# Manual of Petroleum Measurement Standards Chapter 9.4—Continuous Density Measurement Under Dynamic (Flowing) Conditions

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## Foreword

This standard, API *MPMS* Chapter 9.4, *Continuous Density Measurement Under Dynamic (Flowing) Conditions*, First Edition, supersedes API *MPMS* Chapter 14.6, *Continuous Density Measurement*, Second Edition, which is withdrawn.

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# Contents

## Contents

Page

Figures

# Contents

Page

Tables

# Continuous Density Measurement
# Under Dynamic (Flowing) Conditions

## 1 Scope

This standard covers the continuous on-line determination and application of flowing liquid densities for custody transfer. This standard covers liquid and dense phase fluids, including: natural gas liquids, refined products, chemicals, crude oil, and other liquid products commonly encountered in the petroleum industry. This document does not apply to the density measurement of natural gas, LNG, multiphase mixtures, semi-solid liquids such as asphalt, and solids such as coke and slurries.

This standard also provides criteria and procedures for designing, installing, operating, and proving continuous on-line density measurement systems for custody transfer. This standard also discusses the different levels and requirements of accuracy for various applications.

## 2 Field of Application

The application of this standard provides a minimum set of requirements for density measurement applications, including custody transfer. In all cases, the measured density has to accurately represent the density of the flowing stream. Accurate density measurements are essential for custody transfer and for many quantitative purposes. For allocation measurement and process control applications, this standard can be used as a guide.

Common technologies utilized in continuous density measurement include vibrating element, buoyancy, and nuclear devices. The most widely utilized device in custody transfer applications is the vibrating element.

This standard also includes analytical systems that work in conjunction with equations of state or empirically derived calculations to determine the flowing density.

## 3 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

### 3.1 API Manual of Petroleum Measurement Standards (*MPMS*)

API MPMS Chapter 8.1, *Standard Practice for Manual Sampling Petroleum and Petroleum Products*

API MPMS Chapter 8.2, *Standard Practice for Automatic Sampling of Petroleum and Petroleum Products*

API MPMS Chapter 8.5, *Standard Practice for Manual Piston Cylinder Sampling for Volatile Crude Oils, Condensates, and Liquid Petroleum Products*

API MPMS Chapter 9.1, *Standard Test Method for Density, Relative Density or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method*

API MPMS Chapter 9.2, *Standard Test Method for Density or Relative Density of Light Hydrocarbons by Pressure Hydrometer*

API MPMS Chapter 9.3, *Standard Test Method for Density, Relative Density, and API Gravity of Crude Petroleum and Liquid Petroleum Products by Thermohydrometer Method*

API MPMS Chapter 11.1, *Temperature and Pressure Volume Correction Factors for Generalized Crude Oils, Refined Products, and Lubricating Oils*

API MPMS Chapter 11.2.2, *Compressibility Factors for Hydrocarbons: 0.350-0.637 Relative Density (60 °F/60 °F) and –50 °F to 140 °F Metering Temperature*

API MPMS Chapter 11.2.4, *Temperature Correction for the Volume of NGL and LPG Tables 23E, 24E, 53E, 54E, 59E, 60E*

API MPMS Chapter 11.2.5, *A Simplified Vapor Pressure Correlation for Commercial NGLs* (supersedes the Addendum to Chapter 11.2.2-1994)

API MPMS Chapter 11.4.1, *Properties of Reference Materials, Part 1—Density of Water and Water Volume Correction Factors for Calibration of Volumetric Provers*

API MPMS Chapter 14.7, *Mass Measurement of Natural Gas Liquids*

API MPMS Chapter 21.2, *Electronic Liquid Volume Measurement Using Positive Displacement and Turbine Meters*

## 3.2 ASTM [1]

ASTM D1217, *Standard Test Method for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pycnometer*

Adjunct to ASTM D1250, *Temperature and Pressure Volume Correction Factors for Generalized Crude Oils, Refined Products, and Lubricating Oils*

ASTM D1298, *Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method*

ASTM D1657, *Standard Test Method for Density or Relative Density of Light Hydrocarbons by Pressure Thermohydrometer*

ASTM D4052, *Standard Test Method for Density, Relative Density and API Gravity of Liquids by Digital Density Meter*

ASTM D4057, *Standard Practice for Manual Sampling of Petroleum and Petroleum Products*

ASTM D4177, *Standard Practice for Automatic Sampling of Petroleum and Petroleum Products*

ASTM D5002, *Standard Test Method for Density and Relative Density of Crude Oils by Digital Density Analyzer*

ASTM D6822, *Standard Test Method for Density, Relative Density, and API Gravity of Crude Petroleum and Liquid Petroleum Products by Thermohydrometer Method*

ASTM D7777, *Standard Test Method for Density, Relative Density, or API Gravity of Liquid Petroleum by Portable Digital Density Meter*

ASTM D8009, *Standard Practice for Manual Piston Cylinder Sampling for Volatile Crude Oils, Condensates, and Liquid Petroleum Products*

ASTM E617, *Standard Specification for Laboratory Weights and Precision Mass Standards*

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[1] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org

## 3.3 GPA [2]

GPA Standard 8182, *Standard for Mass Measurement of Natural Gas Liquids*

GPA TP-15, *A Simplified Vapor Pressure Correlation for Commercial NGLs*

GPA TP-27, *Temperature Correction for the Volume of NGL and LPG — Tables 23E, 24E, 53E, 54E, 59E and 60E*

## 3.4 OIML [3]

OIML R 111-1, *Weights of classes* $E_1$, $E_2$, $F_1$, $F_2$, $M_1$, $M_{1\text{-}2}$, $M_2$, $M_{2\text{-}3}$, *and* $M_3$, *Part 1: Metrological and technical requirements*

# 4 Terms, Definitions, and Symbols

## 4.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

### 4.1.1 API gravity

A special function of relative density 60 °F/60 °F, represented by:

$$°API = \frac{141.5}{RD_{(60\,°F/60\,°F)}} - 131.5 \qquad 1$$

### 4.1.2 calibration

A set of operations that establish, under specified conditions, the relationship between the values indicated by a measuring device and the corresponding known values indicated when using a suitable measuring standard, which is then applied to adjust the values determined by the measuring device.

### 4.1.3 certification

The process of establishing and documenting the accuracy of a measurement device or the value of a parameter of a reference material (4.1.27) by comparison to a reference standard (4.1.31).

NOTE Certification can be performed by a regulatory body or a certifying body (4.1.6), such as a commercial lab with equipment traceable to a national metrology institute (NMI) (4.1.23), or directly from a NMI, such as NIST.

### 4.1.4 certified

The process and documentation whereby a device or material is accepted as a reference standard, accurate within prescribed limits, and traceable to a NMI.

### 4.1.5 certified reference material (CRM)

Reference material (4.1.27), accompanied by a certificate, one or more of whose property values are certified by a procedure that establishes traceability (4.1.35) to an accurate realization of the unit in which the property values are expressed, and for which each certified value is accompanied by an uncertainty at a stated level of confidence.

NOTE A standard reference material (SRM) is a CRM issued under the National Institute of Standards and Technology (NIST) trademark.

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[2] GPA Midstream, 6060 American Plaza, Suite 700, Tulsa, Oklahoma 74135, gpamidstream.org

[3] International Organization of Legal Metrology, 11 rue Turgot, 75009 Paris, France, www.oiml.org/en

### 4.1.6 certifying body

A technically accepted body (organization or firm, public or private) that performs certification.

### 4.1.7 conditions, base

Reference conditions of pressure and temperature for the calculation of quantities or properties (volume, density, etc.) set by regulation or contract.

NOTE Although often the same as standard conditions (4.1.11), a different pressure or temperature can be specified. In the measurement of light hydrocarbon liquids, for example, the base pressure (4.1.24) is often set to the equilibrium vapor pressure rather than the standard pressure (4.1.26).

### 4.1.8 conditions, flowing
### line conditions
### actual conditions

Conditions of pressure and temperature of the fluid in the line for the calculation of quantities or properties (volume, mass, density, etc.).

### 4.1.9 conditions, observed

Conditions of pressure and temperature existing at the measurement device when a value of a process variable is determined.

### 4.1.10 conditions, reference

Conditions of reference temperature and pressure to which a measurement of volume or density at observed conditions is converted.

NOTE Although not technically precise, in industry, the terms “base,” “reference,” and “standard” are often used interchangeably. However, reference includes any set of specified conditions; standard specifies explicit conditions typically for a country or a measurement system such as SI; and base conditions are set by contract or regulation.

### 4.1.11 conditions, standard

### STP

Defined reference conditions of standard temperature (4.1.34) and standard pressure (4.1.26).

NOTE Standard conditions are defined by the government or scientific community, are typically consistent for an entire country, and are used in various measurement calculations.

### 4.1.12 continuous

Any determination made at least once per second on a recurring basis.

### 4.1.13 density

The mass of a substance per unit of volume at a specified temperature and pressure.

### 4.1.14 density, absolute

Density excluding the effect of atmospheric buoyancy.

NOTE Absolute density is sometimes referred to as “density in vacuum” or as “true density.” When reporting density, the units of mass and volume used and the temperature of the determination has to be stated, e.g. kilograms per cubic meter (kg/m$^3$) at $t$ °C or pounds per cubic foot (lb/ft$^3$) at $t$ °F.

### 4.1.15 density, base

Density at base conditions.

### 4.1.16 density, factored

Density at flowing conditions with the density meter factor applied. This is equivalent to and interchangeable with observed density, i.e. density at observed conditions, for fluids as used in API MPMS Chapter 11.1.

NOTE Refer to Figure 18.

### 4.1.17 density, unfactored

Density at flowing conditions with calibration coefficients applied and corrected for the effect of temperature and pressure on the materials of the density meter (excluding DMF).

NOTE Refer to Figure 18.

### 4.1.18 density, reference

Density at reference conditions (4.1.10) of temperature and pressure.

### 4.1.19 density, relative

In reference to liquid densities, the ratio of the mass of a given volume of liquid at a specific temperature to the mass of an equal volume of pure water at the same or different temperature. Both reference temperatures shall be explicitly stated.

### 4.1.20 density meter factor (DMF)

Dimensionless term equal to the ratio of the density as determined by a reference device to the corresponding density of the density meter.

NOTE For subsequent density determinations, the density of the density meter is multiplied by this DMF to obtain the flowing density attributable to the system.

### 4.1.21 mass

Absolute measure of the quantity of matter.

### 4.1.22 mass, apparent

Value obtained by weighing in air against standard masses without making correction for the effect of air buoyancy on either the standard masses or the object weighed.

### 4.1.23 national metrology institute (NMI)

An agency, usually of the national government, qualified to make primary measurements, verify performance against reference standards (4.1.31), and issue certifications.

NOTE NIST is an example of such an agency.

### 4.1.24 pressure, base

$P_b$

The agreed-upon reference pressure used in various calculations.

NOTE It is often taken to mean, and is set equal to, standard pressure (4.1.26).

### 4.1.25 pressure pycnometer

Vessel whose pycnometer base volume (PBV) and evacuated weight ($W_o$) are precisely known and have been determined and certified.

NOTE In many parts of the world, pycnometer is spelled pyknometer. Either spelling is acceptable.

### 4.1.26 pressure, standard

Defined reference pressure used in various calculations equal to an absolute pressure of 101.325 kPa, which is equivalent to 14.696 psia.

### 4.1.27 reference material (RM)

Material or substance one or more of whose property values is sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or for assigning values to materials.

### 4.1.28 representative sample

Portion extracted from the total quantity that contains the constituents in the same proportions that are present in that total quantity.

NOTE For custody transfer measurement, the representative sample provides information used for the physical and fiscal documentation of a change in ownership and/or a change in responsibility.

At the time of sampling, the true representative nature of the sample may not be determinable; however, the most accurate practice available is automatic sampling. Where automatic sampling is not available, manual sampling becomes the best available practice.

### 4.1.29 sensor, density

Sensing component of a density meter that responds directly to the density of the fluid.

### 4.1.30 standard, primary

Standard having a certified (4.1.4) accuracy when compared to a standard held by a national metrology institute (4.1.23), such as NIST.

### 4.1.31 standard, reference

Standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived.

NOTE A reference standard is usually a primary standard (4.1.30) or a secondary standard (4.1.32).

### 4.1.32 standard, secondary

Standard having a certified (4.1.4) accuracy when compared to a primary standard (4.1.30).

### 4.1.33 temperature, base

$T_b$

The agreed-upon reference temperature used in various calculations.

NOTE It is often taken to mean, and is set equal to, standard temperature (4.1.34).

### 4.1.34 temperature, standard

Defined reference temperature used in various calculations equal to 15 °C in SI units and 60 °F in U.S. customary (USC) units.

NOTE Standard temperature is defined by the government or scientific community, and is typically consistent for an entire country.

### 4.1.35 traceability

Property of the result of a measurement or the value of a standard, whereby it can be related to stated references, usually through an unbroken chain of documented comparisons, all having stated uncertainties.

### 4.1.36 value, observed

Value of a measured parameter taken as a reading, with no corrections or conversions applied.

### 4.1.37 verification

The process or procedure of comparing an instrument to a reference standard or a reference material to ensure its indication (output) or registration is in satisfactorily close agreement, without making an adjustment.

### 4.1.38 weight

The net force exerted on an object’s mass compared to a reference standard (4.1.31).

NOTE In most situations, the net force is a combination of the earth’s gravity and the buoyancy of the fluid surrounding the object. Weighing is defined as measuring the net force acting on an object’s mass.

### 4.1.39 weight, tare

A deduction from the combined weight of a substance and its container made in allowance for the weight of the container.

## 4.2 Symbols, Acronyms, and Abbreviations

| Symbol | Definition | Units | |
|---|---|---|---|
| | | USC | SI |
| $AM_{fl}$ | apparent mass of fluid | g | g |
| $AM_{tw}$ | apparent mass of test weights | g | g |
| $C_{bw}$ | correction for air buoyancy on weighing | -- | -- |
| CPL | correction for the effect of pressure on liquid | -- | -- |
| CTL | correction for the effect of temperature on liquid | -- | -- |
| CTPL | correction for the effect of temperature and pressure on liquid | -- | -- |
| $C_{tsp}$ | correction for the effect of temperature on steel pycnometer | -- | -- |
| DB&B | double block and bleed valve | -- | -- |
| DMF | density meter factor | -- | -- |
| DnP | density prover | -- | -- |
| DPC | differential pressure controller | -- | -- |
| DT | density transmitter | -- | -- |
| $E$ | modulus of elasticity of the element | psi | kg/cm$^2$ |
| $E_p$ | coefficient of cubical expansion due to pressure on pycnometer[4] | cm$^3$/psi | cm$^3$/kPa |
| $E_t$ | coefficient of cubical expansion due to temperature on pycnometer | 1/°F | 1/°C |
| $f$ | natural oscillation frequency | -- | -- |
| $F_m$ | virtual mass factor | -- | -- |

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[4] The SI designated volume unit is mL; however, this standard uses cm$^3$.

| Symbol | Definition | Units | |
|---|---|---|---|
| | | USC | SI |
| $F_{\mathrm{bfl}}$ | buoyancy force on fluid | lbf | N |
| $F_{bs}$ | buoyancy force on steel of pycnometer | lbf | N |
| $F_{\mathrm{btw}}$ | buoyancy force on test weights | lbf | N |
| $F_{\mathrm{bv}}$ | buoyancy force on evacuated pycnometer volume | lbf | N |
| $F_{\mathrm{fl}}$ | gravitational force on fluid | lbf | N |
| $F_{\mathrm{s}}$ | gravitational force on steel of pycnometer | lbf | N |
| $F_{\mathrm{tw}}$ | gravitational force on test weights | lbf | N |
| $F_{\mathrm{1pyc}}$ | total forces on steel of pycnometer when fluid-filled | lbf | N |
| $F_{\mathrm{2pyc}}$ | total forces on steel of pycnometer when evacuated [5] | lbf | N |
| $F_{\mathrm{3pyc}}$ | total forces on steel of pycnometer when air-filled | lbf | N |
| FCV | flow control valve | -- | -- |
| FI | flow indicator | -- | -- |
| GC | gas chromatograph | -- | -- |
| $g_c$ | dimensional conversion constant,<br>32.17405(lbm· ft)/(lbf · s$^2$) or 1(kg · m)/(N · s$^2$) | -- | -- |
| $g_{\mathrm{l}}$ | local gravitational constant | ft/s$^2$ | m/s$^2$ |
| $H$ | elevation of weigh scale above sea level | ft | m |
| $I$ | stiffness of the element | -- | -- |
| ID | inside diameter | in | mm |

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[5] Includes buoyancy force associated with the internal volume.

| Symbol | Definition | Units | |
|---|---|---|---|
| | | USC | SI |
| $L$ | probe length | in | mm |
| $M$ | mass of any object | g | g |
| $M_1$ | mass of the element | g | g |
| $M_2$ | mass of the fluid in the element | g | g |
| $M_{fl}$ | mass of fluid | g | g |
| MAWP | maximum allowable working pressure (gauge) | psig | kPa(g) |
| $M_{\mathrm{tw}}$ | mass of test weights | g | g |
| OD | outside diameter | in | mm |
| $P_b$ | pressure, base | psi | kPa |
| $P_d$ | datum pressure of pycnometer<br>(absolute pressure: 14.696 psia or 101.325 kPa)<br>(gauge pressure: 0 psig or 0 kPa) | psi | kPa |
| $P_f$ | pressure at flowing conditions | psi | kPa |
| $P_r$ | pressure at reference conditions | psi | kPa |
| PBV | pycnometer base volume, pycnometer volume at datum pressure and datum temperature | $cm^3$ | $cm^3$ |
| PDI | differential pressure indicator | -- | -- |
| PI | pressure indicator | -- | -- |
| PT | pressure transmitter | -- | -- |
| $PV_p$ | pycnometer volume at datum temperature and test pressure | $cm^3$ | $cm^3$ |
| $PV_t$ | pycnometer volume at test temperature and 0.0 psia or 0.0 kPa | $cm^3$ | $cm^3$ |
| $PV_{tp}$ | pycnometer volume at test temperature and test pressure | $cm^3$ | $cm^3$ |

| Symbol | Definition | Units | |
|---|---|---|---|
| | | USC | SI |
| QTR | quantity transaction record | -- | -- |
| RD | relative density | -- | -- |
| RO | restriction orifice | -- | -- |
| $S$ | Strouhal number | -- | -- |
| $T_d$ | datum temperature of pycnometer (0.0 °F or –17.78 °C) | °F | °C |
| $T_f$ | temperature at flowing conditions | °F | °C |
| TI | temperature indicator | -- | -- |
| $T_{in}$ | indicated temperature | °F | °C |
| $t_r$ | temperature at reference conditions | °F | °C |
| TT | temperature transmitter | -- | -- |
| TW | temperature test well (thermowell) | -- | -- |
| $V$ | volume of any object | $cm^3$ | $cm^3$ |
| $\bar{V}$ | velocity of fluid | ft/s | m/s |
| VCF | volume correction factor | -- | -- |
| VOS | velocity of sound | ft/s | m/s |
| $V_{tw}$ | volume of test weights | $cm^3$ | $cm^3$ |
| $W_{fa}$ | weight of air-filled pycnometer (with fittings) | g | g |
| $W_a$ | weight of air-filled pycnometer (without fittings) | g | g |
| $W_{ff}$ | weight of fluid-filled pycnometer (with fittings) | g | g |
| $W_f$ | weight of fluid-filled pycnometer (without fittings) | g | g |

| Symbol | Definition | Units | |
|---|---|---|---|
| | | USC | SI |
| $W_{fo}$ | weight of pycnometer with all air evacuated (with fittings) | g | g |
| $W_o$ | weight of pycnometer with all air evacuated (without fittings) | g | g |
| $\rho$ | density | g/cm$^3$ | kg/m$^3$ |
| $\rho_A$ | density of dry air | g/cm$^3$ | kg/m$^3$ |
| $\rho_{ftp}$ | density of fluid at test temperature and test pressure | g/cm$^3$ | kg/m$^3$ |
| $\rho_{in}$ | indicated density | g/cm$^3$ | kg/m$^3$ |
| $\rho_m$ | density at the meter run | g/cm$^3$ | kg/m$^3$ |
| $\rho_p$ | density of the probe material | g/cm$^3$ | kg/m$^3$ |
| $\rho_{tp}$ | density compensated for thermal and pressure effects on sensor (unfactored density) | g/cm$^3$ | kg/m$^3$ |
| $\rho_{te}$ | density compensated for thermal effects on sensor | g/cm$^3$ | kg/m$^3$ |
| $\rho_{TWf}$ | density of field test weights | g/cm$^3$ | kg/m$^3$ |
| $\rho_{TWr}$ | density of reference test weights | g/cm$^3$ | kg/m$^3$ |
| $\tau$ | periodic time of oscillation | s | s |

# 5 Safety Precautions

## 5.1 Overview

Personnel involved in the handling of petroleum products and related fluids are exposed to hazards that demand constant attention to many precautions peculiar to the type of measurement equipment and commodities handled. This section shall not take the place of standards, codes, or individual company safety instructions.

## 5.2 Equipment Design

The following are some of the precautions that should be considered:

a) All electrical components shall be designed in accordance with the appropriate electrical hazardous area classification.

b) All equipment shall be designed to withstand the maximum operating pressure to which it can be exposed. The pressure rating of the pycnometer shall meet or exceed the highest design pressure rating of facility equipment and piping.

c) All materials used shall be resistant to corrosive attack by the fluids with which they come in contact.

d) All materials used with high-vapor-pressure products shall be compatible with cryogenic temperatures that may occur as a result of auto-refrigeration.

e) Adequate facilities shall be provided for isolating, depressurizing, venting, flaring, and draining.

f) Pycnometers should be double-walled. Single–walled pycnometers can present safety concerns, and their use is not recommended. At a minimum, construct pycnometers of 316 or 316L stainless steel.

## 5.3 Operation

### 5.3.1 General

Personnel shall be aware of the specific hazards involved in continuous density measurement.

### 5.3.2 Personal Protective Equipment (PPE)

Appropriate PPE should be worn at all times.

### 5.3.3 Pycnometers

Filling, weighing, and emptying of pycnometers should be accomplished with minimal time delay, to limit any rise in temperature that might result in vessel rupture. The pycnometer shall be stored and transported in a clean and empty condition when not in use.

### 5.3.4 Pressure Hydrometers

Exercise care when using these devices; adhere to all safety requirements as identified in the appropriate standards.

### 5.3.5 Fluids

Ensure personnel are familiar with the fluid’s properties and hazards.

Make available current safety hazard sheets documenting the fluid properties and required safety measures (i.e. safety data sheets or SDS).

### 5.3.6 Static Electricity and Vapor Clouds

Do not enter vapor clouds resulting from the release of hydrocarbon vapors to the atmosphere. These types of discharges can produce static electricity, which could serve as an ignition source for personnel entering the vapor cloud. Liquefied petroleum gas vapors are particularly hazardous.

# 6 Density Determination Methods

There are many ways to determine density. Density can be measured directly or calculated from composition or other fluid properties. Density can be measured directly on-line or measured off-line via a representative sample. On-line density measurement can be accomplished with a device located in the main flowing stream or located in a slipstream representative of the main stream.

This standard addresses density measured continuously on-line, as shown in the shaded flowchart boxes in Figure 1. "Continuous," as defined in this standard (see 4.1.12), is at least once per second on a recurring basis. Off-line and calculated density measurements may be used, where appropriate, as a means of verifying or calibrating an on-line density meter in-situ (see 11.4 for details).

The two primary dimensions to consider in selecting a density measurement method are the variability and predictability of the fluid density and the impact of density uncertainty on the final value in question, such as product value, quantity, quality, or other measure.

