specifications are permitted since the intent of this document is to serve as a rigorous standard.

1.3 Organization of Standard

This standard is organized into five separate parts. Part 1 contains a general introduction for dynamic calculations. Part 2 focuses on the calculation of metered quantities for fiscal purposes or measurement tickets. Part 3 applies to meter proving calculations for field operations or proving reports. Parts 4 and 5 apply to the determination of base prover volumes (BPVs).

1.3.1 PART 1—INTRODUCTION

The base (reference or standard) volumetric determination of metered quantities is discussed along with the general terms required for solution of the various equations.

General rules for rounding of numbers, including field data, intermediate calculational numbers, and discrimination levels, are specified within the context of this standard.

For the proper use of this standard, a discussion is presented on the prediction of the liquid's density at flowing and base conditions.

An explanation of the principal correction factors associated with dynamic measurement are presented in a clear, concise manner.

1.3.2 PART 2—MEASUREMENT TICKETS

The application of this standard to the calculation of metered quantities is presented for base volumetric calculations in conformance with North American industry practices.

Recording of field data, rules for rounding, calculational sequence, and discrimination levels are specified, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the requirements stated in this part.

1.3.3 PART 3—PROVING REPORTS

The application of this standard to the calculation of proving reports is presented for base volumetric calculations in conformance with North American industry practices. Proving reports are utilized to calculate the following meter correction and performance indicators: meter factors (MF), composite meter factors (CMF), K-factors (KF), composite K-factors (CKF), and meter accuracy factor (MA). The determination of the appropriate term is based on both the hardware and the user's preference.

Recording of field data, rules for rounding, calculational sequence, and discrimination levels are specified, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the requirements stated in this part.

1.3.4 PART 4—CALCULATION OF BASE PROVER VOLUMES BY WATERDRAW METHOD

The BPV may be determined by one of two methods—waterdraw or master meter. The waterdraw method involves the displacing (or drawing) of water from the prover into certified volumetric field measures. Alternatively, for open tank provers, the waterdraw method may involve the displacing (or drawing) of water from the certified volumetric test measures into the open tank prover. Certification of the field measures are traceable to the appropriate national weights and measures organization (i.e., National Institute of Standards and Technology).

Recording of field data, rules for rounding, calculational sequence, and discrimination levels are specified, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the requirements stated in this part.

1.3.5 PART 5—CALCULATION OF BASE PROVER VOLUMES BY MASTER METER METHOD

The BPV may be determined by one of two methods—waterdraw or master meter. The master meter method employs the use of a master meter (or transfer standard). The master meter is proved under actual operating conditions by a master prover that has been calibrated by the waterdraw method. The master prover, master meter, and field prover are piped in series allowing fluid to pass through the three devices simultaneously.

Recording of field data, rules for rounding, calculational sequence, and discrimination levels are specified, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the requirements stated in this part.

1.4 Referenced Publications

Several documents served as references for the revisions of this standard. In particular, previous editions of Chapter 12.2 (ANSI/API 12.2) provided a wealth of information. The following are other publications that served as a resource of information for this revision:

API
Manual of Petroleum Measurement Standards (MPMS)
  Chapter 4, "Proving Systems"
  Chapter 5, "Metering"
  Chapter 6, "Metering Assemblies"
  Chapter 7, "Temperature Determination"
  Chapter 9, "Density Determination"
  Chapter 10, "Sediment and Water"
  Chapter 11, "Physical Properties Data"

ASTM[1]
  D1250 (Historical Edition—1952), "Petroleum Measurement Tables"
  D1550 "ASTM Butadiene Measurement Tables"
  D1555 "Calculation of Volume and Weight of Industrial Aromatic Hydrocarbons"

NIST[2]
  Handbook 105-3, "Specifications and Tolerances for Reference Standards and Field Standards"
  Monograph 62, "Testing of Metal Volumetric Standards"

1.5 Field of Application

1.5.1 APPLICABLE LIQUIDS

This standard applies to liquids that, for all practical purposes, are considered to be clean, single-phase, homogeneous, and Newtonian at metering conditions. Most liquids and dense phase liquids associated with the petroleum and petrochemical industries are usually considered to be Newtonian.

The application of this standard is limited to liquids that utilize tables and/or implementation procedures to correct metered volumes at flowing temperatures and pressures to corresponding volumes at base (reference or standard) conditions. To accomplish this, the liquid's density shall be determined by appropriate technical standards, or if necessary, proper correlations or equations of state. If multiple parties are involved in the measurement, the method selected for determining the liquid's densities shall be mutually agreed upon.

1.5.2 BASE CONDITIONS

Historically, the measurement of some liquids for custody transfer and process control have been stated in volume units at base (reference or standard) conditions.

The base conditions for the measurement of liquids, such as crude petroleum and its liquid products, having a vapor pressure equal to or less than atmospheric at base temperature are as follows:

United States Customary (USC) Units:
  Pressure—14.696 psia (101.325 kPa_a)
  Temperature—60.0˚F (15.56˚C)

International System (SI) Units:
  Pressure—14.696 psia (101.325 kPa_a)
  Temperature—59.00˚F (15.00˚C)

For liquids, such as liquid hydrocarbons, having a vapor pressure greater than atmospheric pressure at base temperature, the base pressure shall be the equilibrium vapor pressure at base temperature.

For liquid applications, base conditions may change from one country to the next due to governmental regulations. Therefore, it is necessary that the base conditions be identified and specified for standardized volumetric flow measurement by all parties involved in the measurement.

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[1] American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103

[2] U.S. Department of Commerce, National Institute of Standards and Technology, Washington, D.C. 20234 (formerly National Bureau of Standards)

1.6 Uncertainty

1.6.1 GENERAL

The user of this standard needs to consider the custody transfer facility from a holistic viewpoint. The user must have defined the desired uncertainty to the designer in order to build, operate, and maintain the facility properly.

At a single metering facility, there are two types of uncertainty. The average of the many readings may be offset from the true value (bias error), and/or the readings may be randomly scattered about the offset (random error).

The uncertainty of the metered quantities depends on a combination of the following:

a. The traceability chain associated with the field standards.
b. The calculation procedure and means of computation (chart integration, flow computer, mainframe, personal computer, and so forth).
c. The uncertainty associated with the liquid density predictions.
d. The sensitivity of the liquid prediction correlation to errors in pressure, temperature, and base density determinations.
e. The design, installation, and operation of the metering facility.
f. The choice of measurement equipment (charts, transmitters, A/D converters, data loggers, and so forth)
g. The data transmission means (analog, pneumatic, digital, manual).
h. The operating/calibration equipment’s effects due to ambient temperature, liquid temperature, liquid pressure, response time, local gravitational forces, atmospheric pressure, and so forth.

The uncertainty is dependent not just on the hardware or equipment, but also on the hardware’s performance, the software’s performance, the method of calculation, the method of calibration, the calibration equipment, the calibration procedures, and the human factor.

1.6.2 HIERARCHY OF ACCURACIES

There is an inevitable or natural hierarchy of accuracies in petroleum measurement. The natural hierarchy of accuracies, often referred to as a traceability chain, is comprised of both bias and random uncertainty components.

The concept of traceability describes how an instrument can be related to a national standard by calibrating it against another device that is closer to the national standard in the traceability chain. For example, the waterdraw method for calibrating provers consists of displacing the contents between detectors into a certified volumetric field standard test measure, which itself has been calibrated using repeated fillings from a secondary standard laboratory measure. This laboratory measure will have been owned and calibrated by the national weights and measures authority, which in turn has been calibrated by comparison with the country’s national primary volumetric and/or mass standard.

To expect equal or lower uncertainty in a lower level of the traceability chain than that which exists in a higher level is physically impossible, given the bias uncertainty component associated with the respective level of the chain. The random uncertainty is minimized by taking a large number of determinations with high precision devices and then finding their mean value.

In summary, the simplified traceability chain associated with a BPV contains both bias and random components. The random component can be reduced during calibration by a large number of repeated measurements. However, no amount of repeated measurement can reduce the bias component; it is a fixed systematic contribution to the uncertainty in any subsequent measurements.

1.7 Precision, Rounding, and Discrimination Levels

The minimum precision of the computing hardware must be equal to or greater than a ten-digit calculator to obtain the same answer in all calculations. For tickets calculated manually in the field utilizing printed CTL and CPL tables and not requiring the same precision, a less precise calculator (eight digit) may be used if agreed to by all parties.

The general rounding rules and discrimination levels are described in the following subsections.

1.7.1 ROUNDING OF NUMBERS

When a number is to be rounded to a specific number of decimals, it shall always be rounded off in one step to the number of figures that are to be recorded and shall not be rounded in two or more steps of successive rounding. The rounding procedure shall be in accordance with the following:

a. When the figure to the right of the last place to be retained is 5 or greater, the figure in the last place to be retained should be increased by 1.
b. If the figure to the right of the last place to be retained is less than 5, the figure in the last place retained should be unchanged.

1.7.2 DISCRIMINATION LEVELS

For field measurements of temperature and pressure, the levels specified in the various tables are maximum discrimination levels.

For example, if the parties agree to use a thermometer graduated in whole ˚F increments, then the device is normally read to levels of 0.5˚F resolution. Likewise, if the parties agree to use a “smart” temperature transmitter, which can indicate to 0.01˚F or 0.005˚C, then the reading shall be rounded to the nearest 0.1˚F or 0.05˚C value prior to recording for calculation purposes.

1.8 Definitions, Symbols, and Abbreviations

The definitions and symbols described below are a compilation of this five-part publication.

1.8.1 DEFINITIONS

1.8.1.1 barrel (bbl): a unit volume equal to 9,702.0 cubic inches, or 42.0 U.S. gallons.

1.8.1.2 base prover volume (BPV): the volume of the prover at base conditions as shown on the calibration certificate and obtained by arithmetically averaging three consecutive successful CPV determinations.

1.8.1.3 calibrated prover volume (CPV): the volume at base conditions between the detectors in a pipe prover or the volume of a proving tank between specified "empty" and "full" levels. The calibrated volume of a bidirectional prover is the sum of the two volumes swept out between detectors during a roundtrip.

1.8.1.4 composite meter factor (CMF): a meter factor corrected from normal operating pressure to base pressure. A CMF may be used for meter applications where the relative density, temperature, and pressure are considered constant during the measurement ticket period.

1.8.1.5 cubic meter (M^3): a unit of volume equal to 1,000,000.0 milliliters (ml), or 1,000.0 liters.

1.8.1.6 gross standard volume (GSV): the volume at base conditions corrected also for the meter's performance (MF, MMF, or CMF).

1.8.1.7 indicated standard volume (ISV): the IV corrected to base conditions. It **does not** contain any correction for the meter's performance (MF, MMF, or CMF).

1.8.1.8 indicated volume (IV): the change in meter reading that occurs during a receipt or delivery. The word *registration*, though not preferred, often has the same meaning.

1.8.1.9 liter (l): a unit of volume equal to 1,000.0 milliliters (ml).

1.8.1.10 master meter: a meter proved using a certified prover and then utilized to calibrate other provers or prove other meters.

1.8.1.11 master meter factor (MMF): a dimensionless term obtained by dividing the gross standard volume of the liquid passed through the master prover (during the proving of the master meter) by the indicated standard volume (ISV_m) as registered by the master meter during proving.

1.8.1.12 master prover: refers to a volumetric standard (conventional pipe prover, SVP, or open tank prover), which was calibrated by the waterdraw method, and is used to calibrate a *master meter*.

1.8.1.13 measurement ticket: the generalized term used in this publication to embrace and supersede long-standing expressions such as "run ticket," "meter ticket," and "receipt and delivery ticket."

1.8.1.14 meter factor (MF): a dimensionless term obtained by dividing the volume of the liquid passed through the prover corrected to standard conditions during proving by the indicated standard volume (ISV_m) as registered by the meter.

1.8.1.15 meter reading (MR_o, MR_c, MMR_o, MMR_c): the instantaneous display on a meter head. When the difference between a closing and an opening reading is being discussed, such a difference should be called an IV.

1.8.1.16 net standard volume (NSV): the gross standard volume corrected for nonmerchantable quantities such as sediment and water (CSW).

1.8.1.17 pass: a single movement of the displacer in a prover that activates the start-stop detectors.

1.8.1.18 prover calibration certificate: a document stating the BPV and other physical data required when proving flowmeters (E, Gc, Ga, Gl). The calibration certificate is a written acknowledgment of a proper calibration of a prover between the authorized representatives of the interested parties.

1.8.1.19 proving report: an organized collection of all information (meter, prover, and other), used during meter proving, meter performance verification, and meter factor determination.

1.8.1.20 round trip: the forward (out) and reverse (back) consecutive passes in a bidirectional prover.

1.8.1.21 run, meter proving: one or more consecutive passes, the results of which, when totalized, are deemed sufficient to provide a single value of the meter factor (MF, CMF, MMF) or K-factor (KF, CKF).

1.8.1.22 run, prover calibration: one or more consecutive passes, the results of which, when totalized, are deemed sufficient to provide a single value of the calibrated prover volume (CPV).

1.8.1.23 U.S. gallon (gal): a unit volume equal to 231.0 cubic inches.

1.8.1.24 weighted average pressure (PWA): the average liquid pressure at the meter for the ticket period.

For volumetric methods, the weighted average pressure is the average of the pressure values sampled at uniform flow intervals and is representative of the entire measurement ticket period.

$$PWA = [SUM_1^n\ (Pi)]/n$$

Where:

n = the number of uniform intervals

For time-based methods, the weighted average pressure is the sum of the pressure values sampled during the time interval, multiplied by the volume or mass determined during the same time interval, and divided by the entire volume measured.

$$PWA = [SUM\ (Pi \times Vi)]/Vt$$

1.8.1.25 weighted average temperature (TWA): the average liquid temperature at the meter for the ticket period.

For volumetric based methods, the weighted average temperature is the average of the temperature values sampled at uniform flow intervals during the entire measurement ticket period.

$$TWA = [SUM_1^n\ (Ti)]/n$$

Where:

n = the number of uniform intervals

For time-based methods, the weighted average temperature is the sum of the temperature values sampled during the time interval, multiplied by the volume or mass determined during the same time interval, and divided by the entire volume measured.

$$TWA = [SUM\ (Ti \times Vi)]/Vt$$

1.8.2 SYMBOLS AND ABBREVIATIONS

While a combination of uppercase, lowercase, and subscripted notation is used in this publication, the uppercase notation may be used for computer programming and other documents as deemed appropriate.

Additional letters may be added to the symbolic notations below for clarity and specificity.

Units

SI	International system of units (pascal, cubic meter, kilogram, metric system).
USC	U.S. customary units (inch, pound, cubic inch, traditional system).

Pipe Dimensions

ID	Inside diameter of prover pipe.
OD	Outside diameter of prover pipe.
WT	Wall thickness of prover pipe.

Liquid Density

API	Density of liquid in degrees API gravity units.
API_b	Base liquid density in degrees API gravity units.
API_{obs}	Observed liquid density at base pressure in degrees API gravity units.
DEN	Density of liquid in kilogram per cubic meter (kg/M3) units.
DEN_b	Base liquid density in kilogram per cubic meter (kg/M3) units.
DEN_{obs}	Observed liquid density at base pressure in kilogram per cubic meter (kg/M3) units.
RD	Density of liquid in relative density.
RD_b	Base liquid density in relative density.
RD_{obs}	Observed liquid density at base pressure in relative density.
RHO	Density of liquid in mass per unit volume.
RHO_b	Base density.
RHO_{obs}	Observed liquid density at base pressure.
RHO_p	Density of liquid in prover (for prover calibrations).
RHO_{tm}	Density of liquid in test measure (for prover calibrations).
RHO_{tp}	Density of liquid at operating temperature and pressure.

Temperature

˚C	Celsius temperature scale.
˚F	Fahrenheit temperature scale.
T	Temperature.
T_b	Base temperature in ˚F or ˚C.
T_d	Temperature of detector mounting shaft or displacer shaft on SVP with external detectors.
T_{obs}	Observed temperature to determine RHO_b (i.e., hydrometer temperature) in ˚F or ˚C.
T_m	Temperature of meter in ˚F or ˚C.
T_{tm}	Temperature of test measure in ˚F or ˚C.
T_{mm}	Temperature of master meter in ˚F or ˚C.
T_p	Temperature of prover in ˚F or ˚C.
T_{mp}	Temperature of master prover in ˚F or ˚C.
TWA	Weighted average temperature of liquid for measurement ticket calculations in ˚F or ˚C.