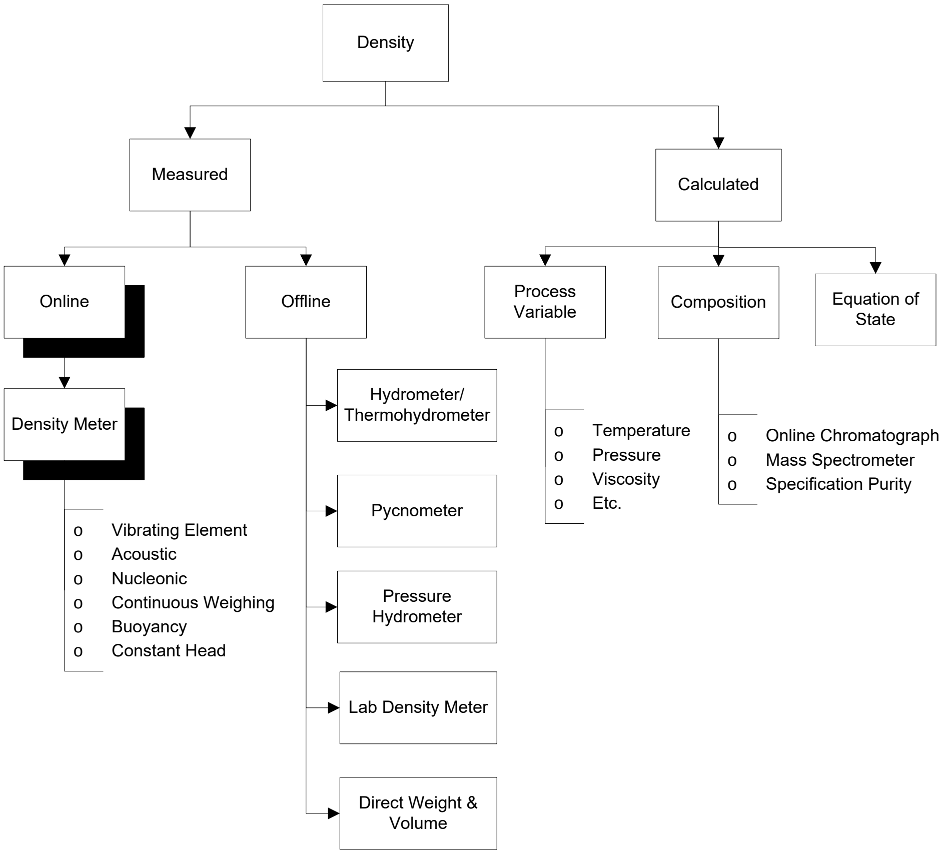


**Figure 1—Density Determination Methods**

# 7 Equipment

## 7.1 General

Most of the density meters that are presently available use one of the techniques described below. The vibrating element (Figure 2) and the vibrating element (insertion style) (Figure 3) are widely used for density measurement since they are able to achieve very high sensitivity while still being adequately rugged. The vibrating cylinder and flat plate forms are generally convenient for in-the-line mounting.

## 7.2 Vibrating Element (Natural Resonance)

If a fluid is contained by, or is part of, a body that is maintained in resonance at its natural frequency, the frequency of resonance, which is dependent on the total mass of the system, will change as the fluid density changes.

The vibrating element may be in the form of a tube or tubes, cylinder, tuning fork, or flat plate. The vibrating-tube arrangement is mainly used for liquid density measurement since it provides a very clean flow path and is least affected by liquid viscosity.

The application of vibrating-element instruments can make them sensitive to mounting position or vibration impacting the element or its supporting structure. Users should refer to manufacturers' recommendations for the preferred mounting arrangement. The frequency output signals from these instruments make them directly compatible with high-accuracy digital computation techniques.

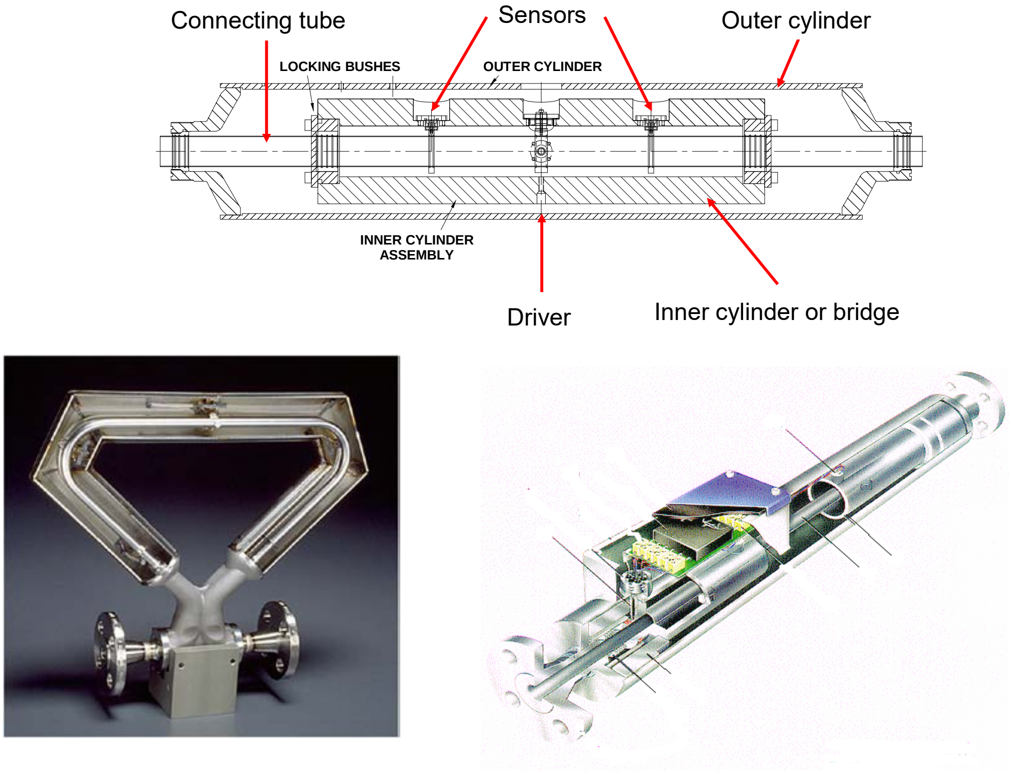


**Figure 2—Vibrating-element Density Meters**

The frequency of vibration is a function of the mass of the sensing element, the mass of the fluid in the element as well as the elasticity and the stiffness of the element. The raw frequency output from the density meter follows the relationship:

$$f = \frac{1}{2\pi}\sqrt{\frac{E \times I}{(M_1 + M_2)}} \qquad 2$$

Where:

$f$ = natural oscillation frequency

$E$ = elasticity of the element

$I$ = stiffness of the element

$M_1$ = mass of the element

$M_2$ = mass of the fluid in the element

The reciprocal of the frequency, $f$, is the periodic time of oscillation, $\tau$. The periodic time of oscillation then is used in conjunction with factory calibration constants to determine the raw density of the fluid. The general form of the equation is:

$$\rho = K_0 + K_1\tau + K_2\tau^2 \qquad 3$$

Where:

$\rho$ = density of the fluid (raw)

$\tau$ = periodic time of oscillation

$K_0$, $K_1$, $K_2$ = factory calibration constants

For high accuracy, it is necessary to apply corrections for secondary effects. These may include effects from changes in temperature, pressure, velocity of sound, viscosity, and flow.

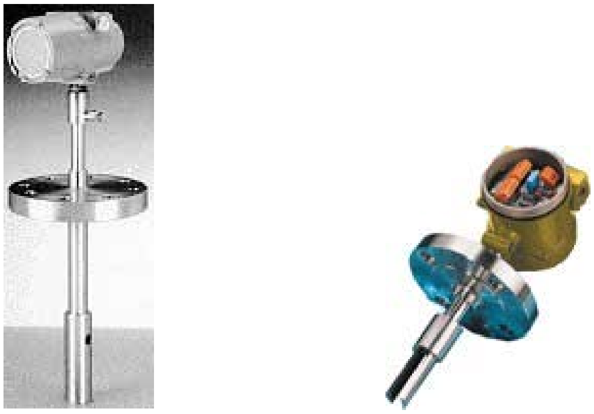


**Figure 3—Vibrating-element (Insertion) Density Meters**

## 7.3 Vibrating Element (Fixed Frequency)

If a fluid is contained in a body that is vibrated at a fixed frequency with constant drive, the amplitude of vibration will change as the system mass changes. In consequence, by measuring the amplitude of vibration, this signal may be used as a measurement of the fluid density. Such instruments are associated with custody transfer measurement and other high-precision applications.

## 7.4 Acoustic

The density of a fluid may be determined from the velocity of the propagation of sound waves through the fluid. Because of the major influence of other variables, such as temperature, this technique is normally only used to indicate changes in density (i.e. batch interface detection).

## 7.5 Nuclear

Radioactive isotopes emit radiation in the form of particles and electromagnetic waves as they undergo the decay process. Gamma radiation has the most suitable energy level for liquid density measurement, and is the type predominantly used for this application. Gamma rays are directed through the fluid and are partially attenuated by it. The source and detector are set a fixed distance apart, usually on either side of a pipe or vessel; see Figure 4. Because of its greater uncertainty and slower response time, this technique is mainly used for difficult applications, such as multiphase flow measurement, where other systems fail to function satisfactorily. It offers the ability to direct the radiation beam through pipe work, and hence provides a non-contact (non-intrusive) measurement. Through the use of different energy gamma sources, it is possible to derive an estimate of the relative concentrations of oil and water in a mixture, as well as measure the mean density.

It should be noted that neutron measurement techniques are sensitive to fluid composition, e.g. carbon-hydrogen ratio and sulphur content, and are not generally employed for high-accuracy hydrocarbon density measurement.

**Figure 4—Nuclear Density Meters**

## 7.6 Continuous Weighing

The continuous weighing technique is probably the most basic method and is carried out either by continuous sampling and weighing in tanks or by passing the product through a horizontal U-tube arrangement. The U-tube is normally pivoted near the inlet points, and the apparent mass of the tube in air is balanced against a counterweight or externally applied force. As the density of the fluid in the tube changes, it is necessary to alter the force to maintain the balance. This force is directly related to the density change and can be applied either electrically or pneumatically. In consequence, the instrument produces an electrical or pneumatic signal that represents the density.

Alternatively, the change in density may cause a displacement of the U-tube from its balanced position, which is then used to generate an electrical output signal representing density.

These instruments are used in industry for liquid density measurement where high precision is not important. It is essential to mount them carefully in a horizontal position in a vibration-free location. They are not normally suitable for high-pressure applications. Corrosive products may be handled by selecting appropriate materials of construction.

## 7.7 Buoyancy

Instruments based on the buoyancy technique normally employ a totally submerged displacer and a means of measuring the up-thrust forces exerted on it by the fluid. Since the up-thrust is caused by the difference between the weight of the displacer and the weight of the displaced fluid, it is directly related to the fluid density. Install these instruments with care since they are sensitive to mounting attitude and some types to vibration. They also tend to be sensitive to flow rate, especially with viscous fluids. Such instruments are not preferred for custody transfer measurement and other high-precision applications.

## 7.8 Hydrostatic Pressure

The hydrostatic pressure caused by a fixed head of a fluid is directly related to the fluid density, and the output signal of a suitably located pressure sensor can be used to indicate density. This simple system is not suitable for accurate density measurement, and therefore not acceptable for custody transfer or inventory control, but is sometimes used for process control. A variant of this technique for liquid density measurement is the bubble tube, where the gas pressure necessary to cause a flow of gas into the base of a constant level tank is used to measure the liquid density.

Alternatively, where the level may vary, the differential pressure between two bubble tubes located at different heights within the liquid may be used.

### 7.9 Gas Chromatograph (GC)

The GC device is also not preferred for custody transfer quality density measurement. The GC has custody transfer accuracy, but the sample analysis is not sufficiently “real time” to qualify as an on-line density device (when the sample is trapped for analysis, the flowing stream is bypassing).

## 8 Applications of Continuous Density Measurement

### 8.1 Overview

This section explains basic applications of continuous density measurement. Depending on the application, continuous density systems can range from basic systems with limited calculation requirements to complex systems with comprehensive computing capabilities.

There are four main purposes in continuously measuring the density of hydrocarbon liquids:

- quantity determination or inventory control for:
    - determination of gross and net standard volumes;
    - determination of volumes from direct mass measurement;
    - inferred mass flow measurement;
    - calculated mass measurement.
- quality determination or monitoring;
- interface detection in batch pipeline operations;
- process control.

### 8.2 Quantity Applications

#### 8.2.1 General

Custody transfer applications are high-accuracy applications that require equipment with high-precision and special-operating procedures.

Custody transfer systems require both a density component and a volume or mass component of sufficient accuracy to determine fiscal quantities.

NOTE For allocation measurement and process control applications, this standard can be used as a guide. These applications often require the same level of precision and accuracy as custody transfer.

### 8.2.2 Volume Measurement

#### 8.2.2.1 Determination of Gross and Net Standard Volumes

Almost all custody transfer and allocation volume determinations require that the volume be stated at reference conditions (4.1.10) of temperature and pressure, which are typically standard conditions (4.1.11). Volumetric measurement at reference conditions requires the correction of the volume measured at flowing conditions (4.1.8) to the corresponding volume at reference conditions.

Densities can be measured at various conditions that require different procedures to correct the factored density (4.1.16) to reference density for the purpose of determining the volume correction factors (VCF). Typical conditions of continuous, on-line density measurement are:

a) density at the volume meter temperature and pressure, e.g. on-line density meter in close proximity to the flow meter;

b) density at temperature and pressure different from the volume meter temperature and pressure, e.g. on-line density meter in a remote location.

The density at reference conditions is used to determine CTL, CPL, or CTPL, which are applied to the indicated volume within the volumetric calculation methodology. The factored density values determined in cases a) and b) above require correction to reference conditions before they can be used in VCF determination.

#### 8.2.2.2 Determination of Volume from a Direct Mass Meter

When a volume is determined from a direct mass meter that also provides the density, the density measurement shall be proven to obtain a factored density (4.1.16).

### 8.2.3 Mass Measurement

#### 8.2.3.1 General

Mass measurement techniques are used on compressible fluids with varying compositions and poorly defined properties of thermal expansion, compressibility, and admixture shrinkage. They are most commonly used for light liquid hydrocarbons because of their sensitivity to the effects of pressure, temperature, intermolecular adhesion, and solution mixing. The criteria given in this standard have been successfully applied to polymer-grade ethylene, ethane, ethane/propane (E/P) mixtures, pure $CO_2$ and $CO_2$ mixtures, liquefied petroleum gas (LPG), and natural gas liquids (NGL), such as raw make streams.

Mass measurement eliminates the substantial errors associated with the solution-mixing effect on these streams and any stream that contains major components of widely varying molecular sizes.

Mass may be calculated from the product of volume and density, with the density being directly and continuously measured (inferred mass measurement) or calculated. Ideally, the conditions for the volume and density measurement would be the same. See Annex A for the sensitivity of density to changes in pressure and temperature. Where a factored density is determined and then corrected to density at reference conditions, additional uncertainty can exist due to differences between the flowing stream composition and the compositions on which the density correction algorithms or tables are based.

Mass flow rate can also be measured directly, but in this case, no density measurement is required and further discussion is therefore excluded.

#### 8.2.3.2 Inferred Mass Measurement

Inferred mass measurement requires the volume of a fluid to be multiplied by its density, ideally with both measured at the same conditions of temperature and pressure, as well as in consistent units of measure.

It can be necessary to convert one or both measurements to the same temperature and pressure conditions. Refer to Annex A for the sensitivity of density to changes in temperature and pressure.

Inferred mass measurement computation shall be performed continuously using on-line density measurements. It is critical to understand that the density and volume should be measured at the same flowing conditions if solution mixing and other errors are to be avoided. This is feasible if the properties of the flowing stream are covered by an industry standard (such as API *MPMS* Chapter 11.2.4/GPA TP-27). Refer to API *MPMS* Chapter 14.7/GPA 8182 for additional details regarding inferred mass measurement.

#### 8.2.3.3 Calculated Mass Measurement

Calculated mass measurement utilizes a density value determined from an equation of state, a direct density measurement of a sample, a compositional analysis, or a default density value. This density value may be used to calculate the mass on a continuous, periodic, or end-of-batch basis.

### 8.3 Quality Determination

Density measurement is used for product quality control purposes where density is used to infer product composition, its value, or other properties, and for product blending systems as a feedback measurement in closed-loop control.

### 8.4 Interface Detection

In applications where a single pipeline is used to move multiple fluids of differing densities (batches), continuous density measurement can be used to detect the end of one batch and the beginning of the next. This information may be used to control valves directing the product to appropriate tanks or distribution points or may be used to begin and end quantity transaction records.

### 8.5 Inventory Control/Process Control

Inventory and process control applications use similar equipment and operational procedures as the other applications. The main difference is that the same tolerance for uncertainty may not be required.

## 9 Performance Requirements— System and Density Meter

### 9.1 General

Performance requirements specify levels of accuracy, repeatability, linearity, and reproducibility for an application. These levels are highest or most stringent for custody transfer applications, and perhaps for quality determination. Less-stringent levels may apply for interface detection, allocation measurement, inventory control, or process control.

The accuracy of the density measurement is only part of overall system performance, which shall include the accuracy parameters for the other devices and calculations in the measurement system, e.g. the flow meter, flow computer, sample, compositional analysis, and volume correction factors.

Repeatability is the ability of the density meter to respond to the same fluid at the same conditions and provide the same density results. The degree of repeatability or stability affects the ability to accurately correct the result through use of a density meter factor (DMF) (4.1.20) and, in turn, overall system accuracy.

The ability of the density meter to respond linearly to changing process conditions allows the user to be confident that the density result, as corrected through a density proving, is accurate over an appropriate range of process conditions, i.e. pressure, temperature, viscosity, and flowing density.

Following are typical examples of metering systems equipped with density meters. Table 1 shows the density meter linearity, repeatability, and uncertainty needed in various services where the overall measurement system uncertainty is 0.25 %. Mass measurement system uncertainty is directly affected by the density meter uncertainty as a first-order effect. The density measurement uncertainty effect on a volumetric system is less because density meter uncertainty is a secondary effect through the volume correction factor. Where volume is determined from a direct mass meter using measured density, the uncertainty of the density meter directly affects the volumetric result similar to a mass measurement system.

**Table 1—Typical Density Meter Performance Expectations at 0.25 % Total Measurement System Uncertainty**

| System Measurement Method | Linearity | Repeatability | Uncertainty | Reproducibility |
|---|---|---|---|---|
| **Volume** | 0.25 % | 0.25 % | 0.50 % | 0.50 % |
| **Inferred Mass** | 0.05 % | 0.05 % | 0.10 % | 0.10 % |
| **Volume by Direct Mass** | 0.05 % | 0.05 % | 0.10 % | 0.10 % |

## 9.2 Inferred Mass Flow Measurement

Inferred mass flow measurement is often used for custody transfer determination. For custody transfer using inferred mass measurement techniques and other high-accuracy applications, the intent of this standard is to provide the user with a density uncertainty of 0.10 %. The intent of the following requirements is to meet custody transfer performance expectations.

a) The uncertainty of the density reading should be better than 0.10 % of the true density.

b) The selected density meter shall have a minimum repeatability of ±0.05 % over the range of design operating conditions.

c) Locate the density meter as close to the flow meter as practical such that the difference in flowing density caused by the difference in temperature or pressure between the two meters is not greater than ±0.03 %. Refer to Annex A for further clarification.

d) Apply the calibration parameters, e.g. $K_0$, $K_1$, $K_2$, $K_{18}$, $K_{19}$, $K_{20}$, and $K_{21}$, as determined by the manufacturer or from the calibration process and as documented in the calibration certificate, to determine the unfactored density (Figure 18).

e) Install the meter in accordance with the criteria given in Section 10, as well as the manufacturer's recommendations.

f) Proving is required to verify density meter performance or to adjust the density meter output to meet accuracy expectations. Proving methods and procedures are given in Section 11.

## 9.3 Volumetric Measurement

Changes in flowing density have less effect on volumetric calculations than on inferred mass measurement. Small changes in flowing density may not significantly affect volume correction factors, CTL, CPL, or CTPL, to the degree density changes impact inferred mass measurement. The higher the density (kg/m$^3$) at standard conditions (4.1.11) or relative density, the less sensitive the volume correction factor is to changes in density or to density meter accuracy. For example, at 80 °F, an error in density measurement of 0.5 % will result in a volume error for 800 kg/m$^3$ crude oil of approximately 0.01 %, for 600 kg/m$^3$ natural gasoline of approximately 0.03 %, and for 500 kg/m$^3$ propane of approximately 0.05 %.

a) The uncertainty of the density reading should be better than 0.50 % of the true density unless otherwise determined through a sensitivity calculation.

b) The selected density meter shall have a minimum repeatability of ±0.25 % over the range of design operating conditions.

c) The preference is to install density meters in close proximity to the quantity meter to minimize fluid density effects caused by differences in pressure, temperature, and composition. Where temperature and pressure instruments are located at the density meter, the contained volume between the density meter and the flow meter should not exceed 5 % of the minimum station hourly flow rate. When the pressure and temperature is measured at the density meter, the density at the quantity meter should be calculated utilizing the appropriate tables or equations of state. If there is no pressure and temperature measured at the density meter, locate the density meter as close to the flow meter as practical such that the difference in flowing density caused by the difference in temperature or pressure between the two meters is not greater than ±0.15 % unless otherwise determined through a sensitivity calculation.

d) Apply the calibration parameters, e.g. $K_0$, $K_1$, $K_2$, $K_{18}$, $K_{19}$, $K_{20}$, and $K_{21}$, as determined by the manufacturer or from the calibration process and as documented in the calibration certificate, to determine the unfactored density (Figure 18).

e) When the flow meter is operating at a different temperature or pressure than the density meter, calculations are required to determine the density at the flow meter temperature and pressure. In this case, use API *MPMS* Chapter 11.1 or other applicable standards to correct the factored density to reference conditions using the temperature and pressure of the fluid at the density meter, and convert the density at reference conditions to density at the flow meter flowing temperature and pressure.

f) Install the meter in accordance with the criteria given in Section 10, as well as the manufacturer's recommendations.

g) Proving is required to verify density meter performance or to adjust the density meter output to factored density. Proving methods and procedures are given in Section 11 and Annex H.

## 9.4 Volume from Direct Mass

The same performance criteria apply as those given for inferred mass. Refer to 9.2 for details.

## 9.5 Other Density Measurement Applications

For quality determination or monitoring applications, allocation measurement, interface detection, inventory control, or process control, performance expectations may be equal to those of quantity determination for custody transfer, but are often less stringent.

The user needs to bear in mind the consequences of not meeting a density specification when determining the performance requirements for the density meter.

For interface detection applications, the quality of the density meter is determined by the degree of difference between the fluids measured. Higher quality density meters or other methods may be required for fluids having close to the same density.

In process control, the ability of the meter to indicate changes is more important than the absolute density it measures. Inventory control applications can be similar to custody transfer.

For applications other than custody transfer, the user may follow these performance expectations to select density meters. Establishing expectations for applications other than custody transfer is beyond the scope of this standard.

# 10 Design of Density Measurement System

## 10.1 General

A systematic approach to the design should include close attention to the following areas:

- purpose of density measurement;
- fluid properties and process conditions;
- density meter selection;
- density sampling system;
- density verification, calibration, and proving;
- integration of density meter within the measurement system.

Section 8 outlines general density measurement applications. Density meter selection and installation varies for each application, and the purpose of the measurement has to be kept in mind when considering the design and installation of equipment. This section provides the appropriate guidance.

## 10.2 Application Considerations

### 10.2.1 Quantity Applications

Use of a density meter for:

- inferred mass measurement;
- on-line determination of CTL, CPL, or CTPL.

Density measurement is most often required for custody transfer applications. For allocation or process applications, less-stringent criteria may be appropriate.

The most commonly used design for custody transfer pipeline applications is the slipstream, or external loop configuration, typically because the meter run line size is too large for an in-line density meter. In-line configurations are used for smaller pipelines, truck loading, and similar applications.

A means shall be provided to prove the density meter when used for custody transfer applications.

The density measuring system used in custody transfer (fiscal) applications shall satisfy the following criteria:

a) The density measurement uncertainty shall meet the minimum performance criteria in Section 9.

b) Install the density metering system such that the process fluid does not bypass either the volume meter or the prover, nor interfere with their proper operation.

c) The proving or verification of the density measurement system shall be in accordance with Section 11.

d) A means of recording the instantaneous density shall be provided for proving or verification.

e) Temperature and pressure measurement points for use during proving or verification shall be provided in accordance with 11.3.

f) Should the density meter fail, the system should use a default density and should generate an alarm to notify appropriate personnel of the failure.

g) Consider recording the measured density for trending, implementing corrections if an instrument fails, etc.

### 10.2.2 Quality Applications

A density meter may be used for the following:

- blending applications such as diluent into crude;
- product quality control (e.g. detecting unacceptable density deviations);
- process control;
- detecting interfaces for batch changes;
- determining the need to switch meter factors;
- detecting flashing or cavitation.

## 10.3 Fluid Properties

### 10.3.1 General

Process fluid properties and behavior should be reviewed to assess the possible impact on the safety, accuracy, and reliability of the system. The following areas should be considered:

a) composition;

b) density variability;

c) contaminants;

d) homogeneity;

e) corrosiveness;

f) polymerization;

g) viscosity;

h) auto-refrigeration;

i) fluid state.

Density meters are single-phase devices for homogenous fluid. Assess fluid separation behavior to prevent liquid-liquid separation or dry ice formation (for $CO_2$ service).

### 10.3.2 Contaminants

Liquids such as glycols, lubricating oils, amines, drag-reducing agents, or injected chemicals, and highly viscous liquids such as asphaltenes, can coat the density meter internal sensor or accumulate within the meter body, disrupting the density meter operation and, in some cases, they can be corrosive. The design of the density meter should consider the effect of contaminants, be self-cleaning to the extent practical, and chemically compatible.

Contaminants can interfere with operation of the density meter. Establish a regularly scheduled inspection and cleaning program based on knowledge of the stream, normal and abnormal operating conditions, and comparison to other density measurements, or through tracking of density meter factors.

Ensure the density meter design is compatible with cleaning techniques that may be used to eliminate or minimize the effect of contaminants.

Using a filter or strainer, heating the fluid, or other means may prevent contaminant deposition. Care shall be taken to not change the density of the fluid.

### 10.3.3 Fluid State

It may be necessary to assess the sensitivity of the fluid density to temperature and pressure for fluids that are at the bubble point, near the critical point, or supercritical, throughout the range of expected conditions. This may be accomplished by means of an equation of state, an enthalpy diagram, a density envelope, or generalized density deviation curves. Evaluate the fluid phase properties over the range of expected operating conditions to determine if the density meter will function properly. The evaluation is also appropriate for assessing if a means of density estimation, such as an equation of state, can be used in place of density determined by a continuous density meter.

## 10.4 Process Conditions

### 10.4.1 General

Flow rate, composition, temperature, and pressure affect fluid properties and density meter performance. Assess these conditions for any influence they may have on system performance. Changes of process conditions can affect the accuracy of the density measurement.

### 10.4.2 Flow Effects

Most density meters are relatively insensitive to flow effects; however, to optimize measurement stability, the user should consider the following:

— Flow rate: The flow rate at the density meter should be within the minimum and maximum flow rates specified by the manufacturer under all operational conditions and sufficient to ensure a representative sample. Flow velocities at the density meter shall be sufficient to prevent product segregation and to provide temperature equilibrium. The velocity shall not cause gas breakout, erosion, or excessive pressure drop. For intermittent flows, consideration shall be given to particulate settlement, fluid corrosivity, wax deposition, fluid solidification, and instrument coating.

— Flow profile: Some density meter designs, i.e. insertion-type elements, can be susceptible to the effect of flow profile or changes in flow profile due to piping configurations that exert unbalanced fluid force(s) on the density meter sensing element(s). For a liquid stream containing two or more immiscible fluids, such as oil/water emulsions, the stream shall be homogenous for a density meter to be able to measure the stream density. A static mixer or other device may be required. Consult the manufacturer for water/liquid mixture measuring limits.

— Swirl: Some density meter designs, i.e. insertion-type elements, can be susceptible to the effect of swirl similar to the effects caused by flow profile.

- Flashing: The density measurement will be in error if the fluid flashes, cavitates, or vaporizes. The design of the system and its components shall prevent flashing and the density meter should be immune from damage caused by flashing. Vaporization, cavitation, or flashing might be prevented by operating at a pressure greater than 1.25 times the equilibrium vapor pressure.

### 10.4.3 Temperature Variations

In vibrating-element density meters, the sensitivity to temperature variations is related to the material of construction of the density meter measuring element.

Variations in temperature from the factory calibrated temperature cause changes in the geometry and material properties of the measuring element. These changes affect the modulus of elasticity (Young's modulus), which affects the resonating frequency.

Temperature effects are minimized or compensated for by specifying measurement element materials with low thermoelastic coefficients (the rate of change of modulus of elasticity with change in temperature) or by measuring the element temperature and applying a correction.

Surface temperature detectors provided on density meter tubes for the calculation of the steel spring constant are not sufficiently accurate for the measurement of fluid temperature for the determination of other corrections. They shall be only used for the modulus of elasticity correction of the tube. The general form of the equation is:

$$\rho_{te} = \rho[1 + K_{18}(t - t_r)] + K_{19}(t - t_r) \qquad 4$$

Where:

$\rho_{te}$ = density compensated for thermal effects on sensor

$\rho$ = density from basic equation using $K_0$, $K_1$, $K_2$

$t$ = flowing temperature at the density meter

$t_r$ = temperature at reference conditions, typically 20 °C or 68 °F

$K_{18}$, $K_{19}$ = constants from calibration certificate

### 10.4.4 Pressure Variations

For vibrating-element density meters, pressure affects the tube stiffness and shall be compensated by calculating a correction based on measured pressure at the density meter or assumed line pressure. The sensitivity to pressure variations is typically related to the design of the density meter. Flow-through tube density meters are affected by pressure variations. Consult with the manufacturer to understand the effect pressure variations have on the density meter. The general form of the equation is:

$$\rho_{tp} = \rho_{te}[1 + K_{20}(p)] + K_{21}(p) \qquad 5$$

Where:

$\rho_{tp}$ = density compensated for thermal and pressure effects on sensor (unfactored density)

$\rho_{te}$ = density compensated for thermal effects on sensor

$p$ = flowing gauge pressure at the density meter

$K_{20} = K_{20\mathrm{A}} + K_{20\mathrm{B}}(p)$

$K_{21} = K_{21\mathrm{A}} + K_{21\mathrm{B}}(p)$

$K_{20\mathrm{A}}, K_{20\mathrm{B}}, K_{21\mathrm{A}}, K_{21\mathrm{B}}$ = constants from calibration certificate

#### 10.4.5 Velocity of Sound (VOS)

VOS of the process fluid might have an effect on the accuracy of the indicated density. Proving in-situ and application of the resulting density meter factor (4.1.20) compensates for VOS effects.

#### 10.4.6 Pulsation

Pulsation and pressure surges are generally caused by pumps, prover initiation, pig launching, and similar actions.

The pressure changes resulting from pulsation can cause the density measurement to be erratic or biased for some density meter designs.

Minimize the effect of pulsation or pressure surges through proper placement of the density meter in the process.

### 10.5 Density Meter and Method Selection

#### 10.5.1 Overview

The consistency of fluid composition and process conditions will determine whether a density meter is required or if density can be determined from other measured parameters.

#### 10.5.2 Density Method Selection

#### 10.5.2.1 General

As indicated in Figure 1, there are a variety of means for determining the density of a flowing stream. First, decide whether the application requires on-line density determination or whether it can be determined off-line. If the choice is off-line, density may be measured or it can be calculated from other properties as defined in other standards. On-line density measurement is typically used for custody transfer applications and is covered under this standard.

Many applications will use directly measured density. For high-purity products and those with a consistent composition, a specified density or a calculated density is often chosen instead of directly measuring density. Specified or calculated density determination is often used for the following fluids:

- ethylene;
- supercritical $CO_2$;
- polymer-grade propylene;
- supercritical ethane.

#### 10.5.2.2 Density Determined by Direct Measurement

Continuous on-line density measurement is typically used for custody transfer applications, and is covered under this standard.

#### 10.5.2.3 Density Determined by On-line Gas Chromatograph

The analysis from an on-line gas chromatograph may be used to calculate density from composition, but the resulting density may have greater uncertainty than a continuous density meter due to sampling frequency, omitting analyzed components, improper grouping of analyzed components, and the uncertainty associated with the equation of state.

#### 10.5.2.4 Density Determined by Composite Analysis

In certain batch oriented operations, often where the composition and density vary little, a composite sample is collected and analyzed off-line to determine the batch density. Since this application is not continuous, density determined by composite analysis is not covered in the scope of this standard.

### 10.5.3 Frequency of Measurement

Depending on the method of density determination selected, density measurements can be instantaneous and continuous, periodic, or performed off-line on a per-batch basis. A continuous density meter is able to respond more quickly to changes in density than an on-line gas chromatograph, and may be coupled with a flow computer for volume or mass calculations. A density meter directly measures the density of the fluid in the meter while an on-line gas chromatograph analyzes the stream at an interval typically measured in minutes.

### 10.5.4 Continuous, On-line Density Meter

#### 10.5.4.1 General

Section 7 describes the techniques employed by density meters for measuring density.

The following portion of this section through 10.10.6 covers density meter placement and mounting and other design features that can be critical to the application.

#### 10.5.4.2 Mounting Location

Density meters may be installed in the flow line or in a slipstream sample loop.

One of the considerations in locating the density meter is to minimize the difference in process conditions between the density measurement point and the quantity measuring point.

To minimize any density deviation due to temperature or pressure, locate the density meter as close as practicable to the flow meter. Section 11 of this document provides additional criteria for evaluating performance.

#### 10.5.4.3 Mounting Style

The four main ways of mounting density meters are:

- full stream;
- pocket mount;
- insertion;

— external mount.

## 10.6 Sample System

### 10.6.1 General

Aside from the density meter itself, consideration has to be given to ensuring that density measurements are made on a sample representative of the stream.

For an externally mounted density meter, properly designed systems will take the influence of fluid properties and operating conditions into consideration prior to selecting a density sampling method.

A properly designed sampling system collects the sample from a dynamic flowing region in the meter system such that it is representative of the fluid passing through the primary flow meter.

Stream velocity may influence density meter operation. The sample system shall be designed according to the density meter requirements.

Sample system design is related to the density meter geometry and operating principle.

Most vibrating-element density meters are relatively insensitive to flow rate as long as there is no excessive hydraulic noise caused by conditions such as product swirl or flashing, so the sample system shall be designed to operate within the minimum and maximum rates specified by the manufacturer.

Excessively high velocities can result in excessive forces and inaccurate readings. Low velocities may result in nonrepresentative samples and/or thermal instability.

Sample systems for custody transfer are typically short to minimize the time difference between the density meter reading and the quantity meter determination so the measured values are synchronized in time.

A properly designed sample system maintains the sample temperature and pressure at the density sensing point similar to that at the quantity meter.

When the quantity meter and density meter temperature and pressure are the same or nearly the same, the impact of density correction uncertainties on calculated densities is minimized.

For a slipstream density meter installation, the piping system shall be designed to provide the appropriate flow rate, provide test points for determining temperature and pressure at the inlet and the outlet of the density meter and at the density proving device, and may include flow-rate indication.

Piping and installation recommendations are provided in the typical installation drawings and should be used for guidance. Design and provide piping connections for the verification and calibration device and method to be used.

Ambient conditions may cause conditions in the sample system to be different from the stream source. Evaluate ambient effects and provide insulation, environmental protection, supports, and other protection as needed.

Density sampling methods include the Pitot tube bypass method (scoop), pump bypass method, and differential pressure driven bypass method.

Additional installation issues that should be considered are given in 10.6.2 to 10.6.6.

### 10.6.2 Phase Separation

Density meters installed in slipstream configurations (Figure 9, Figure 10, Figure 11, and Figure 12) should be installed in such a way as to avoid settlement of heavy components and to prevent the accumulation of vapor.

### 10.6.3 Piggable Lines

Where the main pipeline may be pigged, means should be provided for withdrawing probes or obstructing devices from the line without disturbing process operations.

### 10.6.4 Representativeness of Flow

In slipstream arrangements (Figure 9, Figure 10, Figure 11, and Figure 12), ensure that the system is designed to provide a representative flow through the density meter within the minimum and maximum flow rates specified by the manufacturer.

It is industry practice that the collection end of the probe be placed within the approximate center one-third of the pipe cross-section. It may be necessary to limit the probe length to avoid resonant vibration. See 10.9.2 for additional information.

### 10.6.5 Slipstream Installations

#### 10.6.5.1 General

Slipstream installations are those in which a representative portion of the liquid flowing in the mainline is diverted from the main pipeline, through the density meter, and back to the mainline. These installations are often referred to as external loops, fast loops, or speed loops.

#### 10.6.5.2 Establishing Flow

Flow in the slipstream should have a sufficient velocity to provide a thermally stable, homogenous sample to the density meter while remaining within the minimum and maximum velocity for the density meter. Various means are used to generate flow in the slipstream. Scoops (i.e. quills, sample extraction probes), pumps, and other devices that create a differential pressure ($\Delta P$) between the inlet and outlet of the slipstream can provide adequate flow. Flow indication is recommended for slipstream density sampling systems. The nominal piping size of the slipstream shall be equal to or greater than that of the density meter. If the $\Delta P$ is too low, the velocity through the density meter will not provide a representative sample and temperature equilibrium will not be achieved. If the $\Delta P$ is too high, the velocity can be excessive, flashing can become more likely, and density meter performance can degrade. Refer to Figure 9, Figure 10, Figure 11, and Figure 12 for typical slipstream systems with in-series proving. Parallel proving systems are shown in Figure 15 and Figure 16.

If a pump is used to establish flow, for light hydrocarbon systems such as NGL and LPG when measured in an inferred mass system, the pump shall be installed downstream of the density meter and its proving connections so that any heat added to the slipstream does not affect the density measurement. This may also apply to light oil systems. Refer to Figure 12 for details.

### 10.6.6 In-line Installations

“In-line” means that the density meter is installed directly in the flow of the mainline. Insertion density meters are included in this category. The pump runs only during the proving.

Figure 13 shows an example of insertion density meter installations.

It should be noted that a means of testing the density meter might require a slipstream design. Figure 14 shows an example of in-line density meter installations.

## 10.7 Sample Conditioning

### 10.7.1 General

The fluid flowing through or around the density meter is the sample of the fluid that is being measured. The fluid properties, such as the viscosity, solids and wax content, entrained air, corrosivity, and coating tendencies, can affect the accuracy of the density measurement.

### 10.7.2 Condition at the Sampling Density and Measurement Points

— Representative flow: The density meter can only measure the density of the liquid presented to it. Take care to ensure that the sample measured is representative of the density of the liquid in the mainline. This can be achieved by carefully siting the instrument if it is in-line or by carefully siting the sampling point, if the sample is presented to the density meter via a slipstream. The liquid should always be homogeneous or well-mixed. Do not install in dead legs.

— Homogeneity: Neither in-line density meters nor slipstream inlets should be installed in a pipe-work configuration that is capable of inducing separation or stratification, e.g. centrifugal forces at bends in pipe work can cause the heavier components to move toward the outside of the bend.

— Deposits: Deposition of wax, scale, and resins can affect the readings of density meters and, where necessary, precautions should be taken, e.g. use of inhibitors, heat tracing, and insulation.

— Mixing: In blending, or process applications where other liquids are injected into the line upstream of the density meter or sampling point, care should be taken to ensure effective mixing.

CAUTION Do not install immediately downstream of the blending point.

— Vapor pressure: The line pressure should be in excess of the liquid vapor pressure to prevent gas or vapor breakout or cavitation from devices, e.g. mechanical dehydrators, static mixers, and pumps under all operating conditions.

Do not install without an adequate probe if utilizing a slipstream sampling system. See API *MPMS* Chapter 8.2/ASTM D4177 for probe design.

## 10.8 Density Meter Signals

### 10.8.1 General

In custody transfer service, the output signal from a vibrating element density meter shall be related to raw density as a frequency signal or as a digital signal that meets the definition of “continuous” in this document (once per second or faster) or as an analog signal. This raw frequency signal shall be transmitted continuously to a signal processor where the raw frequency is converted to raw density, in prescribed engineering units, and further corrected for the effects of temperature and/or pressure on the sensing element using the factory calibration coefficients, as described in 7.2, 10.4.3, and 10.4.4.

### 10.8.2 Signal Types

A frequency signal is typically used for a density meter in custody transfer service. Digital signals and analog signals may also be used if they meet the criteria in 10.8.1. The user is cautioned to consider the analog circuit resolution and scaling performance relative to the requirements in this standard.

### 10.8.3 Signal Processing and Integrity

If density meter signals are used for custody transfer, follow the guidance provided in API *MPMS* Chapter 21.2. Additionally, the calibration parameters and the DMF shall be applied only once. Figure 18 describes the process of applying these parameters and factors.

NOTE Correction of factored density to reference conditions shall only be applied once.

## 10.9 Mechanical Considerations

### 10.9.1 General

Accurate continuous density measurement can require thermal insulation of the flow meter, density meter, proving device, and all interconnecting piping to minimize density deviations due to temperature differences.

For inferred mass measurement applications, all of the devices, temperature, and pressure instrumentation, as well as interconnecting piping, shall be insulated unless an evaluation demonstrates that the range of operating conditions meets the tolerances described in this standard without insulation.

### 10.9.2 Mechanical Integrity

Resonant vibration can occur when the vortex shedding frequency resulting from a probe inserted into a flowing fluid is equal to or greater than the probe's natural resonant frequency. This can be a concern for insertion density meters or sample probes for slipstreams.

The formula below (referenced from EEMUA Publication No. 138:1988) may be used to calculate the maximum recommended probe length.

The probe length is defined as the distance between the probe tip and its point of attachment. The probe depth is the distance between the probe tip and the inner pipe wall.

In SI units:

$$L = \left[ \left( \frac{(F_m \times 4.38 \times OD \times 10)}{(S \times \bar{V})} \right) \times \left( \frac{E}{\rho} \times (OD^2 \times ID^2) \right)^{0.5} \right]^{0.5} \qquad 6$$

Where:

$L$ = probe length (mm)

$F_m$ = virtual mass factor—a constant to take account of the extra mass of the cylinder due to the fluid surrounding it and vibrating with it. For a gas, $F_m$ = 1.0, and for water and other liquids, $F_m$ = 0.9

$OD$ = outside diameter of probe (mm)

$ID$ = inside diameter of probe (mm)

$S$ = Strouhal number, which is a function of the Reynolds number and the shape of the cylinder, but can be taken as 0.4 for worst case or 0.2 as suggested by API *MPMS* Chapter 8.

$\bar{V}$ = velocity of fluid (m/s)

$E$ = modulus of elasticity of probe material (kg/cm$^2$)

$\rho$ = density of probe material (kg/m$^3$)

In U.S. customary units:

$$L = \left[ \left( \frac{(F_m \times 1.205 \times OD)}{(S \times \bar{V})} \right) \times \left( \frac{E}{\rho} \times (OD^2 \times ID^2) \right)^{0.5} \right]^{0.5} \qquad 7$$

Where:

$L$ = probe length (inches)

$F_m$ = virtual mass factor—for a gas, $F_m$ = 1.0, and for water and other liquids, $F_m$ = 0.9

$OD$ = outside diameter of probe (inches)

$ID$ = inside diameter of probe (inches)

$S$ = Strouhal number, which is a function of the Reynolds number and the shape of the cylinder, but can be taken as 0.4 for worst case or 0.2 as suggested by API *MPMS* Chapter 8.

$\bar{V}$ = velocity of fluid (ft/s)

$E$ = modulus of elasticity of probe material (psi)

$\rho$ = density of probe material (g/cm$^3$)

### 10.9.3 Attitude and Alignment of the Sensor Body Relative to the Piping

For single-path, flow-through density meters, the attitude is typically vertical with the product flowing from the bottom up to avoid trapping bubbles. For fluids where particulate matter is of concern, i.e. crude oils, an alternate flow direction may be considered to avoid trapping the particulates. For insertion-type density meters on horizontal piping, the process connection is usually in the side of the pipe to avoid bubbles at the top of the pipe or sediment at the bottom. Refer to the manufacturer for proper alignment and attitude of such devices.

### 10.9.4 Mechanical or Flow-induced Vibration

A density meter design shall meet mechanical integrity requirements to withstand external vibration from the connected piping or the fluid flow, and this external vibration shall not influence or impact the sensor operation or its measured density output signal.

The design of the density meter shall be capable of withstanding the vibration at the installation or provide methods of isolating the density meter from vibration.

The measurement performance of some density meters may be adversely affected by certain vibration frequencies that are multiples or partial multiples of the density meter operating frequency. Consult the manufacturer for sensitivity to vibration and frequencies to avoid, if any.

### 10.9.5 Piping Stresses

Piping stresses can be introduced as a result of misalignment, inadequate support, thermal expansion or contraction, improper spacing between flanges, and improper bolt torquing sequence, for example. Excessive piping stresses may not allow the density meter to perform as designed. Refer to manufacturer requirements and eliminate or isolate the sources of excessive piping stress.

### 10.9.6 Density Prover Piping

The connection piping between the prover and the process valves can contain a substantial volume of pressurized fluid. The connecting piping shall have a means of being depressurized and drained in a safe and environmentally appropriate manner. Take steps to ensure this piping is not over-pressured due to thermal expansion of the fluid.

## 10.10 Installation Configurations

### 10.10.1 Design for Quantity Measurement

In flow calculations, the pressure and temperature at the flow meter and at the density meter must be known. To the extent that the pressure and temperature are the same at both devices, any potential for error is minimized. The flow meter and the density meter may be positioned close to each other to achieve this goal or it must be possible to convert the density and the flow results to the same conditions of pressure and temperature.

Density meters shall be installed so as to minimize density errors that can result from temperature, pressure, or composition differences in the measurement system. The following sections describe for the measurement principle the location of the density meter relative to the flow meter.

Avoid disturbing the flow profile for any velocity inference flow meter. The extraction and return point for the slipstream or the location of the in-line density meter element shall be outside of the upstream and downstream meter tube sections. Flow shall not bypass the flow meter.

### 10.10.2 Design for Volume Measurement

A density meter may be positioned at one of the locations, A through D, as shown in Figure 5. Refer to 10.10.5 for the installation details of the density meter and its associated components. The location selected for the density meter installation depends on factors such as space availability and temperature, as well as pressure differences between the density meter location and mainline flow meter.

Temperature and pressure shall be known at the flow meter and at the density meter. Refer to 12.3 and Annex I for the process to adjust the density at the density meter to a comparable density at the conditions at the flow meter.

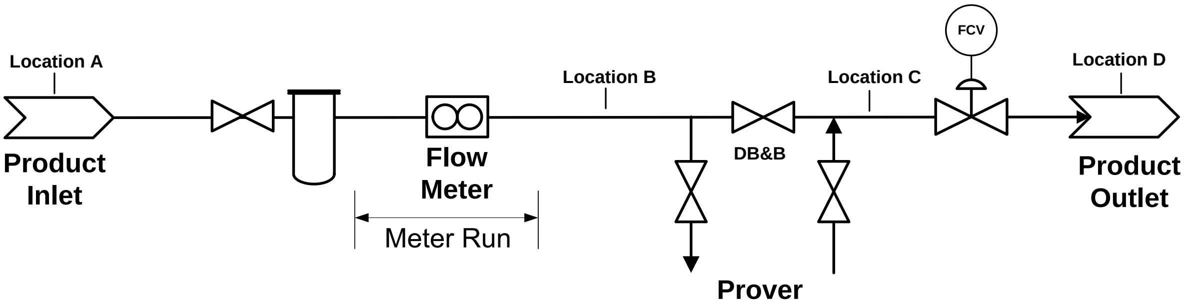


**Figure 5—Volume Measurement**

### 10.10.3 Design for Inferred Mass Flow Measurement

Inferred mass measurement meter stations used in custody transfer service, such as shown in Figure 6, require that the measured density match that of the fluid in the custody transfer flow meter within the tolerances listed in this standard.