Pressure

kPa	Kilopascals (SI) pressure units.
kPa_a	Kilopascals in absolute pressure units.
kPa_g	Kilopascals in gauge pressure units.
psi	Pounds per square inch (USC) pressure units.
psia	Pounds per square inch in absolute pressure units.
psig	Pounds per square inch in gauge pressure units.
P	Pressure.
Pb	Base pressure in psi or kPa pressure units.
Pb_a	Base pressure in absolute pressure units.
Pb_g	Base pressure in gauge pressure units.
P_m	Pressure of liquid in meter in gauge pressure units.
P_{mm}	Pressure of liquid in master meter in gauge pressure units.
P_{mp}	Pressure of liquid in master prover in gauge pressure units.
P_p	Pressure of liquid in prover in gauge pressure units.

PWA	Weighted average pressure of liquid for measurement ticket calculations in gauge pressure units.
Pe	Equilibrium vapor pressure of liquid at normal operating conditions in absolute pressure units.
Pe_{b}	Equilibrium vapor pressure of liquid at base temperature in absolute pressure units.
Pe_{m}	Equilibrium vapor pressure of liquid in meter at proving conditions in absolute pressure units.
Pe_{mm}	Equilibrium vapor pressure of liquid in master meter in absolute pressure units.
Pe_{p}	Equilibrium vapor pressure of liquid in prover at proving conditions in absolute pressure units.

Correction Factors

CCF	Combined correction factor.
CCF_{m}	Combined correction factor for meter at proving conditions.
CCF_{mm}	Combined correction factor for master meter at proving conditions.
CCF_{mp}	Combined correction factor for master prover at proving conditions.
CCF_{p}	Combined correction factor for prover at proving conditions.
CPL	Correction for compressibility of liquid at normal operating conditions (for CMF and ticket calculations).
CPL_{m}	Correction for compressibility of liquid in meter at proving conditions.
CPL_{mm}	Correction for compressibility of liquid in master meter at proving conditions.
CPL_{mp}	Correction for compressibility of liquid in paster prover at proving conditions.
CPL_{p}	Correction for compressibility of liquid in prover at proving conditions.
CPS	Correction for the effect of pressure on steel (see Appendix A).
CPS_{m}	Correction for the effect of pressure on steel test measure.
CPS_{mp}	Correction for the effect of pressure on steel master prover.
CPS_{p}	Correction for the effect of pressure on steel prover.
CSW	Fiscal correction for sediment and water.
$CTDW_{p}$	Correction for the effect of temperature difference of water for prover calibrations.
CTL	Correction for the effect of temperature on liquid at normal operating conditions (for ticket calculations).
CTL_{m}	Correction for the effect of temperature on liquid in meter at proving conditions.
CTL_{mm}	Correction for the effect of temperature on liquid when using a master meter for proving operations.
CTL_{mp}	Correction for the effect of temperature on liquid in master prover.
CTL_{p}	Correction for the effect of temperature on liquid in prover.
CTS	Correction for the effect of temperature on steel (see Appendix A).
CTS_{m}	Correction for the effect of temperature on steel test measure.
CTS_{mp}	Correction for the effect of temperature on steel master prover.
CTS_{p}	Correction for the effect of temperature on steel prover.
CCTS	Combined correction for the effect of temperature on steel prover and steel test measure.
E	Modulus of elasticity of steel prover.
F	Compressibility factor of liquid in meter at normal operating conditions (for CMF and ticket calculations).
F_{m}	Compressibility factor of liquid in meter at proving conditions.
F_{mm}	Compressibility factor of liquid in master meter at proving conditions.
F_{mp}	Compressibility factor of liquid in master prover.
F_{p}	Compressibility factor of liquid in prover.
Gl	Linear coefficient of thermal expansion on displacer shaft or detector mounting.
Ga	Area coefficient of thermal expansion of prover chamber.
Gc	Cubical coefficient of thermal expansion of prover.
Gcm	Cubical coefficient of thermal expansion of test measure or master prover.
MA	Meter accuracy factor.
MF	Meter factor.
CMF	Composite meter factor.
MMF	Master meter factor.
MMF_{start}	Master meter factor at start of each master meter calibration run.
MMF_{stop}	Master meter factor at stop of each master meter calibration run.
MMF_{avg}	Average master meter factor for each master meter calibration run.
NKF	Nominal K-factor, pulses per unit volume.
KF	K-factor, pulses per unit volume.
CKF	Composite K-factor, pulses per unit volume.

Volumes

BMV	Base test measure volume.
BMVa	Base test measure volume adjusted for scale reading.

BPV	Base prover volume for prover.
BPV_{mp}	Base prover volume for master prover.
CPV	Calibrated prover volume.
GV	Gross volume.
GSV	Gross standard volume (for ticket calculations).
GSV_m	Gross standard volume of meter for proving operations.
GSV_{mm}	Gross standard volume when using a master meter for proving operations.
GSV_{mp}	Gross standard volume of master prover for proving operations.
GSV_p	Gross standard volume of prover for proving operations.
IV	Indicated volume (for ticket calculations).
IV_m	Indicated volume of meter for proving operations.
IV_{mm}	Indicated volume of master meter for proving operations.
ISV	Indicated standard volume.
ISV_m	Indicated standard volume of meter for proving operations.
ISV_{mm}	Indicated standard volume of master meter for proving operations.
MR_o	Opening meter reading.
MR_c	Closing meter reading.
MMR_o	Opening master meter reading.
MMR_c	Closing master meter reading.
N	Number of whole pulses for a single proving roundtrip.
Ni	Number of interpolated pulses for a single proving roundtrip
N_{avg}	Average number of pulses for the proving roundtrips that satisfy the repeatability requirements.
NSV	Net standard volume (for ticket calculations).
SR	Scale reading of test measure.
SRu	Upper scale reading of open tank prover.
SRl	Lower scale reading of open tank prover.
SWV	Sediment and water volume (for ticket calculations).
V	Volume
V_b	Volume of container at base conditions.
V_{tp}	Volume of container at operating temperature and pressure conditions.
WD	Waterdraw's test measure volume adjusted for scale reading and corrected for CTDW and CCTS.
WDz	Sum of all test measures' WD values for a single pass.
WDzb	Sum of all test measures' WDz values for a single pass corrected to Pb.

1.9 Liquid Density

The density of the liquid shall be determined by appropriate technical standards or, if necessary, by either proper correlations or equations of state. If multiple parties are involved in the measurement, the method selected for determining the liquid's densities shall be mutually agreed upon.

The density of the liquid at both flowing and base conditions can be obtained by using one of three methods:

a. Empirical density correlation.
b. An equation of state.
c. An appropriate technical expression.

The liquid's flowing density (RHO_{tp}) is determined from the following expression:

$$RHO_{tp} = RHO_b \times CTL \times CPL$$

and

$$RHO_{tp}/RHO_b = CTL \times CPL$$

It is important to note that RHO_b must be known to accurately calculate RHO_{tp}. Appendix B—Liquid Density Correlation contains a list of recommended liquid versus API correlations in accordance with API's position paper dated 1981. Where an API correlation does not currently exist, the appropriate ASTM standard has been provided to assist the user community.

1.10 Derivation of Liquid Base Volume Equations

The volume correction factors for the liquid utilized by the petroleum industry are based on the following fundamental expressions.

1.10.1 DETERMINATION OF INDICATED VOLUME

The IV is the change in meter reading that occurs during a receipt or delivery. The word *registration*, though not preferred, often has the same meaning. The IV is obtained by subtracting the Opening Meter Reading (MR_o) from the Closing Meter Reading (MR_c).

$$IV = MR_c - MR_o$$

1.10.2 DETERMINATION OF GROSS STANDARD VOLUME

The GSV is correlated by the following physical expression:

$$GSV = Mass/RHO_b$$

and the mass of the metered quantities by

$$Mass = IV \times MF \times RHO_{tp}$$

As a result, the GSV can be calculated by substituting the various terms to arrive at the following traditional expression:

$$GSV = IV \times CTL \times CPL \times MF$$

or

$$GSV = IV \times CTL \times CMF$$

Note: When using temperature compensated meter readings (MR_o, MR_c, IV), the CTL value shall be set to 1.0000.

1.10.3 DETERMINATION OF NET STANDARD VOLUME

The NSV is the equivalent volume of a liquid at its base conditions that does not include nonmerchantable items such as sediment and water. The formula for calculating NSV is as follows:

$$NSV = GSV \times CSW$$

The correction for sediment and water content (CSW) is explained in the subsequent section.

1.10.4 DETERMINATION OF S&W VOLUME

The sediment & water volume (SWV) is a calculated quantity based upon the percent sediment and water (%S&W) determined by a representative sample of the quantity of liquid being measured. It represents the nonhydrocarbon portion of the liquid and is calculated as follows:

$$SWV = GSV - [GSV \times (1 - [\%S\&W/100])]$$

1.11 Principal Correction Factors

Calculations in this publication are based on correcting the measured volume of the petroleum liquid to its volume at base conditions. Correction factors are provided to adjust the metered volume and the volume of prover or test measures to base conditions.