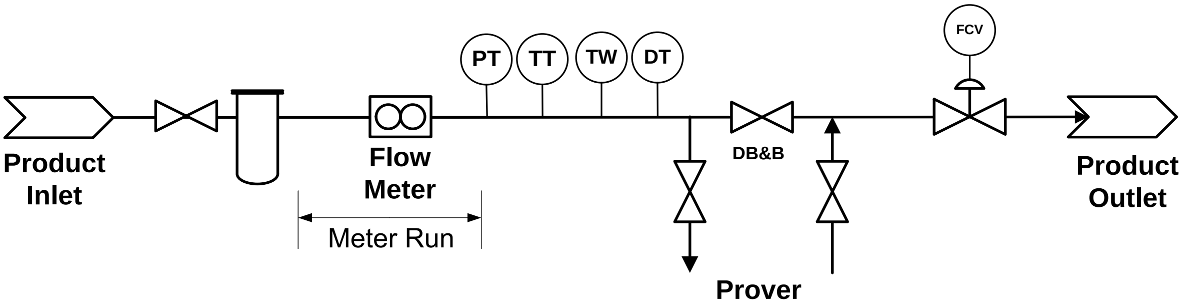


Figure 6—Inferred Mass Flow Measurement

The difference in temperatures and pressures between the flow meter, density meter, and density proving device shall result in a calculated density deviation that does not exceed 0.05 %.

a) The calculated density deviation resulting from pressure differences should not exceed 0.01 %.

b) The calculated density deviation resulting from temperature differences should not exceed 0.04 %.

Refer to Annex A for additional guidance on the sensitivity of density to temperature and pressure changes. Various industry standard tables, algorithms, or equations of state may be utilized to evaluate the density deviation.

For some fluids, the deviation criteria above are not practical (for example, applications in which operation is close to the critical temperature or critical pressure of the fluid). For these applications, the density meter shall be installed so that the following criteria are met:

1) To minimize any density deviation due to pressure, the density meter shall be located as close as is practical to the volume meter.

2) To minimize any density deviation due to temperature, all meter run piping upstream of the density meter, as well as the entire density meter slipstream piping (if installed) and the density meter, shall be fully insulated.

### 10.10.4 Multiple Meter Runs

Density meters may be located on each meter run or one per station on either the inlet or the outlet common or header piping. The preferred installation is a density meter on each meter run.

A typical multiple meter run system with one inlet header, one outlet header, and one density meter on each meter run is shown in Figure 7, a typical inferred mass measurement installation.

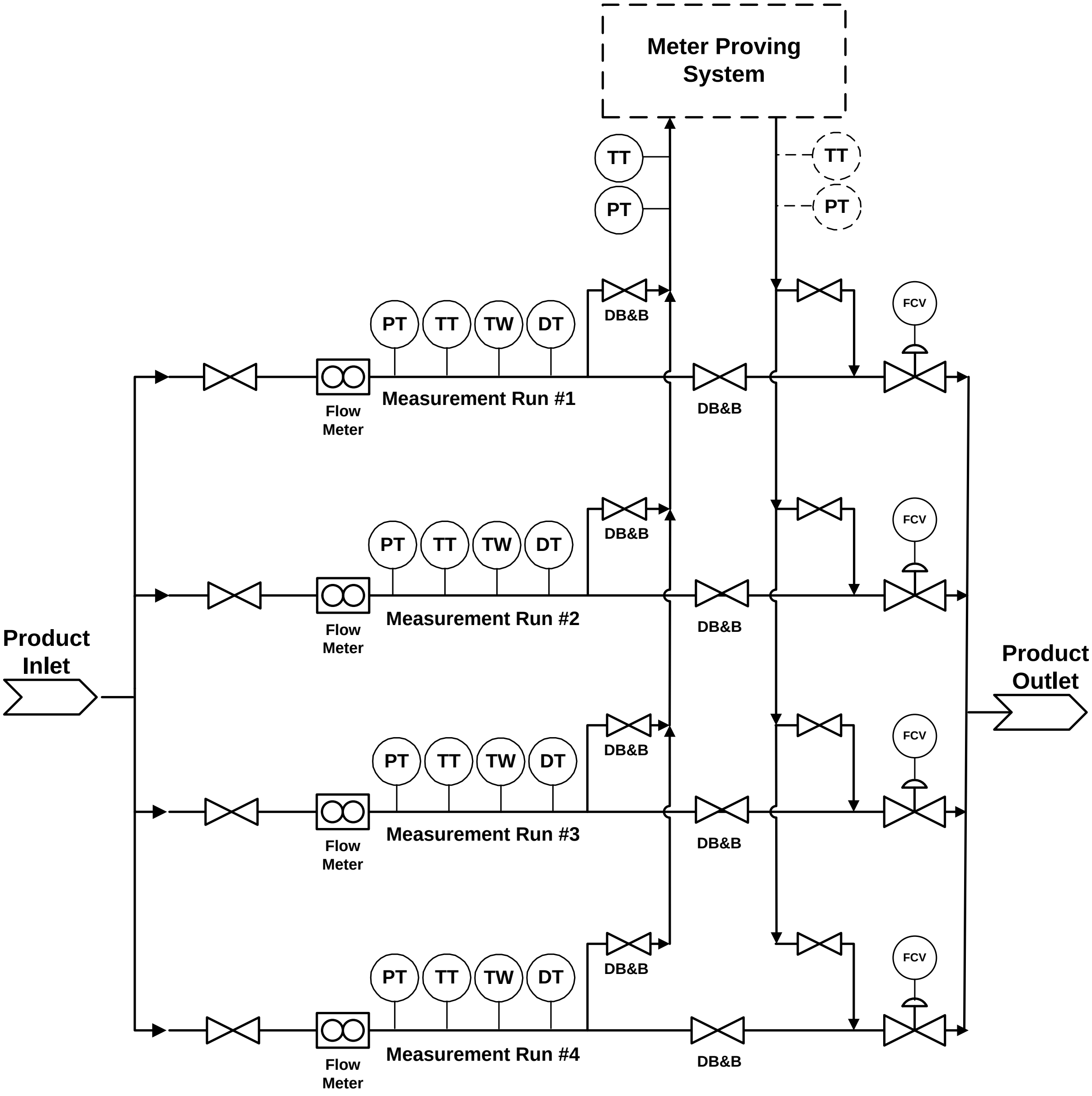


Figure 7—Multiple Meter Runs with Individual Density Meters

A meter run system with a common density meter on the inlet or outlet header is shown in Figure 8, which is typical of volume measurement systems. The density meter on the inlet header or on the outlet header and its dedicated temperature and pressure transmitters can be used to determine the density for the fluid that will be measured by each of the meter runs. If operating conditions, i.e. temperature and pressure, are different between the density meter and the flow meter, refer to 12.3 and Annex I for the process to adjust the indicated density at the density meter to a comparable indicated density at the conditions at the flow meter.

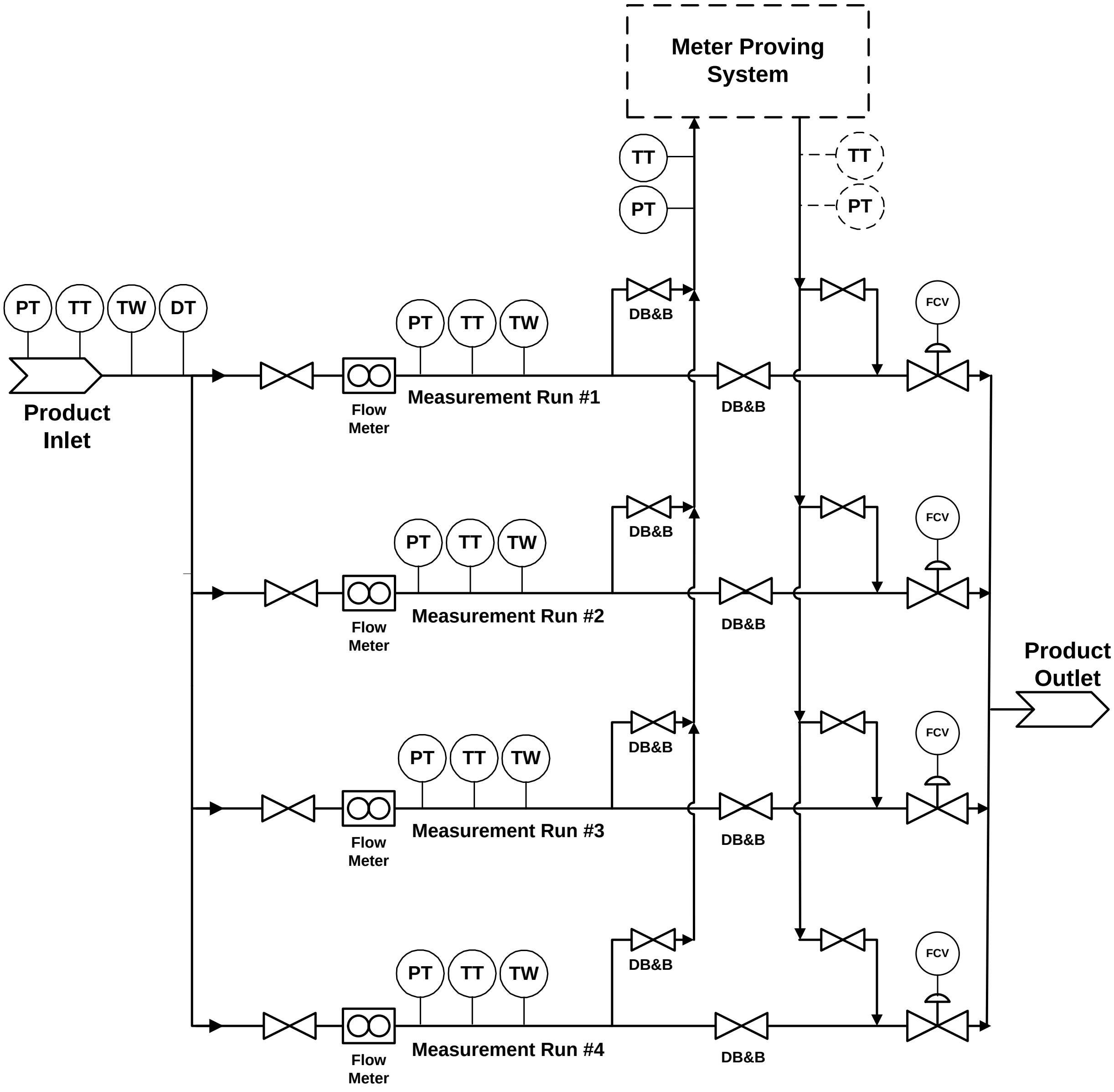


Figure 8—Typical Multiple Meter Run with Common Density Meter on Inlet

### 10.10.5 Density Meter with Density Prover

The density meter in a mass measurement meter station is typically proven using a density prover. In both slipstream and mainline density meter installations, adequate flow is required through both the density meter and the density prover to obtain a representative sample in the density prover, which is demonstrated by achieving thermal equilibrium. Several example installation schematics follow in this section. Density provers are installed in the system for proving purposes only; therefore, the connections shall be capped, plugged, or otherwise secured to avoid leaks while the piping remains in service.

If insulation is required, see 10.10.3. The insulation should encompass the density prover connections.

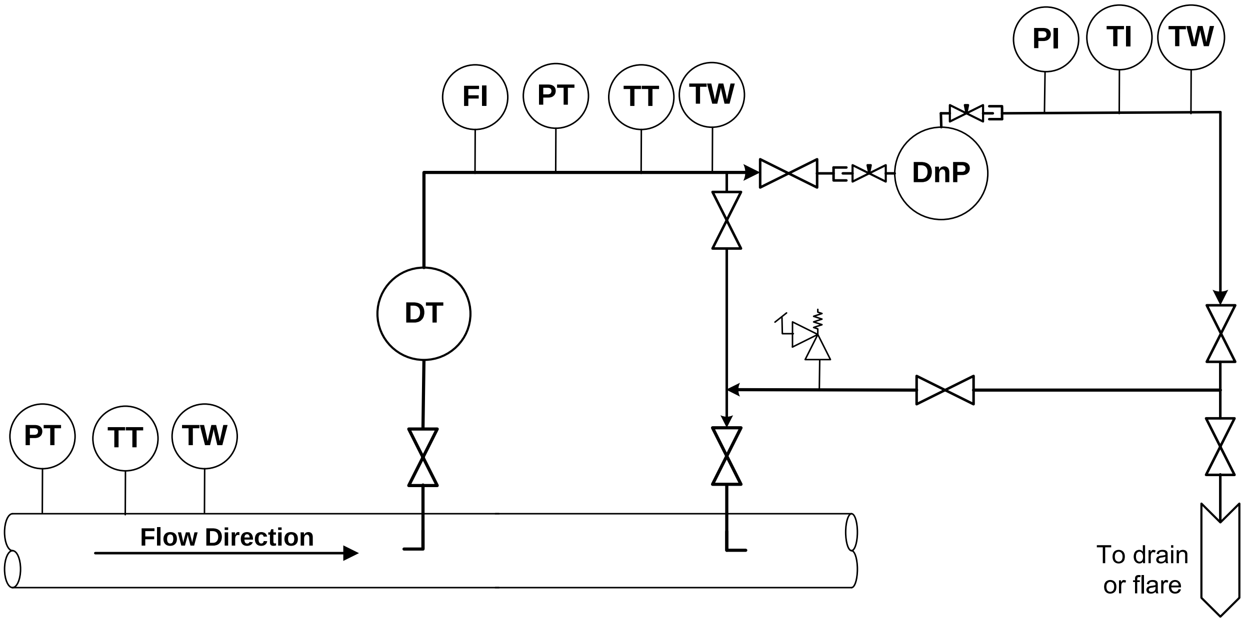


Figure 9—Slipstream-type Sampling System: Velocity Head Devices

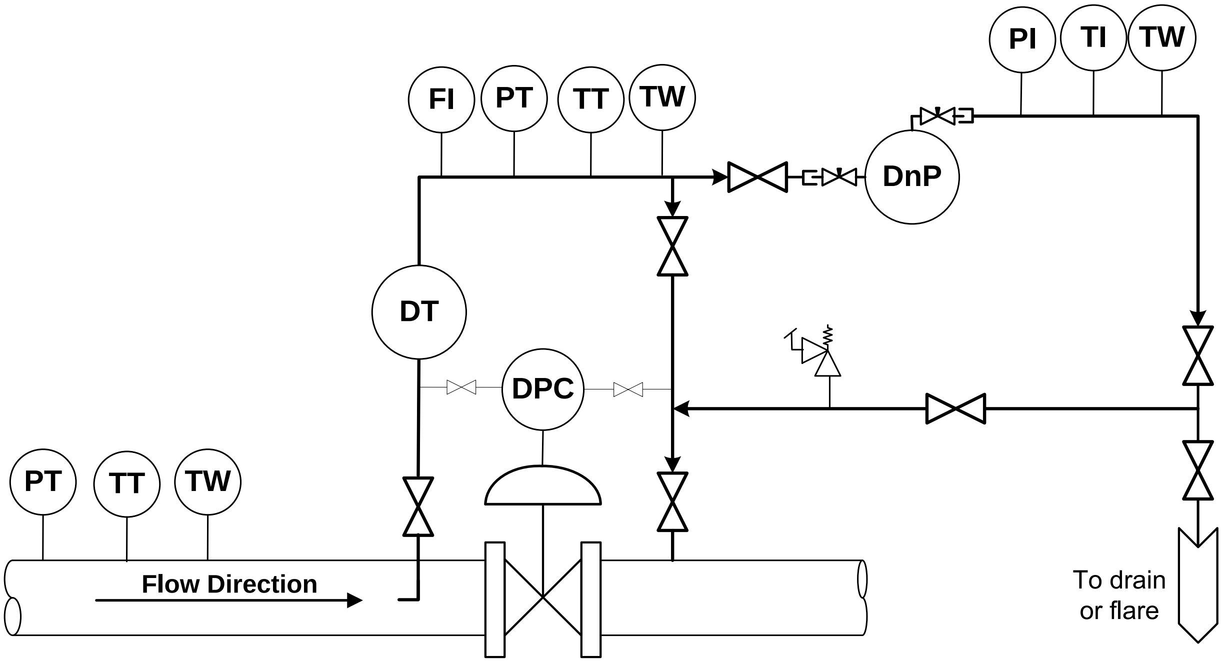


Figure 10—Slipstream-type Sampling System: Valve Restriction Devices

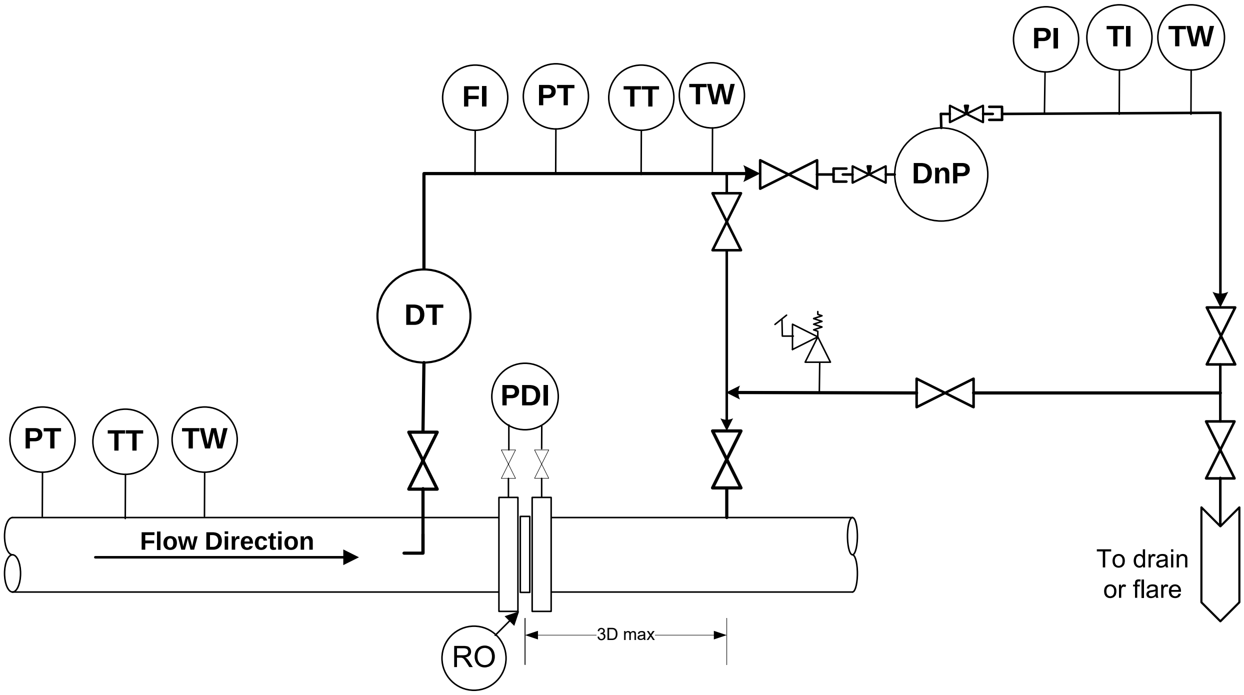


Figure 11—Slipstream-type Sampling System: Orifice Restriction Devices

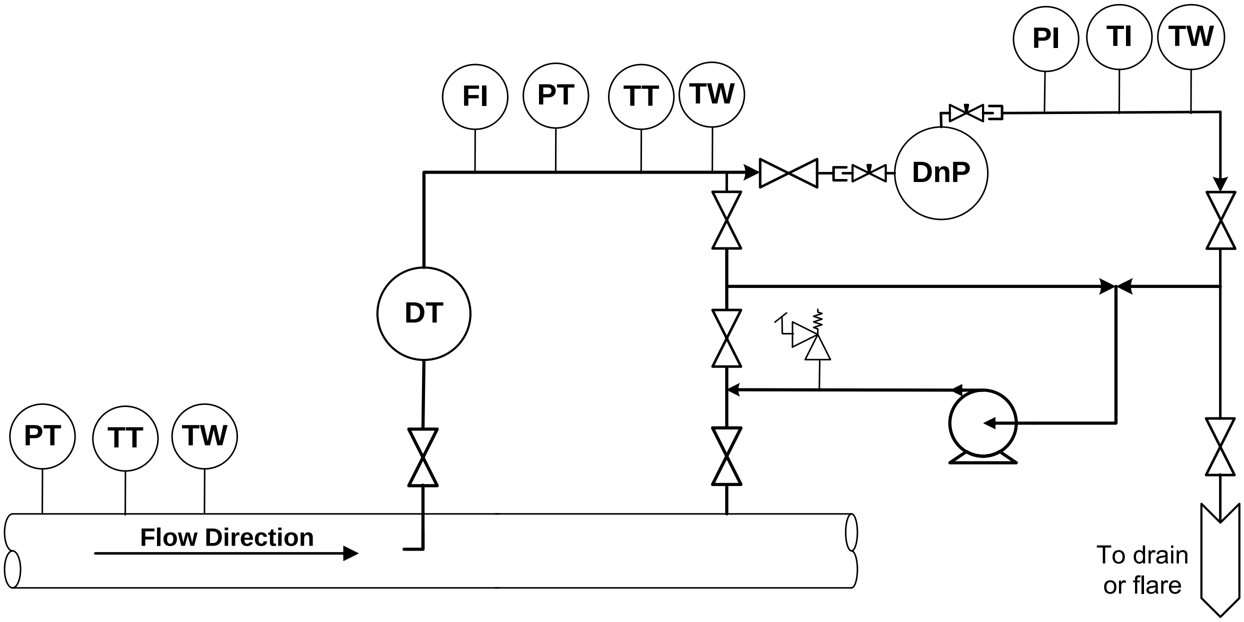
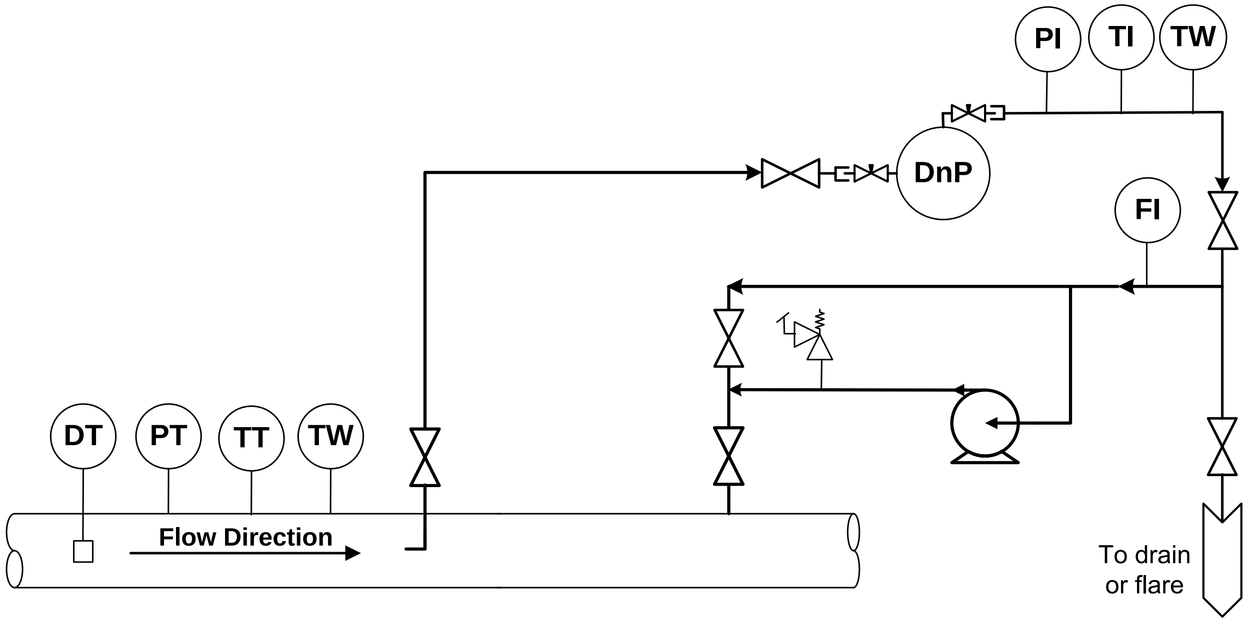
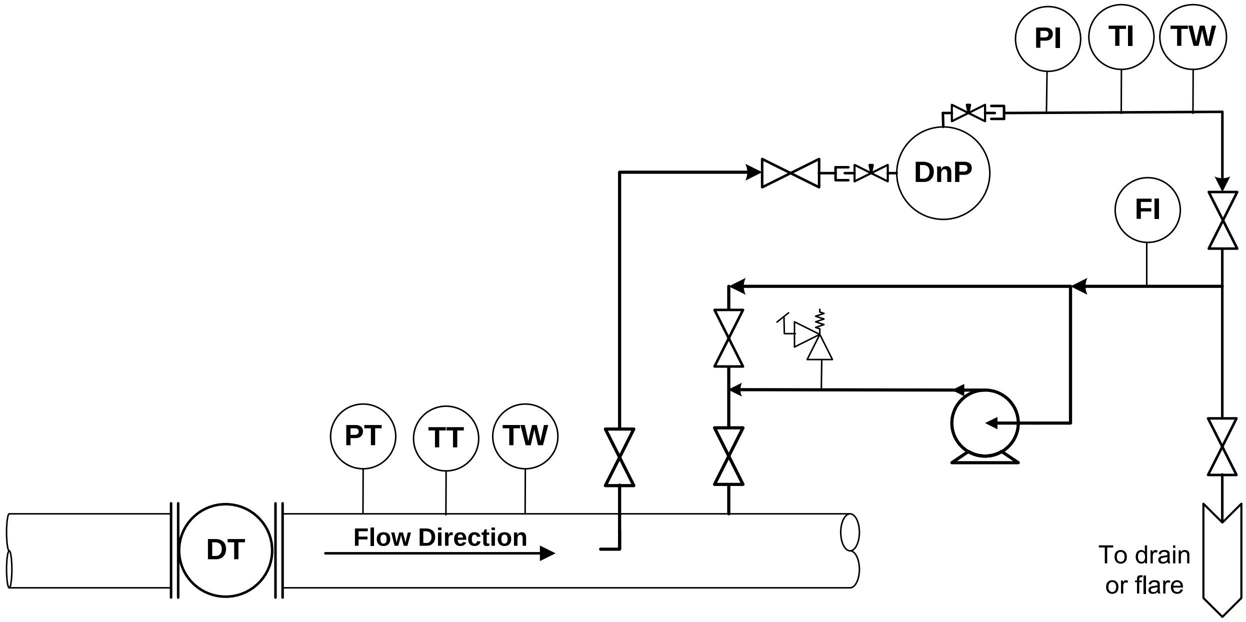