1.11.1 LIQUID DENSITY CORRECTION FACTORS

Liquid density correction factors are employed to account for changes in density due to the effects of temperature and pressure upon the liquid. These correction factors are as follows:

CTL	corrects for the effect of temperature on the liquid density.
CPL	corrects for the effect of compressibility on the liquid density.

1.11.1.1 Correction for Effect of Temperature on Liquid (CTL)

If a petroleum liquid is subjected to a change in temperature, its density will decrease as the temperature rises or increase as the temperature falls. This density change is proportional to the thermal coefficient of expansion of the liquid, which varies with base density (RHO_b) and the liquid temperature.

The correction factor for the effect of temperature on the liquid's density is called CTL. The appropriate standards for the thermal expansion factor for a liquid (CTL) may be found in Appendix B—Liquid Density Correlation.

1.11.1.2 Correction for Compressibility on Liquid (CPL)

If a petroleum liquid is subjected to a change in pressure, its density will increase as the pressure increases and decrease as the pressure decreases. This density change is proportional to the liquid's compressibility factor (F), which depends upon both its base density (RHO_b) and the liquid temperature. The appropriate standards for the compressibility factor (F) may be found in Appendix B—Liquid Density Correlation.

The correction factor for the effect of pressure on the liquid's density (CPL) can be calculated using the following expression:

$$CPL = 1/(1 - [P - (Pe_a - Pb_a)] \times [F])$$

and

$$(Pe_a - Pb_a) \geq 0$$

Where:

Pb_a = base pressure, in absolute pressure units.
Pe_a = equilibrium vapor pressure at the temperature of the liquid being measured, in absolute pressure units.
P = operating pressure, in gauge pressure units.
F = compressibility factor for liquid.

The liquid equilibrium vapor pressure (Pe_a) is considered to be equal to base pressure (Pb_a) for liquids that have an equilibrium vapor pressure less than or equal to atmospheric pressure at flowing temperature.

1.11.2 PROVER AND FIELD MEASURE STEEL CORRECTION FACTORS

Prover correction factors are employed to account for changes in the prover volume due to the effects of temperature and pressure upon the steel. These correction factors are as follows:

CTS	corrects for thermal expansion and/or contraction of the steel in the prover shell due to the average prover liquid temperature.
CPS	corrects for pressure expansion and/or contraction of the steel in the prover shell due to the average prover liquid pressure.

When the volume of the container at base conditions (V_b) is known, the volume at any other temperature and pressure (V_{tp}) can be calculated from the following equation:

$$V_{tp} = V_b \times CTS \times CPS$$

Conversely, when the volume of the container at any temperature and pressure (V_{tp}) is known, the volume at base conditions (V_b) can be calculated by

$$V_b = V_{tp}/(CTS \times CPS)$$

1.11.2.1 Correction for the Effect of Temperature on Steel (CTS)

Any metal container, be it a pipe prover, a tank prover, or a portable test measure, when subjected to a change in temperature, will change its volume accordingly. The volume change, regardless of prover shape, is proportional to the cubical coefficient of thermal expansion of the material. The cubical coefficient of thermal expansion is valid when the calibrated section and its detector switch mountings are constructed of a single material (pipe provers, tank provers, and field measures).

Corrections for Single-Walled Container or Prover

The CTS for pipe provers, open tank provers, and portable test measures assumes a singular construction material and may be calculated from the following:

$$CTS = 1 + [(T - T_b) \times Gc]$$

Where:

Gc = Mean coefficient of cubical expansion per degree temperature of the material of which the container is made between T_b and T.
T_b = Base temperature.
T = Mean liquid temperature in the container.

The cubical coefficient of expansion (Gc) for a pipe prover or open tank prover shall be the one for the materials used in the construction of the calibrated section. However, the Gc values contained in Table 1 shall be used if the coefficient of cubical expansion is unknown.

The cubical coefficient of expansion (Gc) on the Report of Calibration furnished by the calibrating agency is the one to be used for that individual field measure.

Corrections for Small Volume Provers With External Detectors

While the cubical coefficient of expansion is used in calculating CTS for pipe provers, tank provers, and field measures, a modified approach is needed for some of the small volume provers due to their design. The detector(s) are mounted externally, rather than on the prover barrel itself. Thus the volume changes that occur due to temperature are defined in terms of the area change in the prover barrel and the change in distance between the detector positions. While occasionally these detector positions may be on a carbon or stainless steel mounting, it is much more likely that they will be on a mounting of a special alloy that has a very small linear coefficient of expansion.

For small volume provers that utilize detectors not mounted in the calibrated section of the pipe, the correction factor for the effect of temperature (CTS) may be calculated from the following:

Table 1—Coefficients of Thermal Expansion for Steel (Gc,Ga,G1)

Type of Steel	Thermal Expansion Coefficient	
	(per ˚F)	(per ˚C)
A. Cubical Coefficient, Gc		
Mild Carbon	1.86E-05	3.35E-05
304 Stainless	2.88E-05	5.18E-05
316 Stainless	2.65E-05	4.77E-05
17-4PH Stainless	1.80E-05	3.24E-05
B. Area Coefficient, Ga		
Mild Carbon	1.24E-05	2.23E-05
304 Stainless	1.92E-05	3.46E-05
316 Stainless	1.77E-05	3.18E-05
17-4PH Stainless	1.20E-05	2.16E-05
C. Linear Coefficient, Gl		
Mild Carbon	6.20E-06	1.12E-05
304 Stainless	9.60E-06	1.73E-05
316 Stainless	8.83E-06	1.59E-05
17-4PH Stainless	6.00E-06	1.08E-05

$$CTS = (1 + [(T_p - T_b) \times (Ga)]) \times (1 + [(T_d - T_b) \times (G1)]$$

Where:

Ga = Area thermal coefficient of expansion for prover chamber.
$G1$ = Linear thermal coefficient of expansion on displacer shaft.
T_b = Base temperature.
T_d = Temperature of the detector mounting shaft or displacer shaft on SVP with external detectors.
T_p = Temperature of the prover chamber.

The linear and area thermal coefficients of expansion used shall be the ones for the materials used in the construction of the prover. However, the values contained in Table 1 shall be used if the coefficients are unknown.

1.11.2.2 Correction for the Effect of Pressure on Steel (CPS)

If a metal container such as a conventional pipe prover, a tank prover, or a test measure is subjected to an internal pressure, the walls of the container will stretch elastically and the volume of the container will change accordingly.

Corrections for Single-Walled Container or Prover

While it is recognized that simplifying assumptions enter the equations below, for practical purposes, the correction factor for the effect of internal pressure on the volume of a cylindrical container, called CPS, may be calculated from

$$CPS = 1 + ([(P - P_b) \times (ID)]/(E \times WT))$$

Assuming P_b is 0 gauge pressure, the equation simplifies to

$$CPS = 1 + [(P \times ID)/(E \times WT)]$$

and

$$ID = OD - (2 \times WT)$$

Where:

P = internal operating pressure of prover, in gauge pressure units.
P_b = base pressure, in gauge pressure units.
ID = internal diameter of container.
E = modulus of elasticity for container material.
OD = outside diameter of container.
WT = wall thickness of container.

The modulus of elasticity (E) for a pipe prover or open tank prover shall be the one for the materials used in the construction of the calibrated section. However, the values contained in Table 2 shall be used if the modulus of elasticity (E) is unknown.

The modulus of elasticity (E) on the Report of Calibration furnished by the calibrating agency is the one to be used for that individual field measure. However, the values contained in Table 2 shall be used if the modulus of elasticity (E) is unknown.

Corrections for Double-Walled Container or Prover

Some provers are designed with a double wall to equalize the pressure inside and outside the calibrated chamber. In this case, the inner measuring section of the prover is not subjected to a net internal pressure, and the walls of this inner chamber do not stretch elastically. Therefore, in this special case,

$$CPS = 1.0000$$

1.11.3 METER FACTORS AND COMPOSITE METER FACTORS (MFs, CMFs)

Meter factors (MFs) and composite meter factors (CMFs) are terms to adjust for inaccuracies associated with the meter's performance as determined at the time of proving. Unless the meter is equipped with an adjustment that alters its registration to account for the MF, an MF must be applied to the indicated volume of the meter.