Figure 12—Slipstream-type Continuous Density Sampling Systems: Pump Devices
(for Light Hydrocarbons and Refined Products)



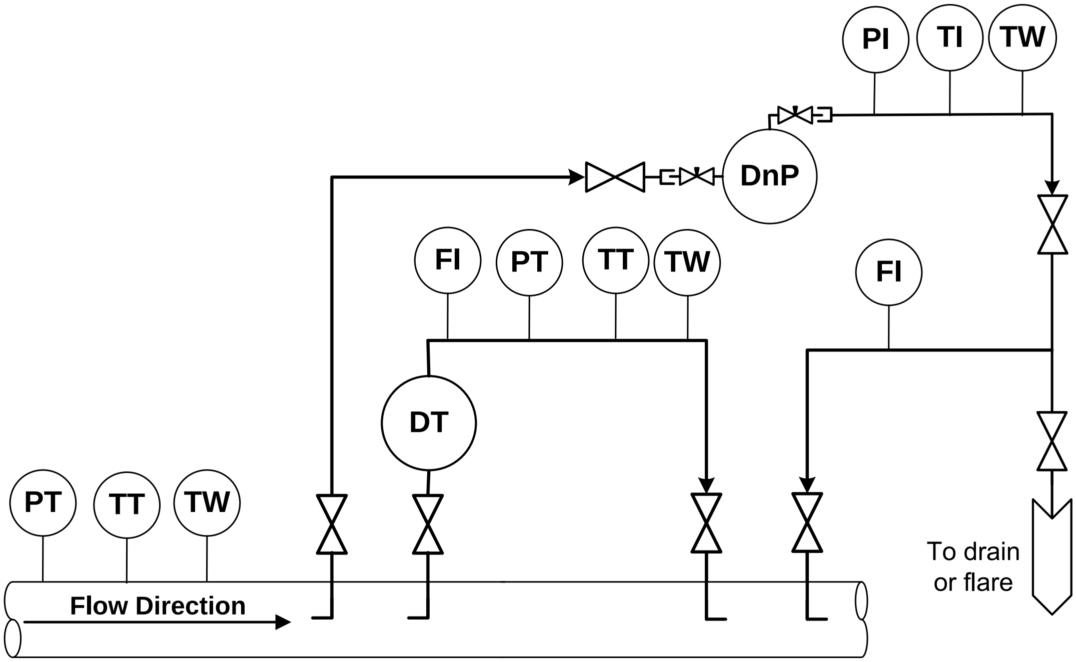
The pump runs only during the proving.

**Figure 13—Insertion-type Sampling System—Pumped Density Prover Loop**



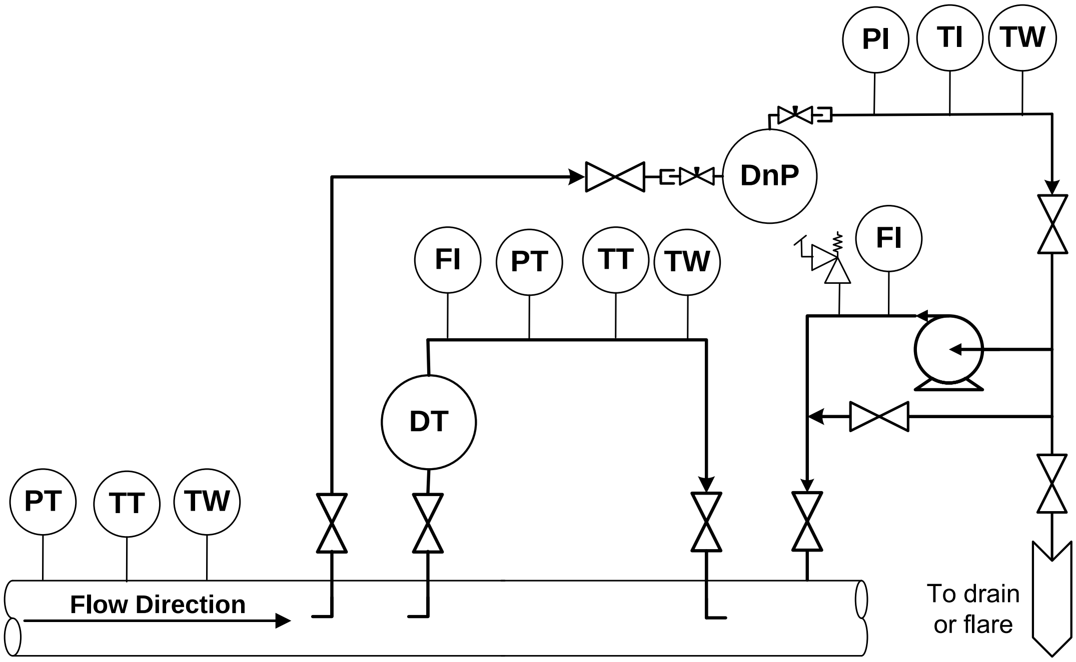
The pump runs only during the proving.

**Figure 14—In-line-type Sampling System with Pumped Density Prover Loop**



The pump runs only during the proving.

Figure 15—Parallel Density Prover Loop



The pump runs only during the proving.

Figure 16—Parallel Pumped Density Prover Loop

#### 10.10.6 Other On-line Density Uses

On-line density measurement for pipeline batch, pigging, process control, or specification/blending management may not need to meet all location, installation, and instrumentation requirements for custody transfer applications if the uncertainty tolerance is greater.

### 10.11 Verification and Proving Design Considerations

#### 10.11.1 General

Verification is used to confirm that the density meter performance meets expectations. When heightened accuracy criteria are specified, such as in custody transfer service, the density meter is proved to establish a density meter factor (DMF).

#### 10.11.2 Installation for Reference Fluid Verification

#### 10.11.2.1 General

This verification procedure requires the use of a fluid of known qualities, such as distilled water or a reference fluid certified by a national metrology institute (e.g., NIST), that falls within the calibrated density range of the operating density meter. The reference fluid and density meter outputs are compared to ensure they are within tolerance.

#### 10.11.2.2 In-situ Verification

The installation requirements are such that the density meter can be isolated in place from the flowing stream, drained, and cleaned. Additional installation requirements include connections to fill and vent the density meter with the reference fluid.

#### 10.11.2.3 Off-site Verification

The installation requirements are such that the operating density meter can be isolated and removed from the flowing stream for the verification procedure to be performed. Off-site verification shall be performed with great care, as it may not result in the same level of performance discrimination, due to installation issues among other criteria, as that resulting from in-situ verification.

#### 10.11.3 Sample Density Determination Methods

The installation requirements for this method require a manual sample tap (see API *MPMS* Chapter 8.1 for a typical tap) installed in close proximity to the piping connecting the density meter to the installation from which a sample may be drawn.

#### 10.11.4 Density by Pycnometer Method

The installation requirements for this method are covered in Annex D.

## 11 Proving, Verification, or Calibration of Liquid Density Meters

### 11.1 General

Calibration is an adjustment process to determine the basic performance parameters of the device according to manufacturer specifications on a fluid or group of fluids.

A proving is a determination of a density meter factor to cause the final result to match the test.

Verification is a comparison between the device under test and a reference device to determine if a device is operating within accepted tolerances.

The frequency of calibration, proving, or verification of density meters may be set by contract or by regulation. The density meter factor can vary with changes in product, pressure, temperature, flow rate, or other fluid or mechanical characteristics. An evaluation of density meter factors over time can be useful to establish the frequency for these tests.

Custody measurements require the application of a density meter factor to adjust the density meter output to match the test result.

When the density meter is adjusted, such as by adjusting the analog output or by changing the characterization constants, a subsequent proving is required to verify that the density result is correct.

Since the density of the liquid being measured is critical to the determination of its quantity or mass for fiscal purposes, prove the density meter on a regularly scheduled basis.

The preferred method of proving the density meter is on site at normal operating conditions, commonly referred to by the term “in-situ.” This is usually accomplished by use of a flow-through density prover. Alternate methods of density proving are discussed in subsequent sections, and may be appropriate if the method uncertainty and the application allow.

## 11.2 Representativeness

For purposes of this standard, representativeness describes the adequacy with which measurements derived from test conditions correlate with the in-situ properties of the process material present in the stream at flowing conditions.

If the test result does not represent the density of the process fluid at the density meter, the resulting proving will be in error. Test results may not be representative because:

— the sample fluid differs in terms of composition, pressure, temperature;

— the sample fluid experiences chemical or physical changes, including dissolved gas content induced by diverting or handling the sample;

— there are homogeneity differences of the fluid being measured from those at the flowing process conditions;

— there are computation errors or inadequacies within the equation of state;

— the analysis is truncated at a carbon number when there are heavier constituents in the stream and components are omitted or the bulk properties of that truncated portion (such as $C_6$+ or $C_9$+) are inadequately characterized;

— there are limitations or misapplications of historical characterization factors for various petroleum material classes, and their corresponding imprecision, relating to petroleum VCF (volume correction factor) behavior;

— there is uncertainty of measurements of the instruments themselves.

Representativeness can be quantified in terms of the total uncertainty or deviation of the measured value for density with respect to the true in-line value.

## 11.3 In-situ Proving

### 11.3.1 Flow-through Pycnometer Method

The flow-through pycnometer procedure is suitable for use with volatile high-vapor-pressure liquids, supercritical fluids, and for stable products (e.g. gasoline, distillates).

Five pieces of equipment are needed to perform an accurate pycnometer proving of a density meter (see Annex B). This equipment is described as follows:

a) pressure pycnometer (see Figure 17);

b) electronic weigh scale;

c) certified test weights;

d) temperature measurement device;

e) pressure measurement device.

The density meter is proved under line conditions by flowing a sample of the line product under actual operating conditions through a pycnometer (a high-pressure vessel for which the volume has been precisely determined; see Annex C).

The proving procedure for a density meter using the pressure pycnometer method is described in Annex D.

The detailed derivation of the air buoyancy equation can be found in Annex E.

Detailed information on the reference fluids of air and water can be found in Annex F.

When proving density meters or comparing density to another value derived from another system, it may be necessary at times to convert units in order to be able to compare two values. Annex G provides useful information to assist the user in converting values from one system of measurement to another, whether density, temperature, or pressure.

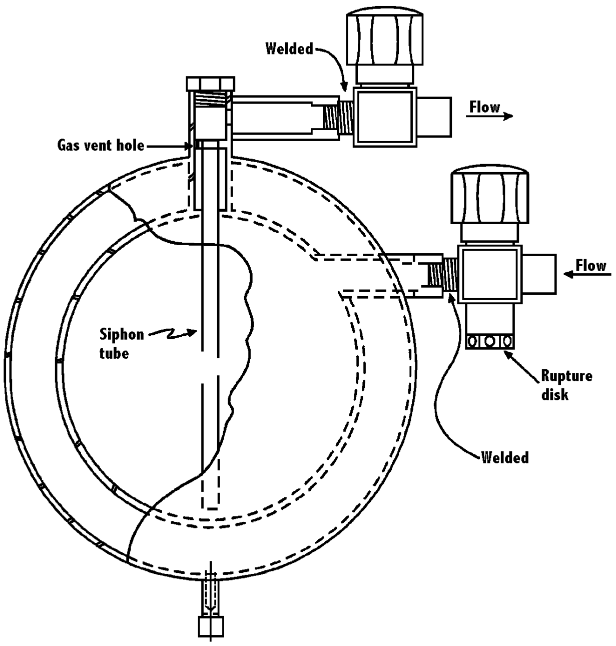


**Figure 17—Double-wall Vacuum Sphere Pycnometer**

### 11.3.2 Pycnometer Proving Procedure

#### 11.3.2.1 General

The pycnometer method consists of four discrete steps:

a) entrapping a homogeneous, representative sample of fluid at the density meter's operating conditions in a pycnometer of precisely known volume and evacuated weight;

b) accurately determining the fluid-filled weight of the pycnometer;

c) correcting the pycnometer volume for the effects of fluid temperature and pressure;

d) correcting for the effect of air buoyancy.

Successful proving criteria require that the density meter factors (DMFs) (4.1.20) for three consecutive proving runs are within the repeatability tolerance of 0.05 %.

#### 11.3.2.2 Pycnometer (Flow-through Design)

Only use pycnometers with a flow-through design. Evaluate the selected pycnometer for sensitivity to the sample system flow rate, vapor exclusion, liquid and particulate accumulation, and atmospheric water condensation.

#### 11.3.2.3 Density Stability

Determinations shall be carried out only when conditions are stable, since the pycnometer takes a time-dependent sample that is not representative when there are rapid and large variations in density.

Unless otherwise agreed upon by the entities involved, conduct proving when fluid conditions approach steady state. If the density varies more than 0.05 % over a period of time required to fully stabilize the pycnometer, the required repeatability of 0.05 % is unlikely to be obtained.

#### 11.3.2.4 Pycnometer Calibration Certificate

The evacuated and air-filled weight, base volume, and temperature and pressure coefficients for the pycnometer are quoted on its calibration certificate. These values are unique to each pycnometer, and care should be taken to ensure that the correct and current calibration data are used. The evacuated and air-filled weight may also be stated with and without connection fittings on the calibration certificate.

#### 11.3.2.5 Impact of Process Conditions

It is critical that the pycnometer test be within the temperature and pressure tolerances specified in 10.10.3 and within the uncertainty tolerance for the fluid itself at operating conditions (refer to Annex A).

It is essential that the maximum flow rate through the density meter not exceed the manufacturer's recommendations. It is also important to ensure that at no time is flow through the density meter reduced to such an extent that the density reading is affected.

## 11.4 Methods for Proving, Verification, and Calibration (In-situ)

### 11.4.1 Proving

#### 11.4.1.1 General

The proving process involves the utilization of a device (i.e. the pycnometer) that has a higher accuracy and lower uncertainty than the density meter and has been calibrated using devices traceable to a national metrological institute (see Annex C and Annex D). This process requires that three or more proves be performed sequentially that agree within a specified tolerance. From these proves, a performance factor is developed that represents the performance of the density meter at flowing conditions compared to a reference standard. These results are used to adjust the result or output of the density measuring device. Refer to Annex D for the proving process.

The use of a pycnometer as a proving device in crude oil or viscous service is not practical. An alternate method to determine DMF can be found in Annex H, Sections H.1 and H.2, of which H.2.4 utilizes the analytical methods shown in 11.4.2.2.

#### 11.4.1.2 Temperature Effects

Measure the flowing fluid temperature at the density meter. The density at the flow meter, at the density meter, and at the calibration/verification device (i.e. the pycnometer), is a function of the fluid temperature. If the temperature is the same at each measurement device, there will be no density change due to temperature. Determine the effect of any temperature difference on density.

Use the surface temperature (class B) sensor in a vibrating-element density meter only for mechanical-correction calculations, and not for determining flowing fluid temperature.

#### 11.4.1.3 Process Pressure Effects

Measure the flowing fluid pressure at the density meter. The density at the flow meter, at the density meter, and at the calibration/verification device (i.e. the pycnometer) is a function of the fluid pressure. If the pressure is the same at each measurement device, there will be no density change due to pressure. Determine the effect of any pressure difference on density.

#### 11.4.1.4 Implementation

Compensation of the density reading may be made manually or may be applied automatically by a signal processor. In flow-measurement applications, it is preferred to carry out the signal processing function within a flow computer, thereby minimizing signal interfaces and sources of error.

### 11.4.2 Verification

#### 11.4.2.1 General

The verification process described in H.3 of Annex H involves the use of a device that has a NMI-traceable calibration. This process requires that one or more comparisons be performed sequentially, between the verification device and the output of the density meter, with both at the same temperature and pressure conditions, and that agree within a specified tolerance. This process is primarily used for crude oil applications where proving with a pycnometer is impractical. This process is not applicable for dynamic mass measurement. It is applicable for volume measurement. If the comparison is within tolerances as shown in Annex H, the density meter may continue to be used with no changes. If the comparison is not within tolerance, the density meter shall be proven, calibrated, replaced, or returned to the manufacturer for recalibration.

#### 11.4.2.2 Verification Methods

##### 11.4.2.2.1 Digital Density Meter Method

Density determination by a digital density meter is generally restricted to liquids that can be handled in a normal fashion at test temperatures between 15 °C and 35 °C. Refer to ASTM D4052 for liquids with vapor pressures below 80 kPa (11.6 psia), ASTM D5002 for crude oils or ASTM D7777 for a portable digital density meter.

##### 11.4.2.2.2 Hydrometer Method

Density determination by hydrometer is generally restricted to crude petroleum, petroleum products, or mixtures of petroleum and nonpetroleum products normally handled as liquids, and having a Reid vapor pressure of 101.325 kPa (14.696 psia) or less. Refer to API *MPMS* Chapter 9.1/ASTM D1298.

##### 11.4.2.2.3 Thermohydrometer Method

Density determination by thermohydrometer is generally restricted to crude petroleum and liquid petroleum products having Reid vapor pressures of 101.325 kPa (14.696 psia) or less. Refer to API *MPMS* Chapter 9.3/ASTM D6822.

##### 11.4.2.2.4 Pressure Thermohydrometer Method

Density determination by pressure thermohydrometer is generally restricted to light hydrocarbons; including liquefied petroleum gases (LPG) having vapor pressures less than 1.4 MPa (200 psi) at the test temperature. Refer to API *MPMS* Chapter 9.2/ASTM D1657.

##### 11.4.2.2.5 Bingham Pycnometer Method

Density determination by a capillary pycnometer is generally restricted to liquids with boiling points between 90 °C and 110 °C (194 °F and 230 °F) at atmospheric pressure. Refer to ASTM D1217. This procedure is not generally used with continuous density measurement devices because of the time required to perform the test.

### 11.4.3 Calibration

The calibration process is primarily applicable to density meters with an analog output, and involves using the verification process to determine the flowing value of density. An alternative method that can produce acceptable results involves the use of a reference fluid instead of the process fluid. The measured density is converted to an electrical value in milliamps that is used to “calibrate” the electrical output of the density meter. The calibration process has a higher uncertainty than proving.

### 11.4.4 GC Analysis Method

Density can be calculated from composition, temperature, and pressure using an appropriate algorithm, such as an equation of state. The composition is determined by a gas chromatograph (GC) analyzing a sample that is representative of the flowing fluid in composition and in time. An appropriate chromatographic analysis method, such as that provided by industry standards, shall be used.

The density of a hydrocarbon mixture is sensitive in varying degrees to temperature and pressure, and can also exhibit sensitivity to solution-mixing effects. Solution mixing occurs when molecules of relatively different sizes, such as ethane and propane, are present in the mixture. Conversely, mixtures of molecules similar in size, such as isobutane and normal butane, exhibit relatively little solution mixing. Pure fluids have no solution-mixing effects.

The density determined by an equation of state is sensitive to accuracy of the physical properties and mixing rules for each of the components in the mixture. The density calculated from the analysis of simple mixtures of light hydrocarbons, such as LPGs, can have lower uncertainty than more complex mixtures since the number of individual components is small and the properties for each of these components is well known.

The uncertainty in calculated density can become unacceptable when the composition of the fluid includes one or more compounds for which the equation of state has no component properties. The density uncertainty can also become unacceptable if the quantities of one or more individual components are not known. These component-property and component-analysis quantification gaps might apply to olefins and hydrogen, as well as compounds in the hexanes, heptanes, octanes, and heavier hydrocarbon groupings.

It is common for an analysis report to include a density or relative density value calculated from composition and component properties at base temperature and pressure, i.e. 15 °C or 60 °F and equilibrium vapor pressure, from an industry standard such as GPA 2145 [19]. Be aware that this calculated analysis density value is not at flowing conditions, and may cause significant error if used in place of flowing density. Solution-mixing effects are not taken into account in this density value at base conditions. The change in density due to temperature and pressure is a function of solution mixing for the components in the stream. Refer to the density sensitivity information in Annex A.

For the density to be representative of the flow period, the temperature, pressure, and composition shall be flow-weighted.

# 12 Calculations

## 12.1 Overview

The density meter calculation sequence is illustrated in Figure 18.