The MF is determined at the time of proving by the following expression:

$$MF = GSV_p / ISV_m$$

The CMF may be used in applications where the gravity, temperature, and pressure are considered constant throughout the measurement ticket period, or anticipated changes in these parameters result in uncertainties unacceptable to the parties or as agreed by the parties as a convenience. The CMF is determined at the time of proving by the following expression:

$$CMF = CPL_m \times MF$$

Table 2—Modulus of Elasticity for Steel Containers (E)

Type of Steel	Modulus of Elasticity		
	(per psi)	(per bar)	(per kPa)
Mild Carbon	3.00E+07	2.07E+06	2.07E+08
304 Stainless	2.80E+07	1.93E+06	1.93E+08
316 Stainless	2.80E+07	1.93E+06	1.93E+08
17-4PH Stainless	2.85E+07	1.97E+06	1.97E+08

1.11.4 METER ACCURACY FACTOR (MA)

Meter accuracy factor (MA) is a term utilized specifically for loading rack meters for refined products. In most truck rack applications, the meter is mechanically or electronically adjusted at the time of proving to ensure that the meter factor is approximately unity. This simplifies the bill of lading and accounting issues associated with truck applications in refined product service.

The MA is determined at the time of proving by the following expression:

$$MA = ISV_m / GSV_p$$

or the reciprocal of the MF

$$MA = 1/MF$$

1.11.5 K-FACTORS AND COMPOSITE K-FACTORS (KFs, CKFs)

For some applications, K-factors (KFs) and composite K-factors (CKFs) are utilized to eliminate the need for applying meter correction factors to the IV. By changing the K-factor or CKF at the time of proving, the meter is electronically adjusted at the time of proving to ensure that the meter factor is approximately unity.

A new K-factor is determined at the time of proving by the following expression:

New KF = (Old KF)/MF

The CKF may be used in applications where the gravity, temperature, and pressure are approximately constant throughout the measurement ticket period. The new CKF is determined at the time of proving by the following expression:

New CKF = (Old CKF)/CMF

1.11.6 COMBINED CORRECTION FACTORS (CCF, CCF_p, CCF_m)

When multiplying a large number (for example, an IV) by a small number (for example, a correction factor) over and over again, a lowering of the precision may occur in the calculations. In addition, errors can occur in mathematical calculations due to sequencing and rounding between different machines or programs. To minimize these errors, the industry selected a method that combines correction factors in a specified sequence and maximum discrimination levels. The method for combining two or more correction factors is to first obtain a CCF by serial multiplication of the individual correction factors and rounding the CCF to a required number of decimal places.

Three CCFs have been adopted to minimize errors in calculations:

a. For measurement ticket calculations to determine GSV,

$$CCF = CTL \times CPL \times MF$$

or

$$CCF = CTL \times CPL \times CMF$$

Note: When using temperature compensated meter readings (MR_o, MR_c, IV), the CTL value shall be set to 1.0000 for CCF measurement ticket calculations.

Note: When using a CMF, the CPL value shall be set to 1.0000 for CCF measurement ticket calculations.

b. For proving calculations to determine GSV_p,

$$CCF_p = CTS_p \times CPS_p \times CTL_p \times CPL_p$$

c. For proving calculations to determine ISV_m,

$$CCF_m = CTL_m \times CPL_m$$

Note: When using temperature compensated meter readings (MR_o, MR_c, ISV_m), the CTL value shall be set to 1.0000 for CCF_m proving report calculations.

1.11.7 CORRECTION FOR SEDIMENT AND WATER (CSW)

Sediment and water are not considered merchantable components of certain hydrocarbon liquids, such as crude oil and certain refined products. The correction to adjust the GSV of the liquid for these nonmerchantable quantities is defined by the following expression:

$$CSW = [1 - (\%S\&W/100)]$$

APPENDIX A—CORRECTION FACTORS FOR STEEL

The abbreviated tables contained in this appendix are designed to assist the user in validating computer calculations.

Table A-1—Temperature Correction Factors for Mild Carbon Steel

	USC (˚F)	SI (˚C)	
T_b[a]	60.0	15.0	Degree
Gc[b]	1.86E-05	3.35E-05	per Degree

USC Units

Observed Temperature (˚F)	CTS	Observed Temperature (˚F)	CTS
0.0	0.998884	100.0	1.000744
1.0	0.998903	101.0	1.000763
2.0	0.998921	102.0	1.000781
3.0	0.998940	103.0	1.000800
4.0	0.998958	104.0	1.000818
5.0	0.998977	105.0	1.000837
6.0	0.998996	106.0	1.000856
7.0	0.999014	107.0	1.000874
8.0	0.999033	108.0	1.000893
9.0	0.999051	109.0	1.000911
10.0	0.999070	110.0	1.000930
50.0	0.999814	150.0	1.001674
51.0	0.999833	151.0	1.001693
52.0	0.999851	152.0	1.001711
53.0	0.999870	153.0	1.001730
54.0	0.999888	154.0	1.001748
55.0	0.999907	155.0	1.001767
56.0	0.999926	156.0	1.001786
57.0	0.999944	157.0	1.001804
58.0	0.999963	158.0	1.001823
59.0	0.999981	159.0	1.001841
60.0	1.000000	160.0	1.001860

SI Units

Observed Temperature (˚C)	CTS	Observed Temperature (˚C)	CTS
-5.00	0.999330	40.00	1.000838
-4.00	0.999364	41.00	1.000871
-3.00	0.999397	42.00	1.000905
-2.00	0.999431	43.00	1.000938
-1.00	0.999464	44.00	1.000972
0.00	0.999498	45.00	1.001005
1.00	0.999531	46.00	1.001039
2.00	0.999565	47.00	1.001072
3.00	0.999598	48.00	1.001106
4.00	0.999632	49.00	1.001139
5.00	0.999665	50.00	1.001173
15.00	1.000000	60.00	1.001508
16.00	1.000034	61.00	1.001541
17.00	1.000067	62.00	1.001575
18.00	1.000101	63.00	1.001608
19.00	1.000134	64.00	1.001642
20.00	1.000168	65.00	1.001675
21.00	1.000201	66.00	1.001709
22.00	1.000235	67.00	1.001742
23.00	1.000268	68.00	1.001776
24.00	1.000302	69.00	1.001809
25.00	1.000335	70.00	1.001843

Note: The correction for the effect of temperature on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The table shown was calculated using the following equation applicable to conventional pipe and open tank provers: $CTS = 1 + [(T - T_b) \times Gc]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

Table A-2—Temperature Correction Factors for 304 Stainless Steel

	USC (˚F)	SI (˚C)	
T_b[a]	60.0	15.0	Degree
Gc[b]	2.88E-05	5.18E-05	per Degree

USC Units

Observed Temperature (˚F)	CTS	Observed Temperature (˚F)	CTS
0.0	0.998272	100.0	1.001152
1.0	0.998301	101.0	1.001181
2.0	0.998330	102.0	1.001210
3.0	0.998358	103.0	1.001238
4.0	0.998387	104.0	1.001267
5.0	0.998416	105.0	1.001296
6.0	0.998445	106.0	1.001325
7.0	0.998474	107.0	1.001354
8.0	0.998502	108.0	1.001382
9.0	0.998531	109.0	1.001411
10.0	0.998560	110.0	1.001440
50.0	0.999712	150.0	1.002592
51.0	0.999741	151.0	1.002621
52.0	0.999770	152.0	1.002650
53.0	0.999798	153.0	1.002678
54.0	0.999827	154.0	1.002707
55.0	0.999856	155.0	1.002736
56.0	0.999885	156.0	1.002765
57.0	0.999914	157.0	1.002794
58.0	0.999942	158.0	1.002822
59.0	0.999971	159.0	1.002851
60.0	1.000000	160.0	1.002880

SI Units

Observed Temperature (˚C)	CTS	Observed Temperature (˚C)	CTS
-5.00	0.998964	40.00	1.001295
-4.00	0.999016	41.00	1.001347
-3.00	0.999068	42.00	1.001399
-2.00	0.999119	43.00	1.001450
-1.00	0.999171	44.00	1.001502
0.00	0.999223	45.00	1.001554
1.00	0.999275	46.00	1.001606
2.00	0.999327	47.00	1.001658
3.00	0.999378	48.00	1.001709
4.00	0.999430	49.00	1.001761
5.00	0.999482	50.00	1.001813
15.00	1.000000	60.00	1.002331
16.00	1.000052	61.00	1.002383
17.00	1.000104	62.00	1.002435
18.00	1.000155	63.00	1.002486
19.00	1.000207	64.00	1.002538
20.00	1.000259	65.00	1.002590
21.00	1.000311	66.00	1.002642
22.00	1.000363	67.00	1.002694
23.00	1.000414	68.00	1.002745
24.00	1.000466	69.00	1.002797
25.00	1.000518	70.00	1.002849

Note: The correction for the effect of temperature on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The table shown was calculated using the following equation applicable to conventional pipe and open tank provers: $CTS = 1 + [(T - T_b) \times Gc]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

Table A-3—Temperature Correction Factors for 316 Stainless Steel

	USC (˚F)	SI (˚C)	
T_b[a]	60.0	15.0	Degree
Gc[b]	2.65E-05	4.77E-05	per Degree

USC Units

Observed Temperature (˚F)	CTS	Observed Temperature (˚F)	CTS
0.0	0.998410	100.0	1.001060
1.0	0.998437	101.0	1.001087
2.0	0.998463	102.0	1.001113
3.0	0.998490	103.0	1.001140
4.0	0.998516	104.0	1.001166
5.0	0.998543	105.0	1.001193
6.0	0.998569	106.0	1.001219
7.0	0.998596	107.0	1.001246
8.0	0.998622	108.0	1.001272
9.0	0.998649	109.0	1.001299
10.0	0.998675	110.0	1.001325
50.0	0.999735	150.0	1.002385
51.0	0.999762	151.0	1.002412
52.0	0.999788	152.0	1.002438
53.0	0.999815	153.0	1.002465
54.0	0.999841	154.0	1.002491
55.0	0.999868	155.0	1.002518
56.0	0.999894	156.0	1.002544
57.0	0.999921	157.0	1.002571
58.0	0.999947	158.0	1.002597
59.0	0.999974	159.0	1.002624
60.0	1.000000	160.0	1.002650

SI Units

Observed Temperature (˚C)	CTS	Observed Temperature (˚C)	CTS
-5.00	0.999046	40.00	1.001193
-4.00	0.999094	41.00	1.001240
-3.00	0.999141	42.00	1.001288
-2.00	0.999189	43.00	1.001336
-1.00	0.999237	44.00	1.001383
0.00	0.999285	45.00	1.001431
1.00	0.999332	46.00	1.001479
2.00	0.999380	47.00	1.001526
3.00	0.999428	48.00	1.001574
4.00	0.999475	49.00	1.001622
5.00	0.999523	50.00	1.001670
15.00	1.000000	60.00	1.002147
16.00	1.000048	61.00	1.002194
17.00	1.000095	62.00	1.002242
18.00	1.000143	63.00	1.002290
19.00	1.000191	64.00	1.002337
20.00	1.000239	65.00	1.002385
21.00	1.000286	66.00	1.002433
22.00	1.000334	67.00	1.002480
23.00	1.000382	68.00	1.002528
24.00	1.000429	69.00	1.002576
25.00	1.000477	70.00	1.002624

Note: The correction for the effect of temperature on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The table shown was calculated using the following equation applicable to conventional pipe and open tank provers: $CTS = 1 + [(T - T_b) \times Gc]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

Table A-4—Temperature Correction Factors for 17-4PH Stainless Steel

	USC (˚F)	SI (˚C)	
T_b[a]	60.0	15.0	Degree
Gc[b]	1.80E-05	3.24E-05	per Degree

USC Units

Observed Temperature (˚F)	CTS	Observed Temperature (˚F)	CTS
0.0	0.998920	100.0	1.000720
1.0	0.998938	101.0	1.000738
2.0	0.998956	102.0	1.000756
3.0	0.998974	103.0	1.000774
4.0	0.998992	104.0	1.000792
5.0	0.999010	105.0	1.000810
6.0	0.999028	106.0	1.000828
7.0	0.999046	107.0	1.000846
8.0	0.999064	108.0	1.000864
9.0	0.999082	109.0	1.000882
10.0	0.999100	110.0	1.000900
50.0	0.999820	150.0	1.001620
51.0	0.999838	151.0	1.001638
52.0	0.999856	152.0	1.001656
53.0	0.999874	153.0	1.001674
54.0	0.999892	154.0	1.001692
55.0	0.999910	155.0	1.001710
56.0	0.999928	156.0	1.001728
57.0	0.999946	157.0	1.001746
58.0	0.999964	158.0	1.001764
59.0	0.999982	159.0	1.001782
60.0	1.000000	160.0	1.001800

SI Units

Observed Temperature (˚C)	CTS	Observed Temperature (˚C)	CTS
-5.00	0.999352	40.00	1.000810
-4.00	0.999384	41.00	1.000842
-3.00	0.999417	42.00	1.000875
-2.00	0.999449	43.00	1.000907
-1.00	0.999482	44.00	1.000940
0.00	0.999514	45.00	1.000972
1.00	0.999546	46.00	1.001004
2.00	0.999579	47.00	1.001037
3.00	0.999611	48.00	1.001069
4.00	0.999644	49.00	1.001102
5.00	0.999676	50.00	1.001134
15.00	1.000000	60.00	1.001458
16.00	1.000032	61.00	1.001490
17.00	1.000065	62.00	1.001523
18.00	1.000097	63.00	1.001555
19.00	1.000130	64.00	1.001588
20.00	1.000162	65.00	1.001620
21.00	1.000194	66.00	1.001652
22.00	1.000227	67.00	1.001685
23.00	1.000259	68.00	1.001717
24.00	1.000292	69.00	1.001750
25.00	1.000324	70.00	1.001782

Note: The correction for the effect of temperature on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The table shown was calculated using the following equation applicable to conventional pipe and open tank provers:
$CTS = 1 + [(T - T_b) \times Gc]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

Table A-5—Pressure Correction Factors for Mild Carbon Steel

	USC (psi)	SI (bar)		USC (in)	SI (mm)
T_b[a]	14.7	15.0	OD[c]	10.750	273.05
Gc[b]	3.00E+07	2.07E+06	WT[d]	0.375	9.53
			ID[e]	10.000	254.00

USC Units

Observed Pressure (psig)	CPS	Observed Pressure (psig)	CPS
0.0	1.000000	500.0	1.000444
5.0	1.000004	505.0	1.000449
10.0	1.000009	510.0	1.000453
15.0	1.000013	515.0	1.000458
20.0	1.000018	520.0	1.000462
25.0	1.000022	525.0	1.000467
30.0	1.000027	530.0	1.000471
35.0	1.000031	535.0	1.000476
40.0	1.000036	540.0	1.000480
45.0	1.000040	545.0	1.000484
50.0	1.000044	550.0	1.000489
50.0	1.000044	800.0	1.000711
55.0	1.000049	805.0	1.000716
60.0	1.000053	810.0	1.000720
65.0	1.000058	815.0	1.000724
70.0	1.000062	820.0	1.000729
75.0	1.000067	825.0	1.000733
80.0	1.000071	830.0	1.000738
85.0	1.000076	835.0	1.000742
90.0	1.000080	840.0	1.000747
95.0	1.000084	845.0	1.000751
100.0	1.000089	850.0	1.000756

SI Units

Observed Pressure (bar-g)	CPS	Observed Pressure (bar-g)	CPS
0.00	1.000000	40.00	1.000515
1.00	1.000013	41.00	1.000528
2.00	1.000026	42.00	1.000541
3.00	1.000039	43.00	1.000554
4.00	1.000052	44.00	1.000567
5.00	1.000064	45.00	1.000580
6.00	1.000077	46.00	1.000593
7.00	1.000090	47.00	1.000605
8.00	1.000103	48.00	1.000618
9.00	1.000116	49.00	1.000631
10.00	1.000129	50.00	1.000644
20.00	1.000258	60.00	1.000773
21.00	1.000271	61.00	1.000786
22.00	1.000283	62.00	1.000799
23.00	1.000296	63.00	1.000812
24.00	1.000309	64.00	1.000824
25.00	1.000322	65.00	1.000837
26.00	1.000335	66.00	1.000850
27.00	1.000348	67.00	1.000863
28.00	1.000361	68.00	1.000876
29.00	1.000374	69.00	1.000889
30.00	1.000386	70.00	1.000902

Note: The correction for the effect of pressure on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The tables shown were calculated using the following equation applicable to single-walled containers or provers: $CPS = 1 + [(P \times ID)/(E \times WT)]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

[c] OD= Outside diameter of prover pipe.

[d] WT= Wall thickness of prover pipe.

[e] ID= Inside diameter of prover pipe.