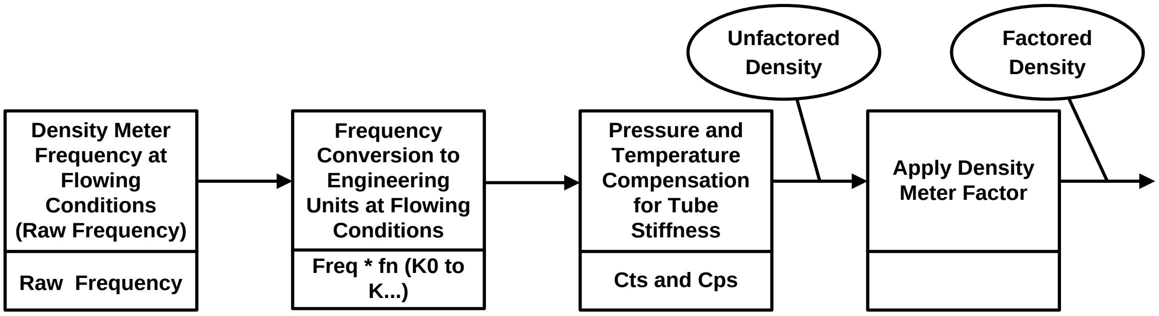


**Figure 18—Density Meter Calculation Sequence**

## 12.2 Volume Correction Factor (VCF) Determination and Density

### 12.2.1 General

Density plays an important role in the determination of various VCFs and can be determined either on a continuous or instantaneous basis as indicated below.

### 12.2.2 Continuous Volume Correction Factors Determination

In some volume-measurement systems, a density meter provides a continuous signal to the flow calculation device, allowing it to perform recurring calculations of the VCF used to determine the volume at reference conditions. These calculations may occur as frequently as more than once per second or as infrequently as once per minute (continuous VCF determination).

Any lesser frequency up to and including once per batch may add to the uncertainty of the correction factor(s).

This measurement technique is most beneficial when:

— the VCF of the fluid being measured is sensitive to density changes;

— the density of the fluid changes rapidly or varies greatly over the course of the quantity transaction record (QTR) or batch.

### 12.2.3 Post-QTR VCF Determination

Alternatively, determine volume correction factors at the completion of a quantity transaction record, based on a density or densities that are representative of the volume transferred. The density may be determined directly by measurement using a continuous density meter. This method can provide operational benefits when incorporated and associated with some sampling systems, while still providing a highly representative measurement of density in cases where the equipment needed to perform continuous VCF determination is not available.

For products with tightly controlled specifications, a pre-determined density may be used.

Density may also be determined by analysis of samples taken by:

— flow-proportional automatic sampler;

— composite spot samples;

— spot samples.

The density may be determined through the use of a hydrometer/thermohydrometer, laboratory density meter, or chromatographic analysis with associated calculations.

This is most beneficial when:

— the VCF of the fluid being measured is insensitive to density changes;

— the density of the fluid is relatively stable;

— the error associated with the use of an average or representative density has minimal financial impact.

These methods avoid the capital and operating costs associated with a continuous density meter and, for many fluids and applications, provide an acceptable density determination.

## 12.3 Density Conditions

### 12.3.1 General

The density of hydrocarbon liquids is affected by temperature and pressure. Therefore, for the density measurement to be meaningful, it is necessary to specify the conditions at which it is determined. For applications other than continuous inferred mass measurement, it is required to convert the density measurement made at flowing conditions to its corresponding equivalent at reference conditions of temperature and pressure.

To accurately convert the density from flowing conditions to reference conditions, the temperature and pressure of the fluid at the density sensor is needed. Using the fluid temperature and pressure measured at the density sensor, the density at reference conditions is calculated using API *MPMS* Chapter 11.1/Adjunct to ASTM D1250. Temperature and pressure measurements should be taken within a few pipe diameters upstream or downstream of the density meter. Then, using the temperature and pressure measured for each meter run and the density at reference conditions determined above, calculate CTL, CPL, or CTPL for each meter run using API *MPMS* Chapter 11.1/Adjunct to ASTM D1250 or other appropriate industry standard.

### 12.3.2 Density at Flowing Conditions ($T_f$ and $P_f$)

Density is measured at stream conditions of temperature and pressure as the fluids flow past or through the density measuring element. For mass measurement using the inferred method, the temperature and pressure conditions of the fluid flowing past or through the density measuring element need to be within the tolerances allowed for the application as compared to temperature and pressure conditions of the fluid flowing through the volume measuring element. For volume measurements, the temperature and pressure conditions of the fluid flowing past or through the density measuring element will be used to calculate reference density, or an intermediate density, depending on the difference between the temperature and pressures at the flow meter and the density meter (see 12.3.1), which is required to calculate the volume correction factor (VCF) as shown in 12.3.4 and Annex I.

### 12.3.3 Density at Static Conditions ($T_{in}$ and $\rho_{\mathrm{in}}$)

This applies to the density determined in a static mode when using thermohydrometers or hydrometers, and after the appropriate corrections are made as indicated in API *MPMS* Chapter 9.1/ASTM D1298, API *MPMS* Chapter 9.2/ASTM D1657, and API *MPMS* Chapter 9.3/ASTM D6822.

### 12.3.4 Density Corrected to Reference Conditions ($T_r$ and $P_r$)

#### 12.3.4.1 Mass Measurement

For a system arrangement, a density meter should be mounted on each metering run. However, the value of density measured by the density meter may not be at the same conditions as at the flow meter. If it is not, the density output from the density meter will be referred to reference conditions and a calculation will be performed to produce corrected meter run density ($\rho_m$). Meter run density is used for the flow calculations. In this system, there typically are no common inlet header measurements of pressure, temperature, or density that are used in the quantity calculation, as each meter run has its own measured parameters. If the meter run measurement equipment fails, the values from one of the other meter runs may be used, a default value may be used, or, if present, inlet header values may be used.

#### 12.3.4.2 Volume Measurement

For a system arrangement, a density meter should be mounted on each metering run when flowing conditions result in slugs of nonhomogeneous fluids during a measurement transaction and the multiple meters are in parallel.

#### 12.3.4.3 Density Measuring Device Correction for Process Conditions

Consider the need for corrections due to the effects of temperature and pressure on the density measurement element (modulus of elasticity).

## 12.4 Fluid Compressibility

The density of a given fluid will be affected by pressure, and the effect can be seen in examples given in Annex A. Pressure will affect the density of one fluid differently than another.

## 12.5 Fluid Expansion/Contraction Due to Temperature

The density of a given fluid will be affected by temperature, and the effect can be seen in examples given in Annex A. Temperature will affect the density of one fluid differently than another.

## 12.6 Density Computation Methods

### 12.6.1 On-line Computation

For mass flow measurement, computation of the mass shall be in accordance with API *MPMS* Chapter 14.7/GPA 8182.

For density used as an input to volume calculation, the density at the density meter shall be at the same flowing conditions found at the volume meter, i.e. temperature and pressure. If the flowing temperature or pressure conditions found at the density meter are different than those found at the volume meter, then the flowing density at the density meter shall first be corrected to base conditions. Then, these conditions are corrected to the flowing temperature and pressure conditions found at the volume meter. These corrections are not required if the difference in density as a result of the difference in temperature or pressure between the density meter and the volume meter result in a correction factor of 1 part in 10,000 or less. Refer to Annex I for this calculation process.

### 12.6.2 Manual Computation

Refer to Annex I for this calculation process.

## 12.7 Flow-weighting

In applications where the average density of a volume transfer is required, and where flow rate, temperature, or pressure variations during the period of transfer are significant, the averages should be flow-weighted for each meter run to take the variations into account. Refer to API *MPMS* Chapter 21.2 for the calculation process.

## 12.8 Density Unit of Measure Conversions

Conversions between various possible units of measure for density, such as kilograms per cubic meter, API gravity, and relative density, can be found in Annex G.

# Annex A
(informative)

# Density Sensitivity—Light Hydrocarbon Liquids

## A.1 Sensitivity to Pressure and Temperature Changes

Fluid density changes as temperature, pressure, or composition changes. Generally, density changes more as temperature changes and pressure changes for hydrocarbon fluids of lower density than it does for higher-density fluids. Equations of state can be used to predict density when given composition, temperature, and pressure. This annex provides examples of typical hydrocarbon fluids (with compositions as indicated in Table A.3) for density sensitivity to temperature, given a fixed pressure and examples for density sensitivity to pressure at fixed temperatures.

## A.2 Sensitivity to Temperature

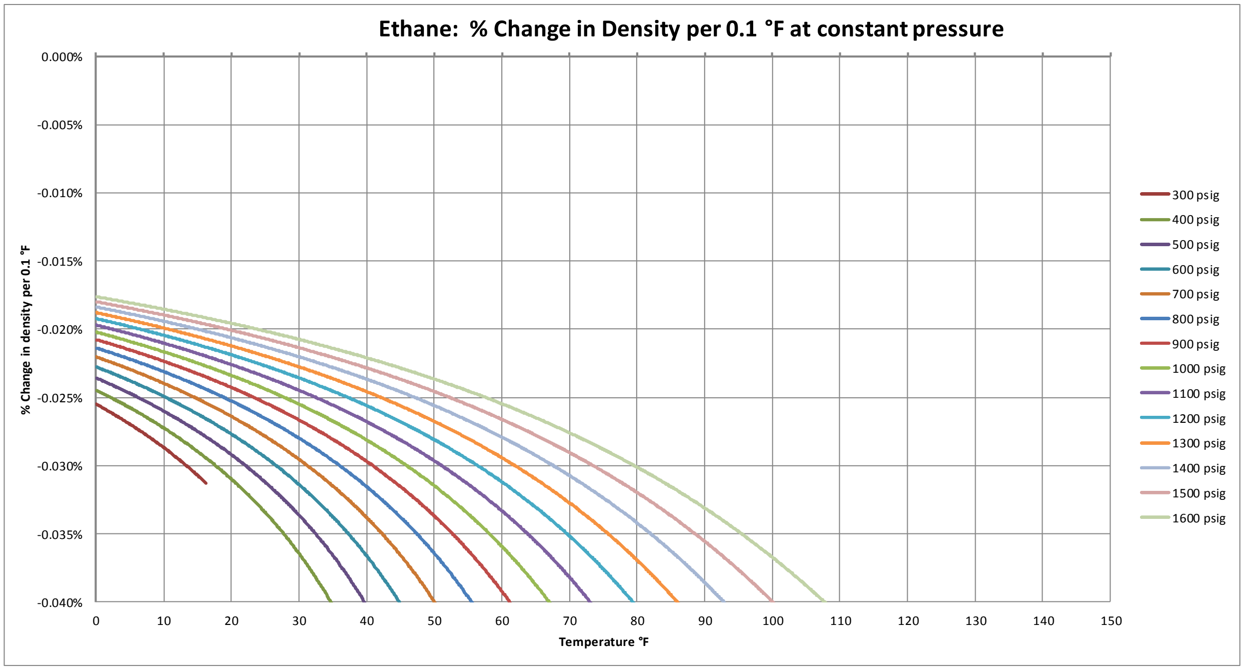
Fluids of lower density are more sensitive to the effect of temperature changes. Fluids at lower pressures are more sensitive to the effect of temperature changes than they are at higher pressures. Table A.1 lists the density change for a 0.2 °F change in temperature at typical operating conditions for the listed fluids only.

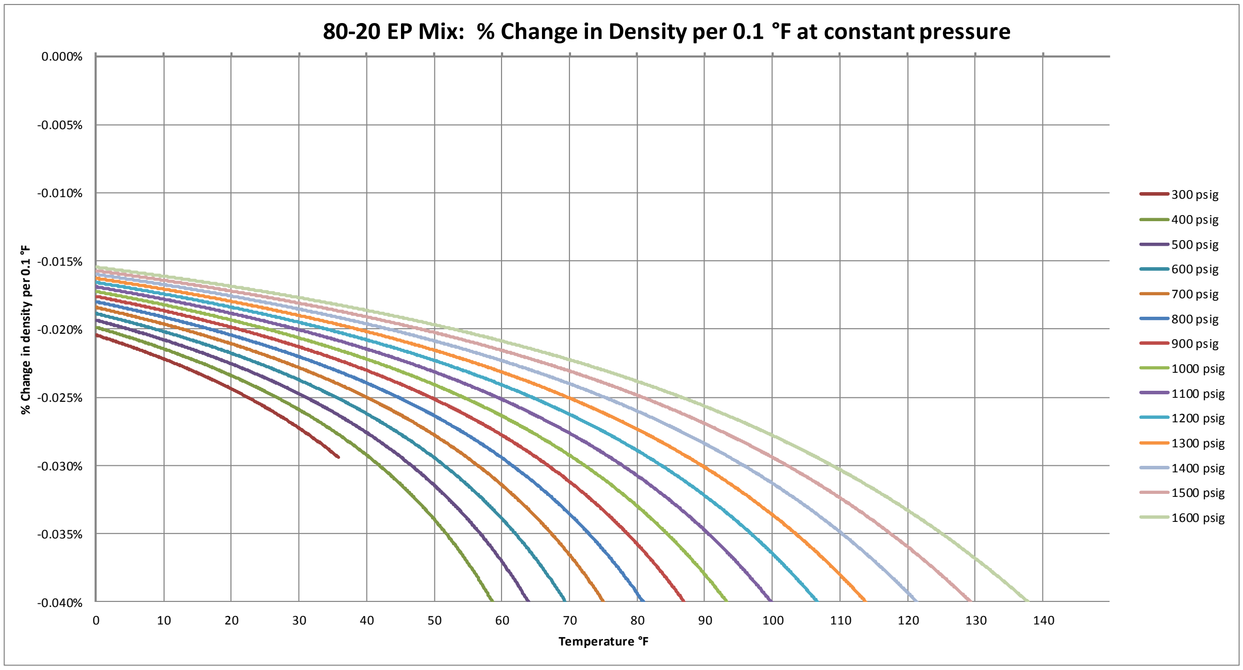
**Table A.1—Density Sensitivity for 0.2 °F Difference for Fluid Temperatures Between 40 °F and 100 °F and Pressures Between 400 psig and 1200 psig**

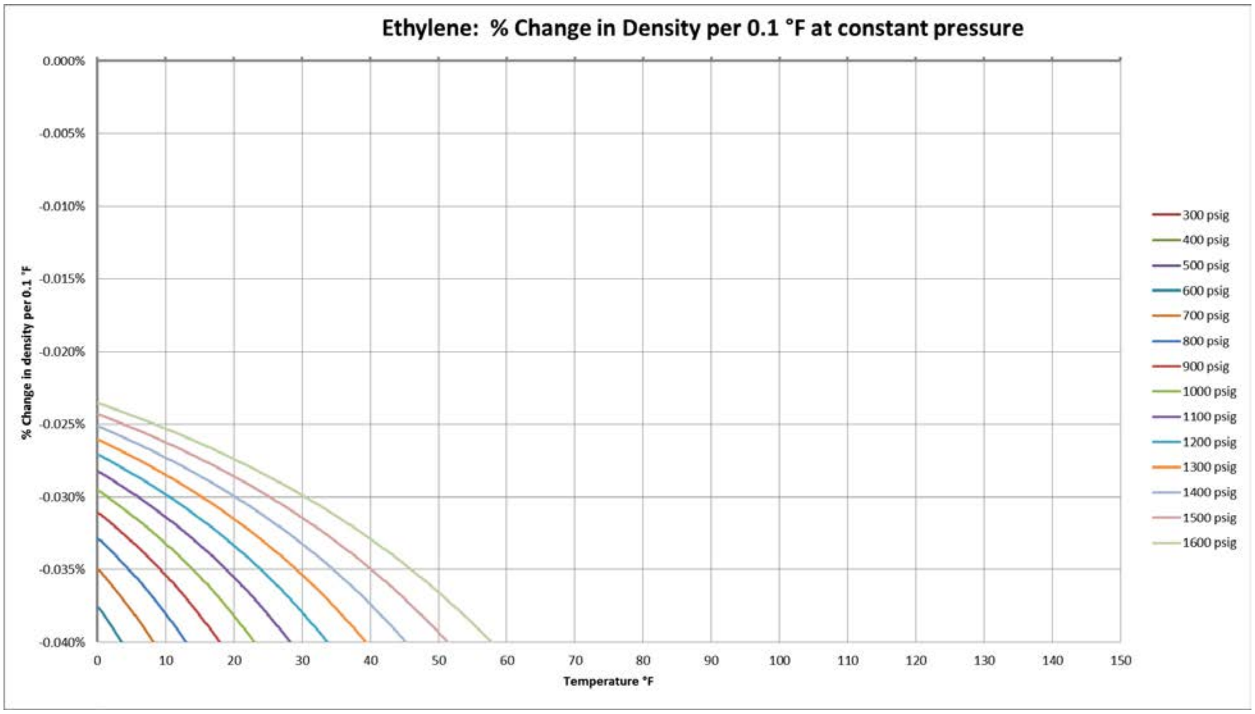
| Fluid | Minimum | Maximum | Notes |
|---|---|---|---|
| Ethane | 0.051 % | 0.888 % | Pressures from 800 psig to 1200 psig |
| 80-20 EP | 0.042 % | 0.128 % | Pressures from 800 psig to 1200 psig |
| Ethylene | 0.088 % | 2.310 % | Pressures from 800 psig to 1200 psig |
| Propane | 0.025 % | 0.041 % | |
| Propylene | 0.026 % | 0.044 % | |
| Propylene mix | 0.026 % | 0.043 % | |
| Isobutane | 0.020 % | 0.026 % | |
| Butane mix | 0.018 % | 0.022 % | |
| Normal butane | 0.018 % | 0.023 % | |
| Natural gasoline | 0.015 % | 0.017 % | |
| High-ethane Y-grade | 0.027 % | 0.049 % | |
| Low-ethane Y-grade | 0.020 % | 0.028 % | |

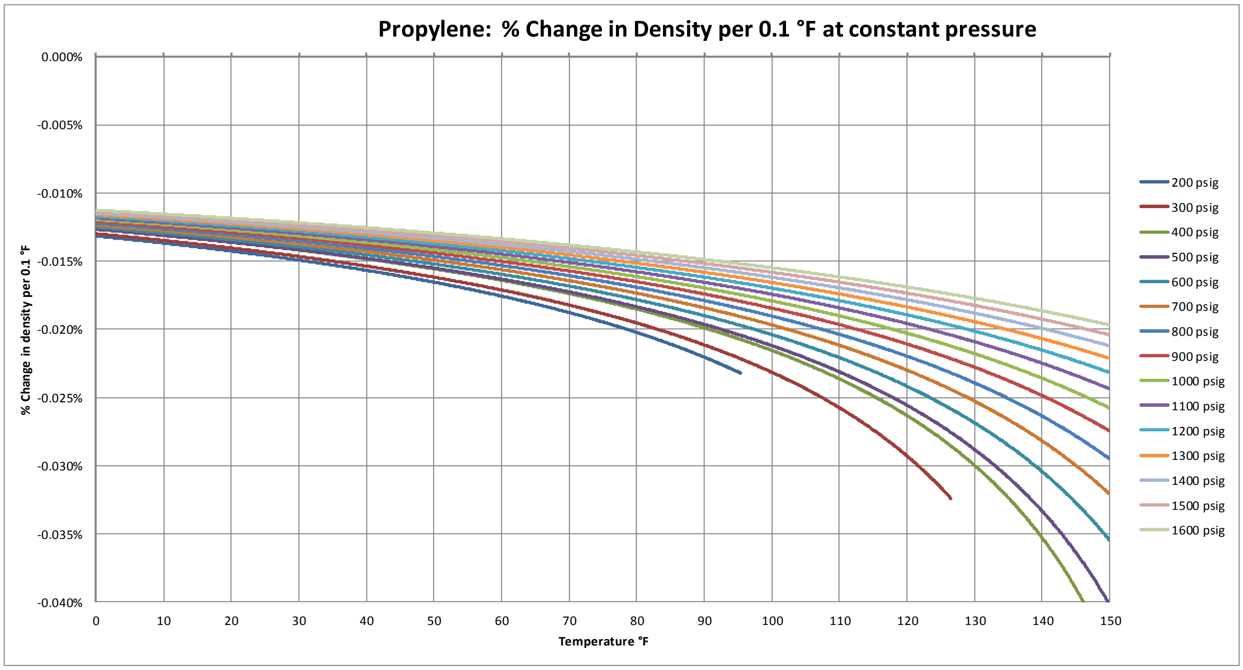
The density for each fluid in the composition matrix was calculated using REFPROP at 0.1 °F increments from 0 °F to 150 °F for constant pressures at 100 psi increments from 200 psig to 1600 psig. The density value at a temperature was then compared to the density at the next higher temperature and the change in density relative to the first density determined. Where a line ends before it reaches the temperature limit denotes that the fluid flashes beyond that point.

The following graphs display a subset of the calculated data.