Table A-6—Pressure Correction Factors for 304 and 316 Stainless Steel

	USC (psi)	SI (bar)		USC (in)	SI (mm)
T_b[a]	14.7	15.0	OD[c]	10.750	273.05
Gc[b]	2.80E+07	1.93E+06	WT[d]	0.375	9.53
			ID[e]	10.000	254.00

USC Units

Observed Pressure (psig)	CPS	Observed Pressure (psig)	CPS
0.0	1.000000	500.0	1.000476
5.0	1.000005	505.0	1.000481
10.0	1.000010	510.0	1.000486
15.0	1.000014	515.0	1.000490
20.0	1.000019	520.0	1.000495
25.0	1.000024	525.0	1.000500
30.0	1.000029	530.0	1.000505
35.0	1.000033	535.0	1.000510
40.0	1.000038	540.0	1.000514
45.0	1.000043	545.0	1.000519
50.0	1.000048	550.0	1.000524
50.0	1.000048	800.0	1.000762
55.0	1.000052	805.0	1.000767
60.0	1.000057	810.0	1.000771
65.0	1.000062	815.0	1.000776
70.0	1.000067	820.0	1.000781
75.0	1.000071	825.0	1.000786
80.0	1.000076	830.0	1.000790
85.0	1.000081	835.0	1.000795
90.0	1.000086	840.0	1.000800
95.0	1.000090	845.0	1.000805
100.0	1.000095	850.0	1.000810

SI Units

Observed Pressure (bar-g)	CPS	Observed Pressure (bar-g)	CPS
0.00	1.000000	40.00	1.000553
1.00	1.000014	41.00	1.000566
2.00	1.000028	42.00	1.000580
3.00	1.000041	43.00	1.000594
4.00	1.000055	44.00	1.000608
5.00	1.000069	45.00	1.000622
6.00	1.000083	46.00	1.000636
7.00	1.000097	47.00	1.000649
8.00	1.000111	48.00	1.000663
9.00	1.000124	49.00	1.000677
10.00	1.000138	50.00	1.000691
20.00	1.000276	60.00	1.000829
21.00	1.000290	61.00	1.000843
22.00	1.000304	62.00	1.000857
23.00	1.000318	63.00	1.000870
24.00	1.000332	64.00	1.000884
25.00	1.000345	65.00	1.000898
26.00	1.000359	66.00	1.000912
27.00	1.000373	67.00	1.000926
28.00	1.000387	68.00	1.000940
29.00	1.000401	69.00	1.000953
30.00	1.000415	70.00	1.000967

Note: The correction for the effect of pressure on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The tables shown were calculated using the following equation applicable to single-walled containers or provers:

$CPS = 1 + [(P \times ID)/(E \times WT)]$

[a] T_b = Base temperature in ˚F or ˚C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

[c] OD= Outside diameter of prover pipe.

[d] WT= Wall thickness of prover pipe.

[e] ID= Inside diameter of prover pipe.

Table A-7—Pressure Correction Factors for 17-4PH Stainless Steel

	USC (psi)	SI (bar)		USC (in)	SI (mm)
T_b[a]	14.7	15.0	OD[c]	10.750	273.05
Gc[b]	2.85E+07	1.97E+06	WT[d]	0.375	9.53
			ID[e]	10.000	254.00

USC Units

Observed Pressure (psig)	CPS	Observed Pressure (psig)	CPS
0.0	1.000000	500.0	1.000468
5.0	1.000005	505.0	1.000473
10.0	1.000009	510.0	1.000477
15.0	1.000014	515.0	1.000482
20.0	1.000019	520.0	1.000487
25.0	1.000023	525.0	1.000491
30.0	1.000028	530.0	1.000496
35.0	1.000033	535.0	1.000501
40.0	1.000037	540.0	1.000505
45.0	1.000042	545.0	1.000510
50.0	1.000047	550.0	1.000515
50.0	1.000047	800.0	1.000749
55.0	1.000051	805.0	1.000753
60.0	1.000056	810.0	1.000758
65.0	1.000061	815.0	1.000763
70.0	1.000065	820.0	1.000767
75.0	1.000070	825.0	1.000772
80.0	1.000075	830.0	1.000777
85.0	1.000080	835.0	1.000781
90.0	1.000084	840.0	1.000786
95.0	1.000089	845.0	1.000791
100.0	1.000094	850.0	1.000795

SI Units

Observed Pressure (bar-g)	CPS	Observed Pressure (bar-g)	CPS
0.00	1.000000	40.00	1.000541
1.00	1.000014	41.00	1.000555
2.00	1.000027	42.00	1.000569
3.00	1.000041	43.00	1.000582
4.00	1.000054	44.00	1.000596
5.00	1.000068	45.00	1.000609
6.00	1.000081	46.00	1.000623
7.00	1.000095	47.00	1.000636
8.00	1.000108	48.00	1.000650
9.00	1.000122	49.00	1.000663
10.00	1.000135	50.00	1.000677
20.00	1.000271	60.00	1.000812
21.00	1.000284	61.00	1.000826
22.00	1.000298	62.00	1.000839
23.00	1.000311	63.00	1.000853
24.00	1.000325	64.00	1.000866
25.00	1.000338	65.00	1.000880
26.00	1.000352	66.00	1.000893
27.00	1.000365	67.00	1.000907
28.00	1.000379	68.00	1.000920
29.00	1.000393	69.00	1.000934
30.00	1.000406	70.00	1.000948

Note: The correction for the effect of pressure on steel values are shown to six decimal places in conformance with the requirements for prover calibrations and to assist the user in validating computer calculations. The tables shown were calculated using the following equation applicable to single-walled containers or provers:

$CPS = 1 + [(P \times ID)/(E \times WT)]$

[a] T_b = Base temperature in °F or °C.

[b] Gc = Cubical coefficient of thermal expansion of prover.

[c] OD= Outside diameter of prover pipe.

[d] WT= Wall thickness of prover pipe.

[e] ID= Inside diameter of prover pipe.

APPENDIX B—LIQUID DENSITY CORRELATION

B.1 General Information

The liquid table, found in Table B-1, provides a guide to the appropriate reference for most of the liquids associated with the petroleum and petrochemical industry (RHO_b, CTL, F).

The text following the table describes the recommended references. The expertise of a physical properties specialist should be consulted before adopting the recommendations contained in the table.

For some older references, tabular values for RHO_b and CTL cannot be curve fit. Therefore, it is recommended that linear interpolation of these tables (between columns and values within a column) be utilized for intermediate calculations.

Density Meter Calculations

When using an online density meter, the liquid's base density (RHO_b) is determined by the following expression:

$$RHO_b = RHO_{tp}/(CTL \times CPL)$$

It is important to note that RHO_{tp} must be known to accurately calculate RHO_b. Also, for low pressure applications, CPL may be assumed to be 1.0000 if a sensitivity analysis indicates an acceptable level of uncertainty.

For some liquids, computer subroutines exist to correct to base density using API MPMS Chapter 11.1 implementation procedures. **However, for elevated pressures, an iterative procedure to solve for base density is required for fiscal purposes.** The manufacturer should be contacted for consultation on elevated pressures.

The computation for correcting from density at flowing conditions (RHO_{tp}) to density at base conditions (RHO_b) may be carried out continuously if mutually agreed between the parties.

B.2 RHO_b Determination

The standards to convert liquid density at observed conditions (RHO_{obs}) to base density (RHO_b) are as follows:

R1. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 5A, 53A, and 23A cover generalized crude oils and JP4. The document specifies the implementation procedures and the rounding and truncating procedures to determine the Base Density (RHO_b) from the Observed Density (RHO_{obs}) and Observed Temperature (T_{obs}) at Base Pressure (P_b).

a. Table 5A, used for base temperature of 60˚F, covers generalized crude oils and JP4 over an API@60 gravity range of 0 to 100. For natural or drip gasolines with API@60 gravities greater than 100, use Table 23 of ASTM D1250 (Historical Edition - 1952).

b. Table 53A, used for base temperature of 15˚C, covers generalized crude oils and JP4 over a DEN_b@15 range of 610 to 1075 kg/m3.

c. Table 23A, used for base temperature of 60˚F, covers generalized crude oils and JP4 over a RD@60 range of 0.6110 to 1.0760.

R2. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 5B, 53B, and 23B cover generalized products. The document specifies the implementation procedures and the rounding and truncating procedures to determine the Base Density (RHO_b) from the Observed Density (RHO_{obs}) and Observed Temperature (T_{obs}) at Base Pressure (P_b).

a. Table 5B, used for base temperature of 60˚F, covers generalized products (excluding JP4) over an API@60 gravity range of 0 to 85.

b. Table 53B, used for base temperature of 15˚C, covers generalized products over a DEN_b@15 range of 653 to 1075 kg/m3.

c. Table 23B, used for base temperature of 60˚F, covers generalized products over a RD@60 range of 0.6535 to 1.0760.