Ethane: % Change in Density per 0.1 °F at constant pressure


80-20 EP Mix: % Change in Density per 0.1 °F at constant pressure


Ethylene: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Temperature °F
300 psig
400 psig
500 psig
600 psig
700 psig
800 psig
900 psig
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Propylene: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Temperature °F
200 psig
300 psig
400 psig
500 psig
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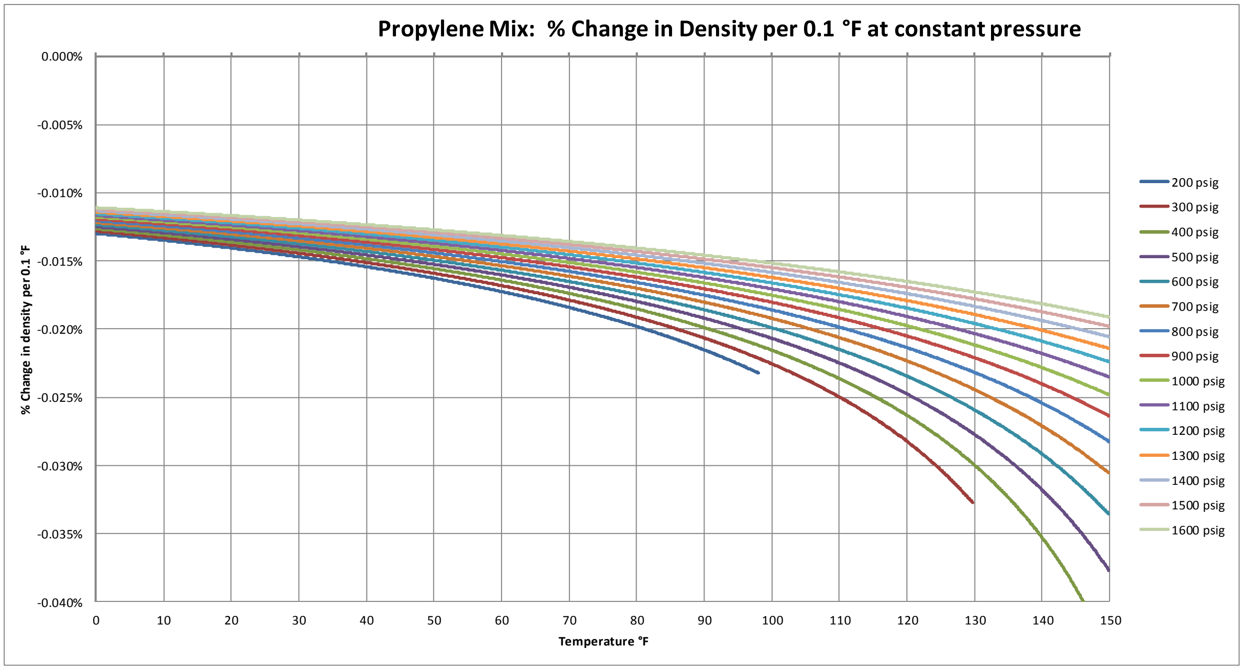
1400 psig
1500 psig
1600 psig


Propylene Mix: % Change in Density per 0.1 °F at constant pressure
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
% Change in density per 0.1 °F
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Temperature °F
200 psig
300 psig
400 psig
500 psig
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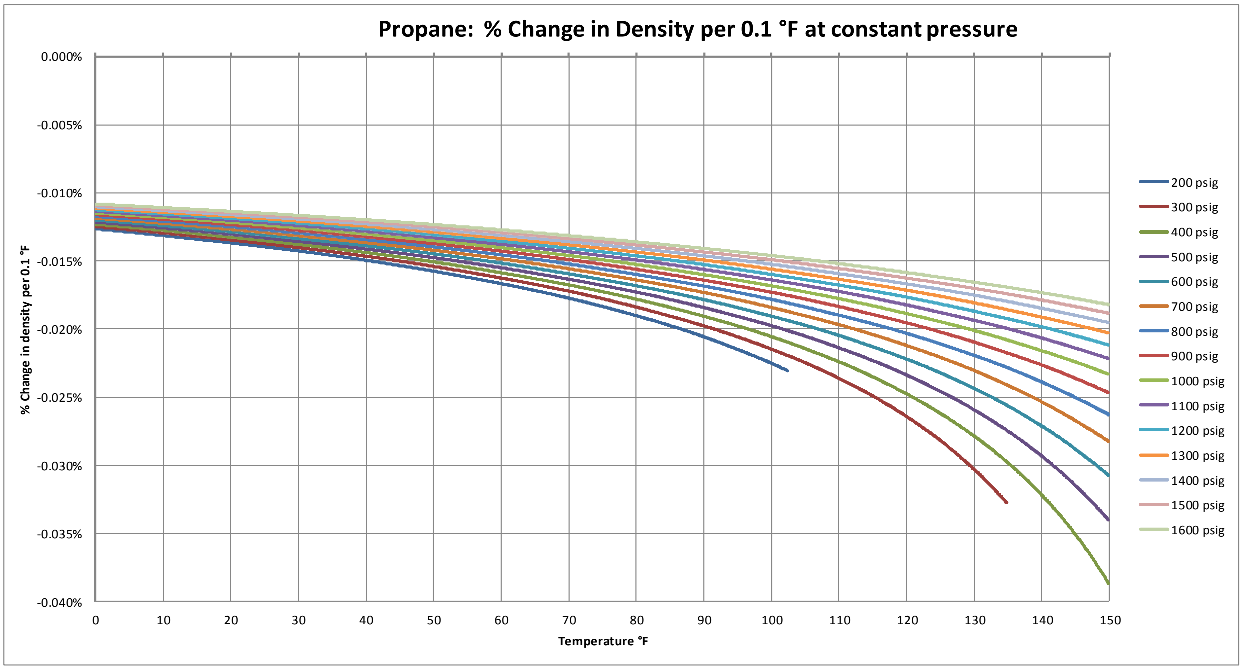
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Propane: % Change in Density per 0.1 °F at constant pressure
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
% Change in density per 0.1 °F
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Temperature °F
200 psig
300 psig
400 psig
500 psig
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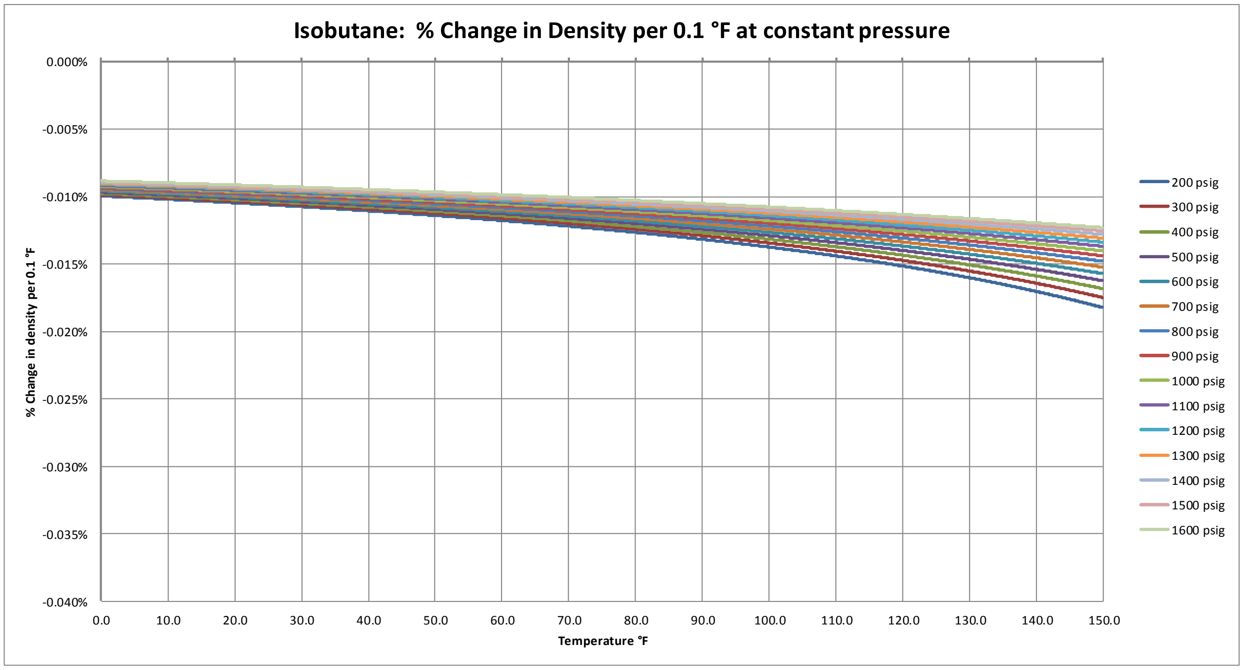
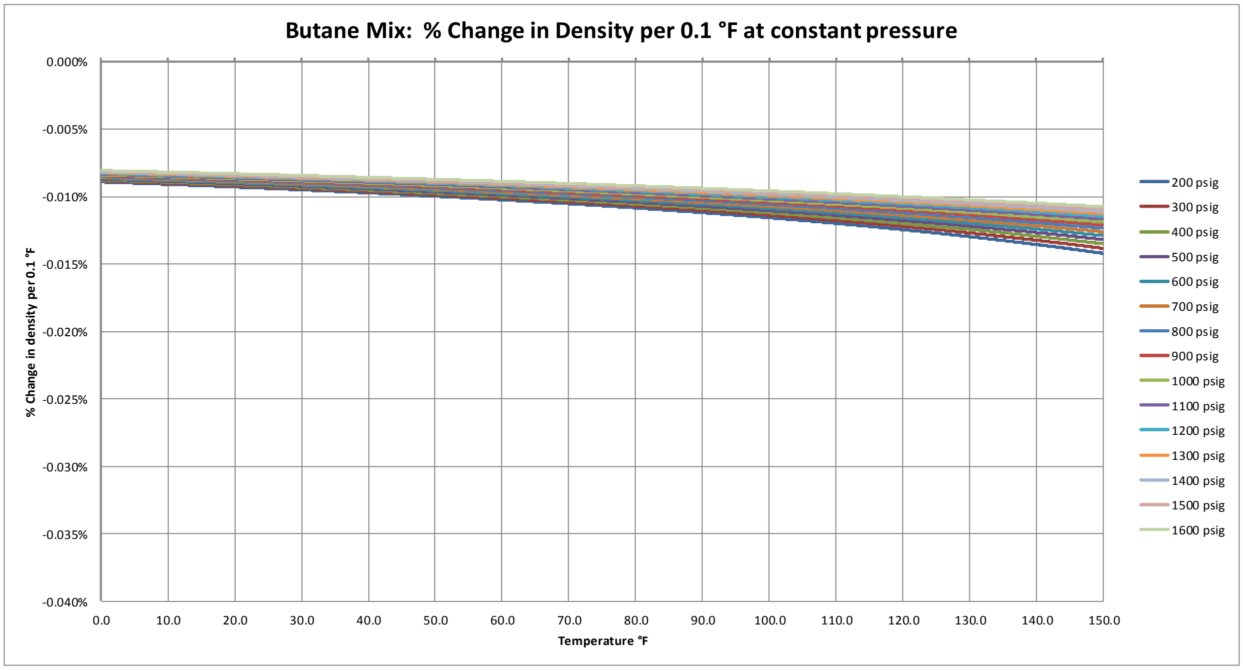
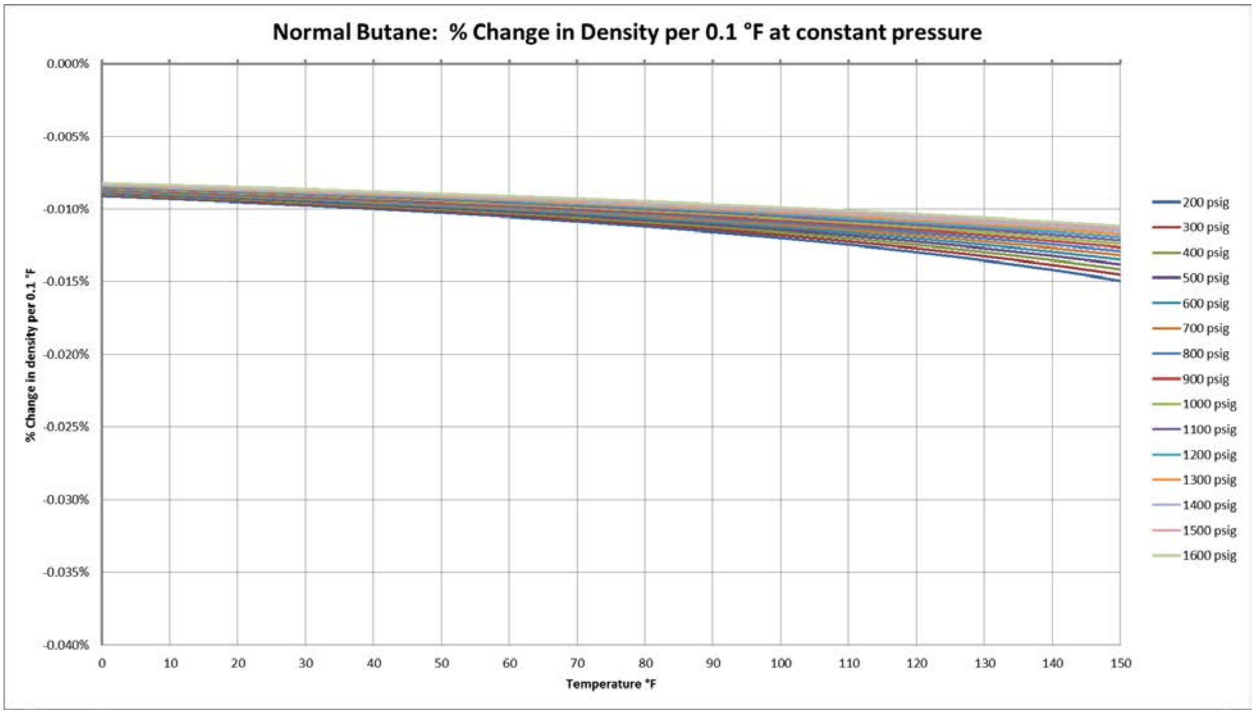
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Isobutane: % Change in Density per 0.1 °F at constant pressure
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
% Change in density per 0.1 °F
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
Temperature °F
200 psig
300 psig
400 psig
500 psig
600 psig
700 psig
800 psig
900 psig
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Butane Mix: % Change in Density per 0.1 °F at constant pressure
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
% Change in density per 0.1 °F
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
Temperature °F
200 psig
300 psig
400 psig
500 psig
600 psig
700 psig
800 psig
900 psig
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Normal Butane: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
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Temperature °F
200 psig
300 psig
400 psig
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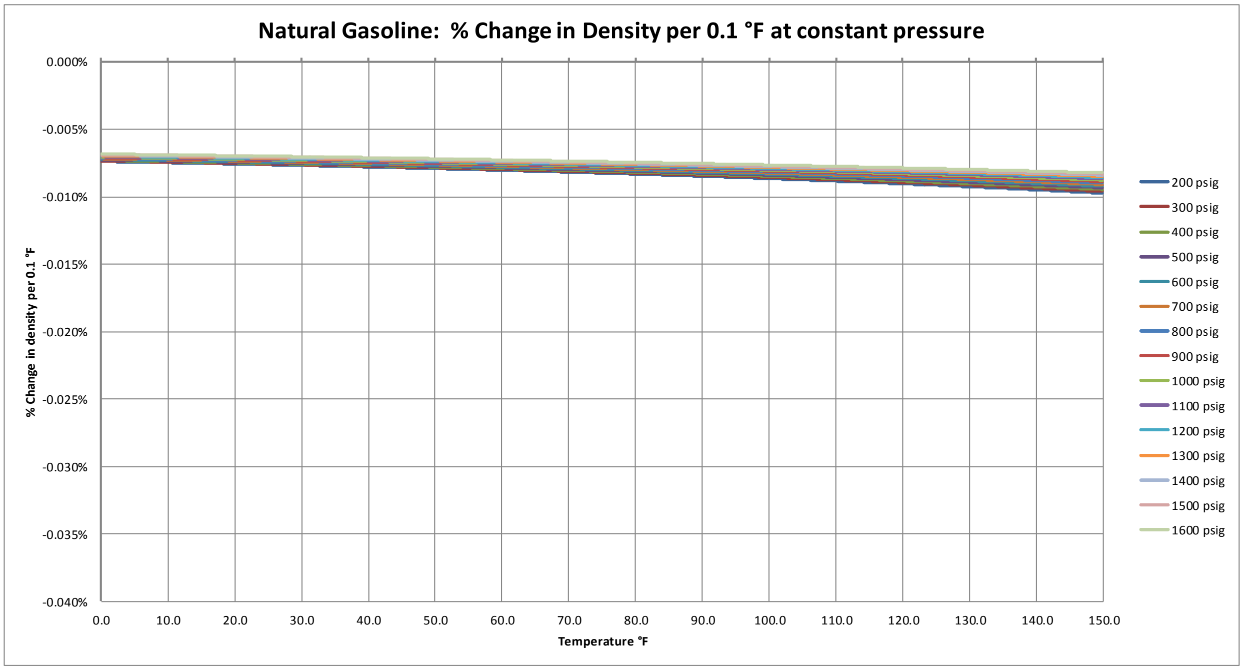
1400 psig
1500 psig
1600 psig


Natural Gasoline: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
0.0
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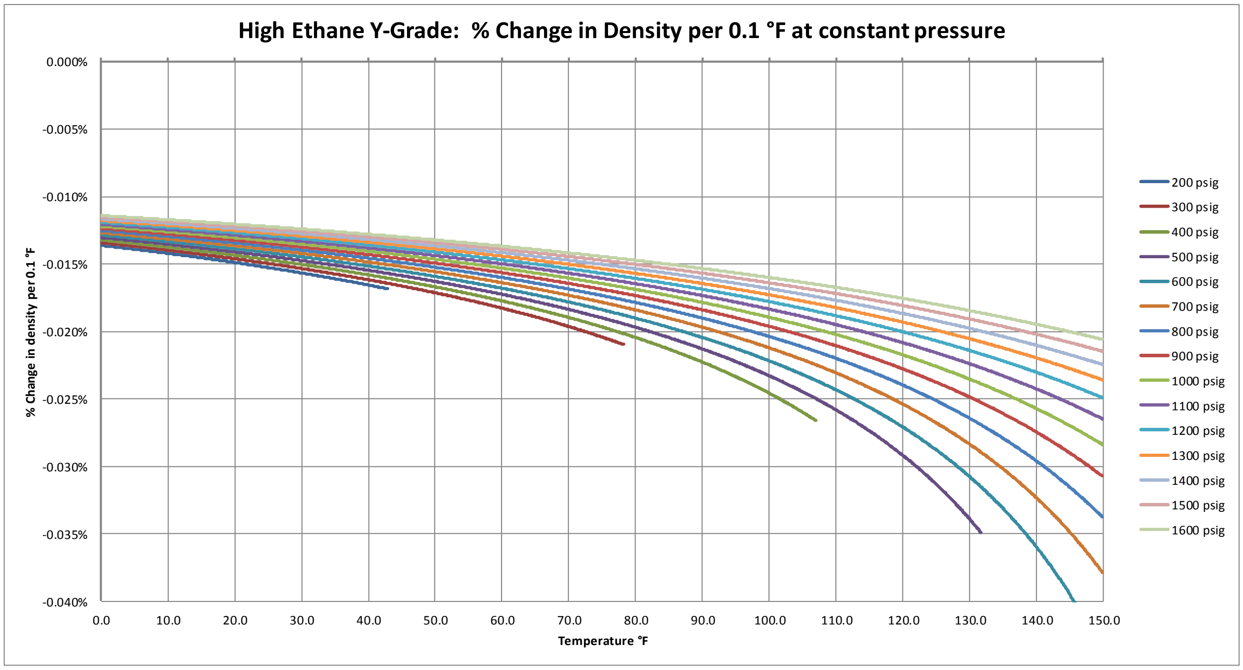
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
Temperature °F
200 psig
300 psig
400 psig
500 psig
600 psig
700 psig
800 psig
900 psig
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


High Ethane Y-Grade: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
Temperature °F
200 psig
300 psig
400 psig
500 psig
600 psig
700 psig
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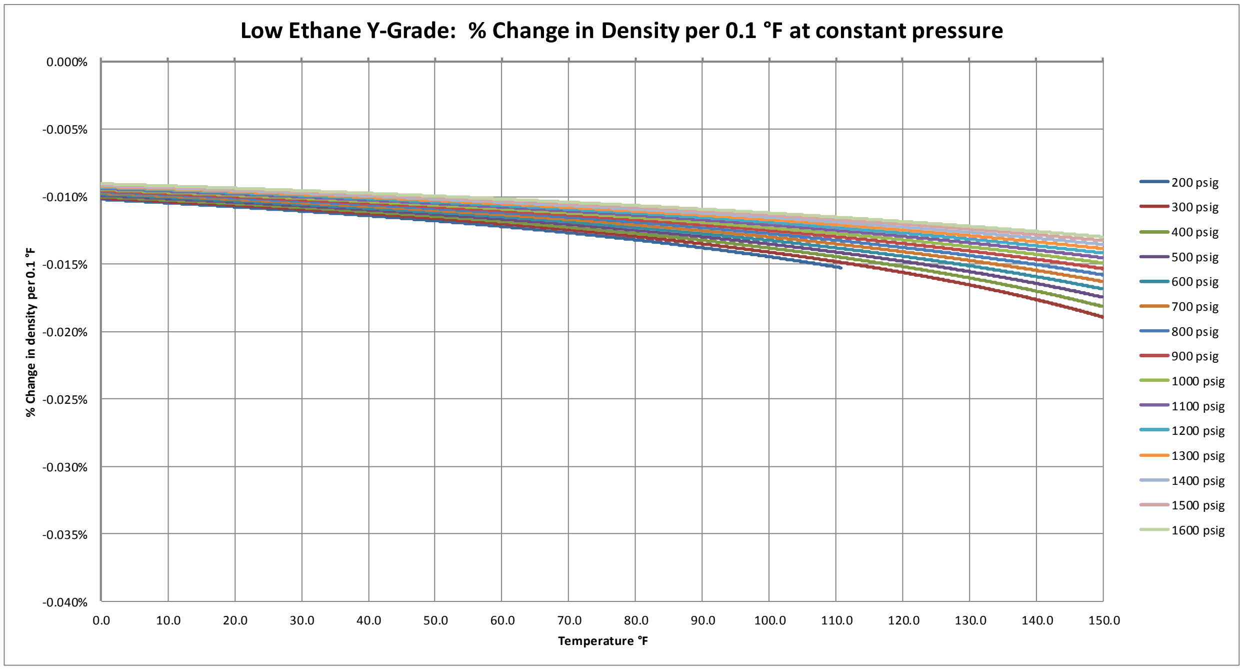
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig


Low Ethane Y-Grade: % Change in Density per 0.1 °F at constant pressure
% Change in density per 0.1 °F
0.000%
-0.005%
-0.010%
-0.015%
-0.020%
-0.025%
-0.030%
-0.035%
-0.040%
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
Temperature °F
200 psig
300 psig
400 psig
500 psig
600 psig
700 psig
800 psig
900 psig
1000 psig
1100 psig
1200 psig
1300 psig
1400 psig
1500 psig
1600 psig

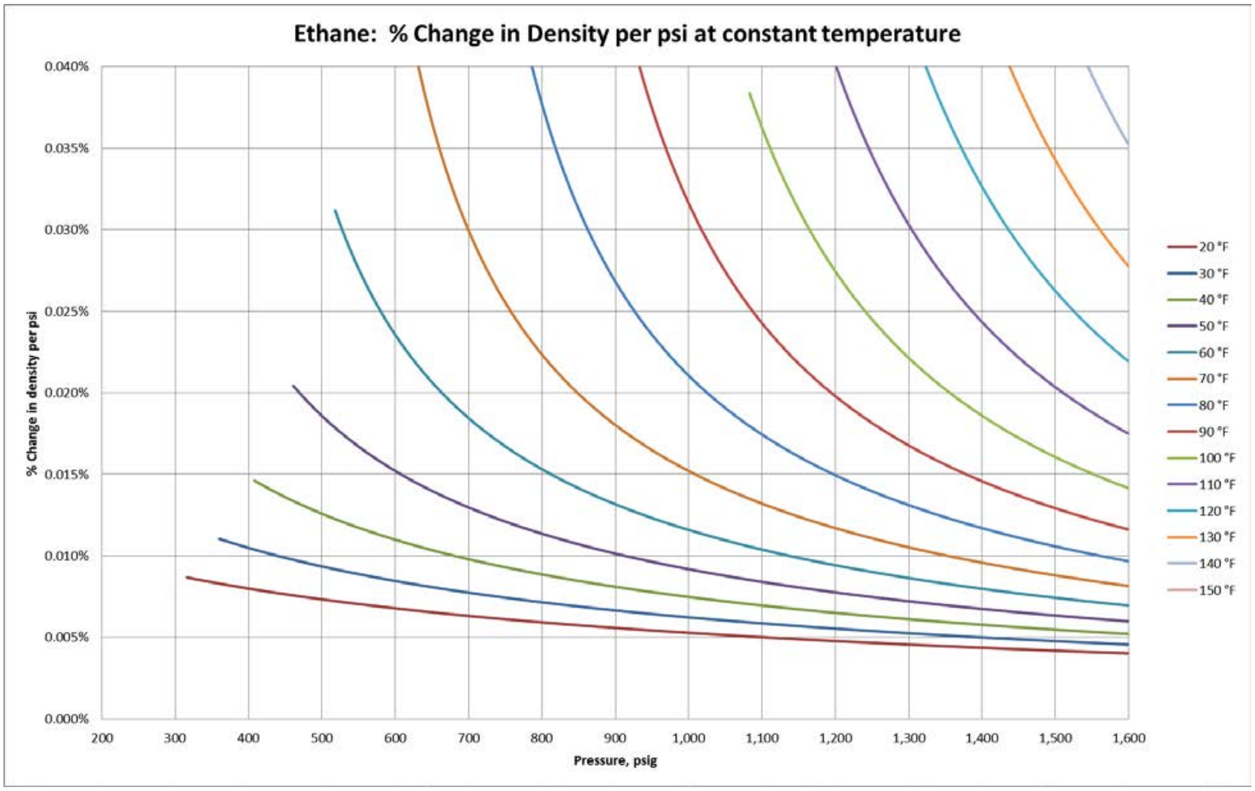
## A.3 Sensitivity to Pressure

Fluids of lower density are more sensitive to the effect of pressure changes. Fluids at higher temperatures are more sensitive to the effect of pressure changes than they are at lower temperatures. Table A.2 lists the density change for 1 psi change in pressure at typical operating conditions for the listed fluids only.