R3. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 5D and 53D cover lubricating oils. The document specifies the implementation procedures and the rounding and truncating procedures to determine the Base Density (RHO_b) from the Observed Density (RHO_{obs}) and Observed Temperature (T_{obs}) at Base Pressure (P_b).

a. Table 5D, used for base temperature of 60˚F, covers lubricating oils over an API@60 gravity range of -10 to 40.

b. Table 53D, used for base temperature of 15˚C, covers lubricating oils over a DEN_b@15 range of 825 to 1164 kg/m3.

R4. ASTM D1250 (Historical Edition - 1952) covers a relative density at 60˚F (RD@60) range of 0.500 to 1.100. Table 23 converts the observed relative density at the observed temperature and equilibrium pressure to the RD@60.

R5. ASTM D1550, used for base temperature of 60˚F, is applicable to both butadiene and butadiene concentrates that contain at least 60 percent butadiene.

B.3 CTL Determination

The standards that have been developed to determine the CTL values for various liquids are as follows:

C1. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 6A, 54A, and 24A cover generalized crude oils and JP4. The document specifies the implementation procedures and the rounding and truncating procedures to determine the CTL from Base Density (RHO_b) and Flowing Temperature (T).

a. Table 6A, used for base temperature of 60˚F, covers generalized crude oils and JP4 over an API@60 gravity range of 0 to 100. For natural or drip gasolines with API@60 gravities greater than 100, use Table 24 of ASTM D1250 (Historical Edition - 1952).
b. Table 54A, used for base temperature of 15˚C, covers generalized crude oils and JP4 over a DEN_b@15 range of 610.5 to 1075.0 kg/m3.
c. Table 24A, used for base temperature of 60˚F, covers generalized crude oils and JP4 over a RD@60 range of 0.6110 to 1.0760.

C2. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 6B, 54B, and 24B cover generalized products. The document specifies the implementation procedures and the rounding and truncating procedures to determine the CTL from Base Density (RHO_b) and Flowing Temperature (T).

a. Table 6B, used for base temperature of 60˚F, covers generalized products (excluding JP4) over an API@60 gravity range of 0-100.
b. Table 54B, used for base temperature of 15˚C, covers generalized products (excluding JP4) over a DEN_b@15 range of 653.0 to 1075.0 kg/m3.
c. Table 24B, used for base temperature of 60˚F, covers generalized products over a RD@60 range of 0.6535 to 1.0760.

C3. API MPMS Chapter 11.1, Volume X (ANSI/ASTM D1250-1980), Tables 6D and 54D cover lubricating oils. The document specifies the implementation procedures and the rounding and truncating procedures to determine the CTL from the Base Density (RHO_b) and Flowing Temperature (T).

a. Table 6D, used for base temperature of 60˚F, covers lubricating oils over an API@60 gravity range of -10 to 40.
b. Table 54D, used for base temperature of 15˚C, covers lubricating oils over a DEN_b@15 range of 825 to 1164 kg/m3.

C4. ASTM D1250 (Historical Edition - 1952) covers a relative density at 60˚F (RD@60) range of 0.500 to 1.100 for LPGs. Table 24 calculates the CTL from the flowing temperature (T) and the RD@60.

C5. ASTM D1250 (Historical Edition - 1952) Table 6, used for base temperature of 60˚F, covers a gravity range for asphalt. Table 6 is recommended by the API and Asphalt Institute for CTL determinations.

C6. ASTM D1555, used for base temperature of 60˚F, is the industry reference for CTL values associated with certain aromatic hydrocarbons.

C7. ASTM D1550, used for base temperature of 60˚F, is the industry reference for CTL values associated with butadiene and butadiene concentrates that contain at least 60 percent butadiene.

C8. API MPMS Chapters 11.2.3 and 11.2.3M cover CTDW values utilized in water calibration of volumetric provers.

a. Chapter 11.2.3, used for base temperature of 60˚F, calculates the CTDW for water from the Prover's Flowing Temperature (T_p) and Test Measure's Flowing Temperature (T_m).
b. Chapter 11.2.3M, used for base temperature of 15˚C, calculates the CTDW for water from the Prover's Flowing Temperature (T_p) and Test Measure's Flowing Temperature (T_m).

Fixed or Small-Variant Liquid Composition

Numerous specification solvents, resins, and chemicals used or manufactured by companies are not compatible with existing industry CTL tables. For these materials, the parties may wish to utilize proprietary liquid property tables that have been used for years and that remain in use for most applications. In applications where Table 6C of API MPMS, Chapter 11.1 is used to maintain industry compatibility, the fluid property tables can be used to calculate the desired alpha value. These values can be used where existing commercial requirements permit.

Table 6C of API MPMS, Chapter 11.1 calculates the CTL for a liquid with a composition that is fixed or does not vary significantly.

Since RHO_b is constant, no correction or determination of observed gravity is necessary. The API MPMS standard is commonly used for specialized products with coefficients of thermal expansion that do not follow Tables 6A, 6B, or 6D of API MPMS, Chapter 11.1.

Use of Table 6C requires an equation of state and/or extensive data on the metered liquid.

B.4 Compressibility Factor Determination (F)

The density of the liquid shall be determined by appropriate technical standards, or if necessary, by either proper correlations or equations of state. To assist in selecting which methods to utilize, the following information has been assembled for clarity.

F1. API MPMS Chapters 11.2.1, 11.2.1M, 11.2.2, and 11.2.2M provide values for compressibility factors (F) for hydrocarbon liquids. The documents specify the implementation procedures and the rounding and truncating procedures to determine the F from base density (RHO_b), flowing temperature (T), and flowing pressure (P).

a. Chapter 11.2.1, used for base temperature of 60˚F, covers hydrocarbon liquids over an API@60 range of 0 to 90.
b. Chapter 11.2.1M, used for base temperature of 15˚C,

covers hydrocarbon liquids over a DEN@15 range of 638 to 1074 kg/m^3.

c. Chapter 11.2.2, used for base temperature of 60˚F, covers hydrocarbon liquids over a RD@60 range of 0.350 to 0.637.

d. Chapter 11.2.2M, used for base temperature of 15˚C, covers hydrocarbon liquids over a DEN@15 range of 350 to 637 kg/m^3.

F2. The compressibility factor (F) for water utilized in the calibration of volumetric provers is defined as follows:

a. For USC units, a constant F value 3.2E+06 per psi for water shall be utilized in the calculations.

b. For SI units, a constant F value 4.6E+07 per kPa or 4.641E+05 per bar for water shall be utilized in the calculations.

Table B-1—Liquid Density

Liquid Type	RHO_b	CTL	F
CRUDE OILS			
Crude Oils	(R1)	(C1)	(F1)
Natural Gasolines	(R1)	(C1)	(F1)
Drip Gasolines	(R1)	(C1)	(F1)
REFINED PRODUCTS			
JP4	(R1)	(C1)	(F1)
Gasoline	(R2)	(C2)	(F1)
Naphthenes	(R2)	(C2)	(F1)
Jet Fuels	(R2)	(C2)	(F1)
Aviation Fuels	(R2)	(C2)	(F1)
Kerosine	(R2)	(C2)	(F1)
Diesel	(R2)	(C2)	(F1)
Heating Oils	(R2)	(C2)	(F1)
Fuel Oils	(R2)	(C2)	(F1)
Furnace Oils	(R2)	(C2)	(F1)
Lube Oils	(R3)	(C3)	(F1)
Propane	(R4)	(C4)	(F1)
Butane	(R4)	(C4)	(F1)
Propane Mixes	(R4)	(C4)	(F1)
Butane Mixes	(R4)	(C4)	(F1)
Isopentane	(R4)	(C4)	(F1)
Asphalt	NA	(C5)	(F1)
SOLVENTS			
Benzene	NA	(C6)	(F1)
Toluene	NA	(C6)	(F1)
Stoddard Solvent	NA	(C6)	(F1)
Xylene	NA	(C6)	(F1)
Styrene	NA	(C6)	(F1)
Orthoxylene	NA	(C6)	(F1)
Metaxylene	NA	(C6)	(F1)
Paraxylene	NA	(C6)	(F1)
Cyclohexane	NA	(C6)	(F1)
Acetone	NA	(C6)	(F1)
BUTADIENE			
Butadiene	(R5)	(C7)	(F1)
Butadiene Mixtures	(R5)	(C7)	(F1)
WATER			
For Volumetric Provers	NA	(C8)	(F2)

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