**Table A.2—Density Sensitivity for 1 psi Difference For Fluid Pressures Between 400 psig and 1200 psig and Temperatures Between 40 °F and 100 °F**

| Fluid | Minimum | Maximum | Notes |
|---|---|---|---|
| Ethane | 0.0065 % | 0.0902 % | 800 psig to 1200 psig range, 40 °F to 90 °F |
| 80-20 EP | 0.0047 % | 0.0300 % | Pressures in 800 psig to 1200 psig range |
| Ethylene | 0.0150 % | 1.0215 % | Pressures in 800 psig to 1200 psig range |
| Propane | 0.0022 % | 0.0056 % | |
| Propylene | 0.0022 % | 0.0059 % | |
| Propylene mix | 0.0022 % | 0.0058 % | |
| Isobutane | 0.0016 % | 0.0030 % | |
| Butane mix | 0.0013 % | 0.0022 % | |
| Normal butane | 0.0013 % | 0.0023 % | |
| Natural gasoline | 0.0010 % | 0.0015 % | |
| High-ethane Y-grade | 0.0025 % | 0.0074 % | |
| Low-ethane Y-grade | 0.0016 % | 0.0031 % | |

The density for each fluid in the composition matrix was calculated using REFPROP at 1 psi increments from 200 psig to 1600 psig for constant temperatures at 10 °F increments from 0 °F to 150 °F. The density value at a pressure was then compared to the density at the next higher pressure and the change in density relative to the first density determined. The following graphs display a subset of the calculated data.


Ethane: % Change in Density per psi at constant temperature
% Change in density per psi
0.040%
0.035%
0.030%
0.025%
0.020%
0.015%
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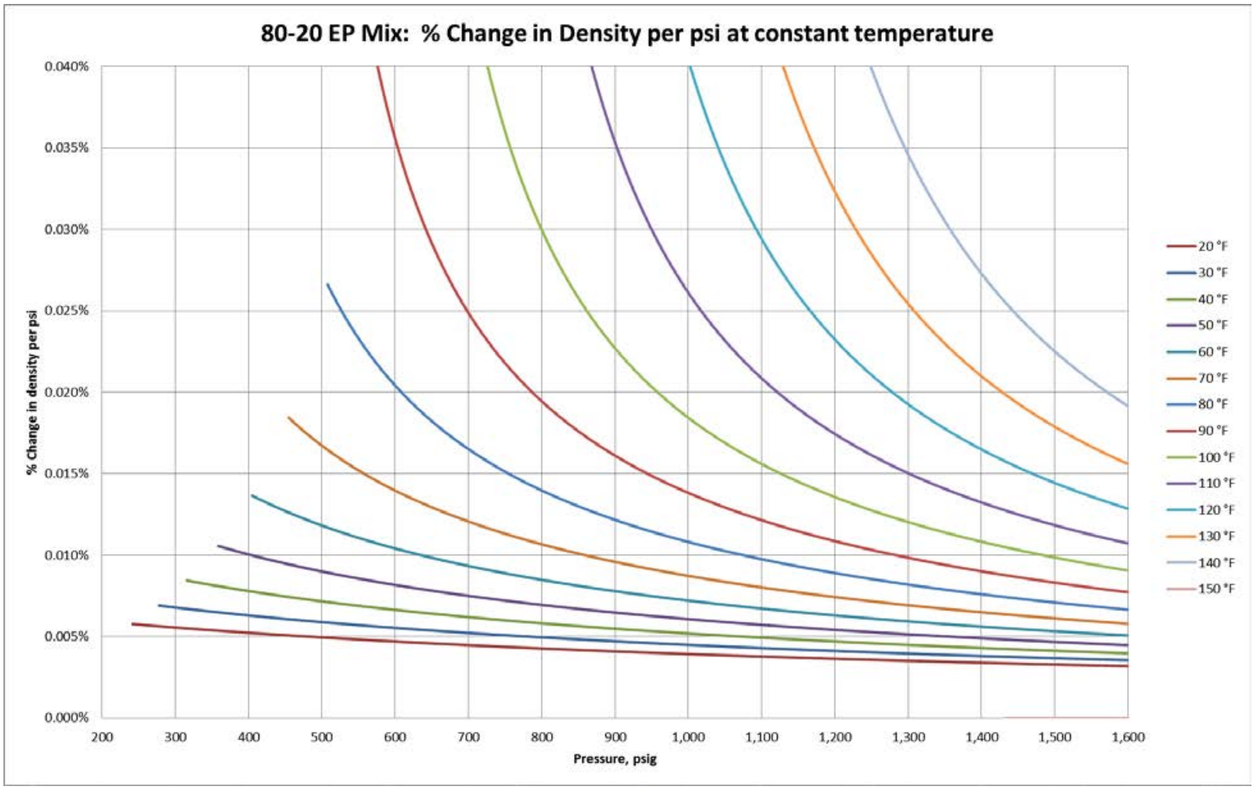
80-20 EP Mix: % Change in Density per psi at constant temperature
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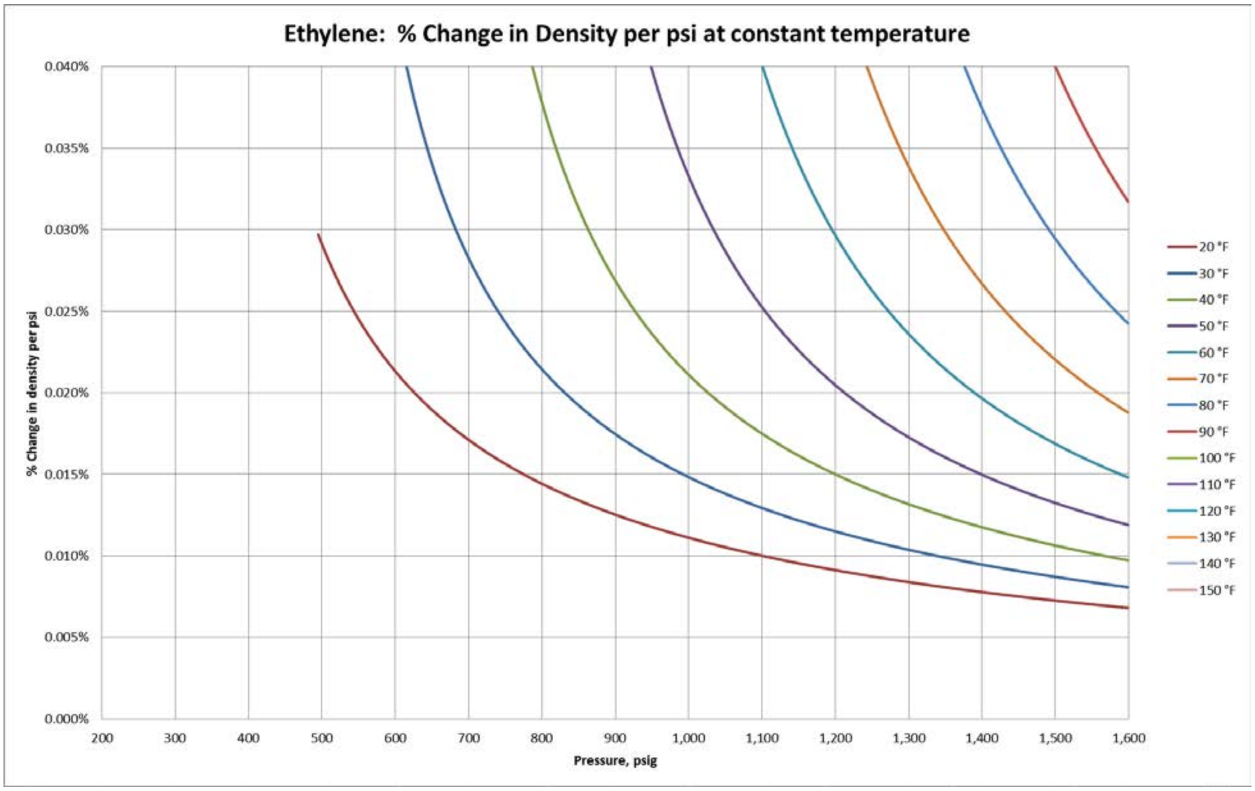
Ethylene: % Change in Density per psi at constant temperature
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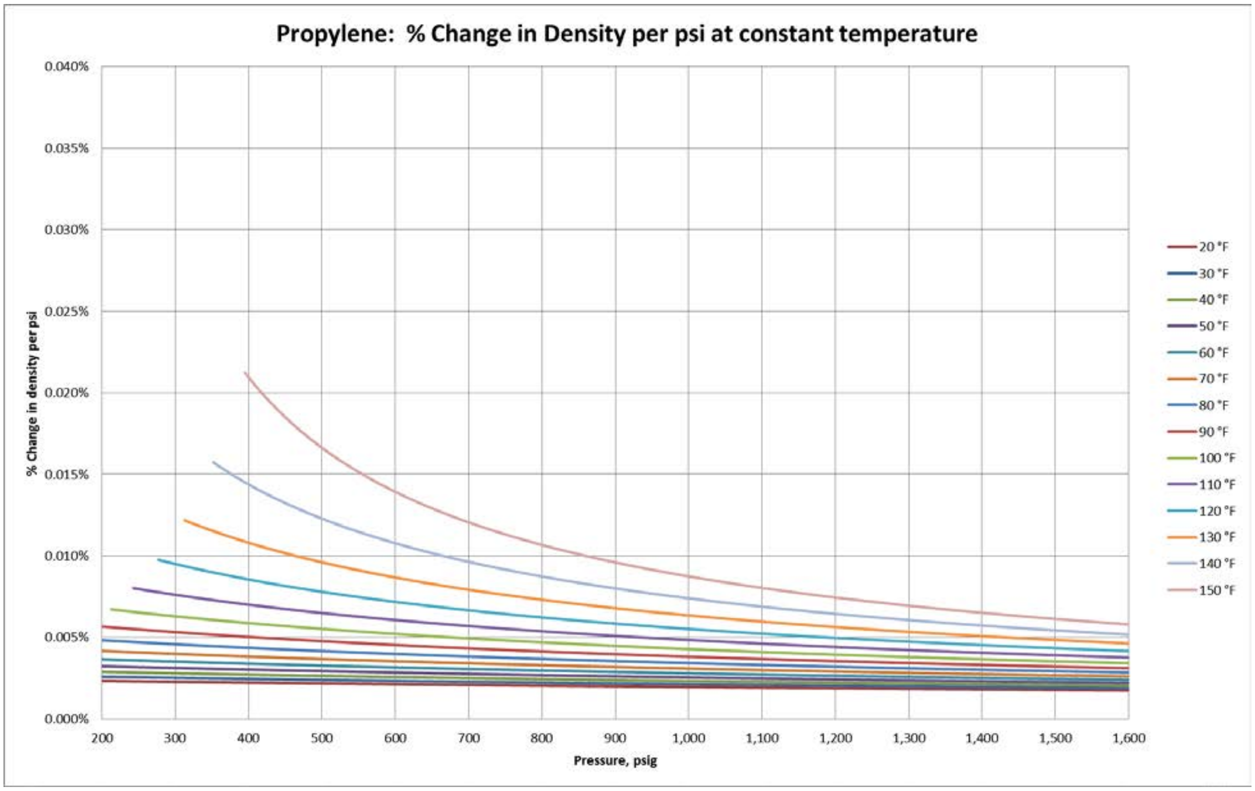
Propylene: % Change in Density per psi at constant temperature
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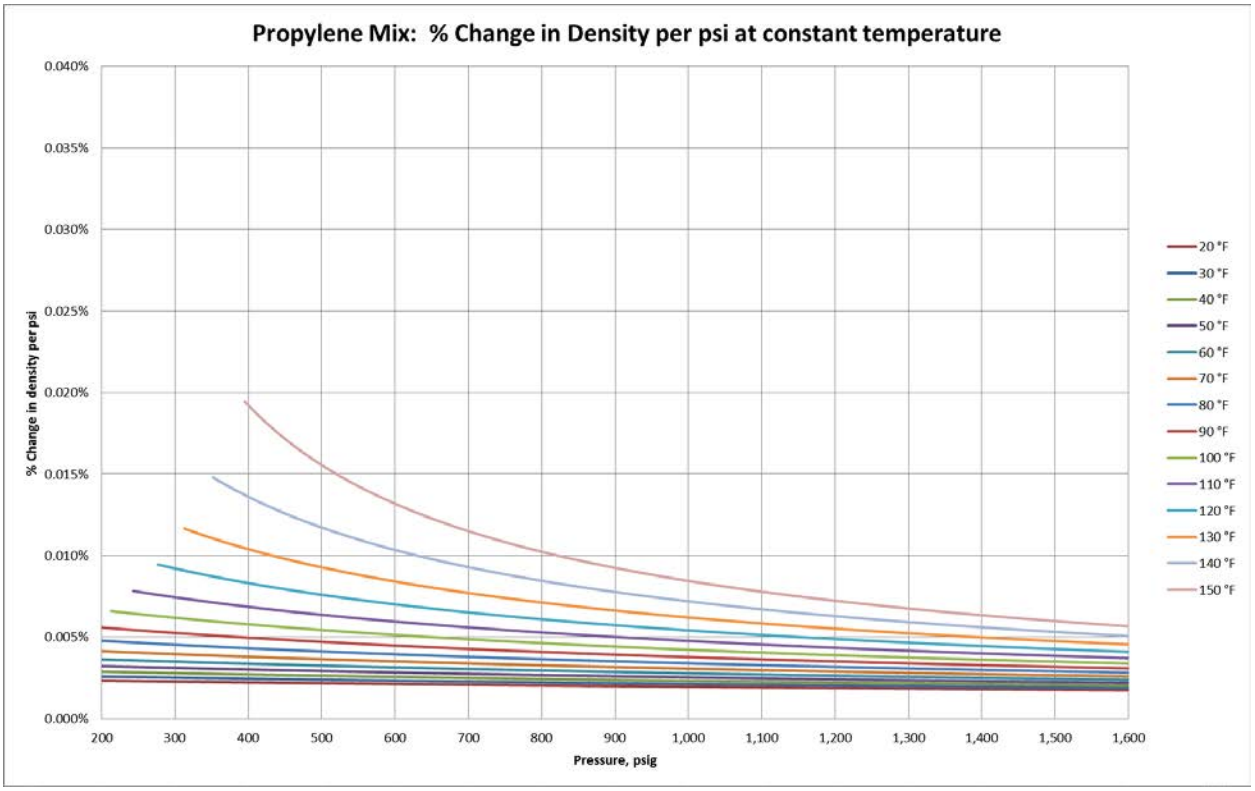
Propylene Mix: % Change in Density per psi at constant temperature
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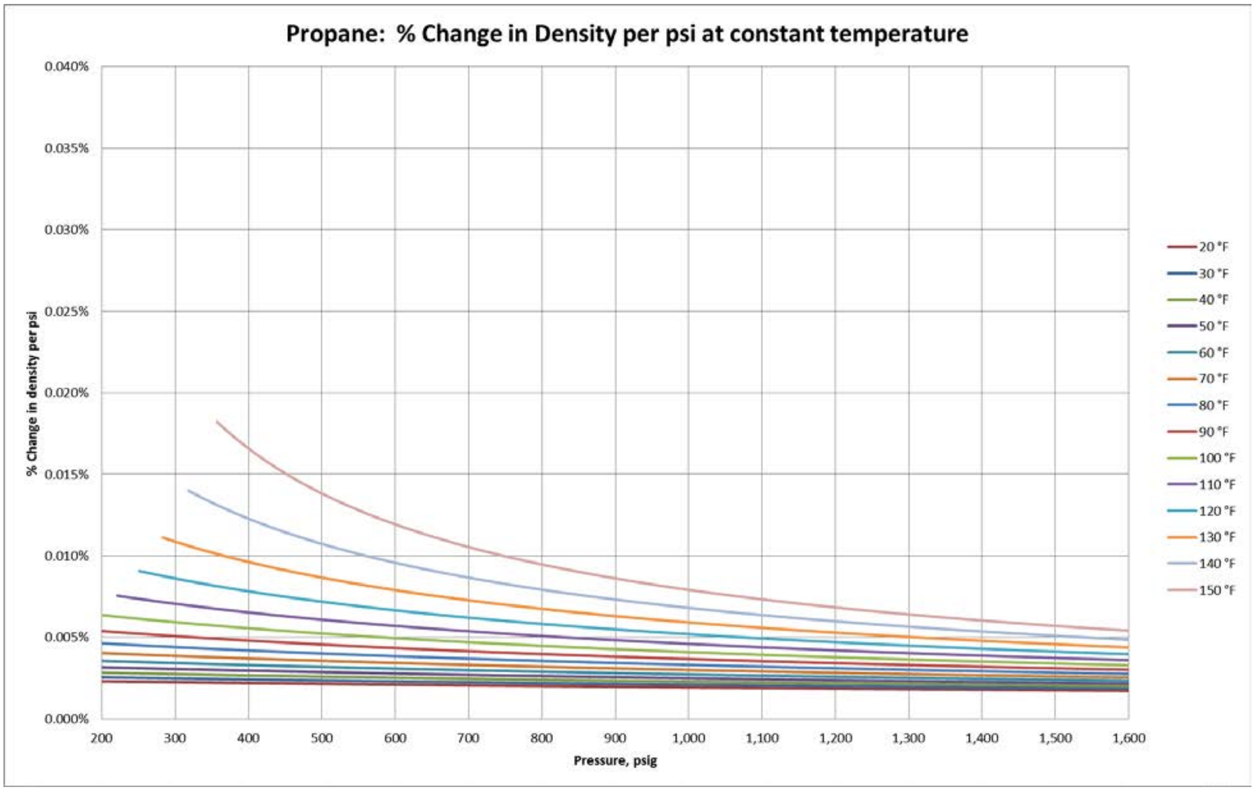
Propane: % Change in Density per psi at constant temperature
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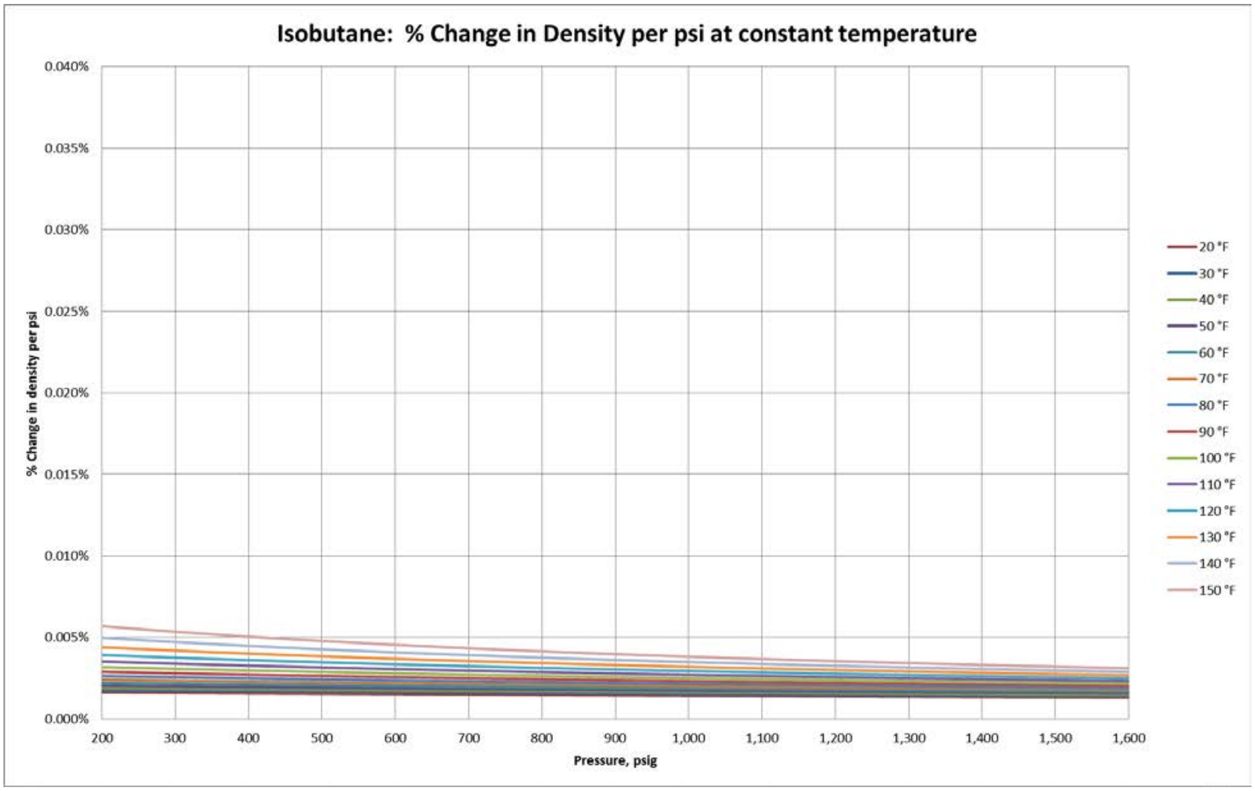
Isobutane: % Change in Density per psi at constant temperature
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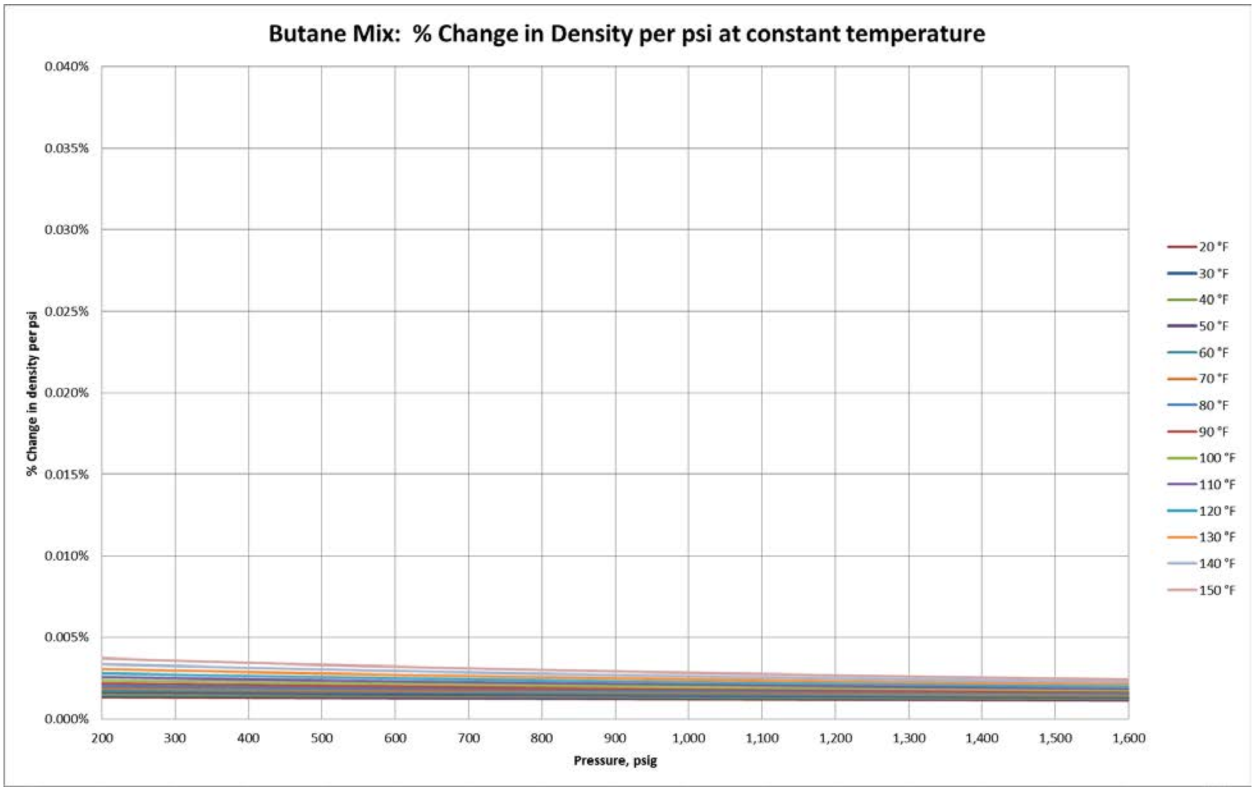
Butane Mix: % Change in Density per psi at constant temperature
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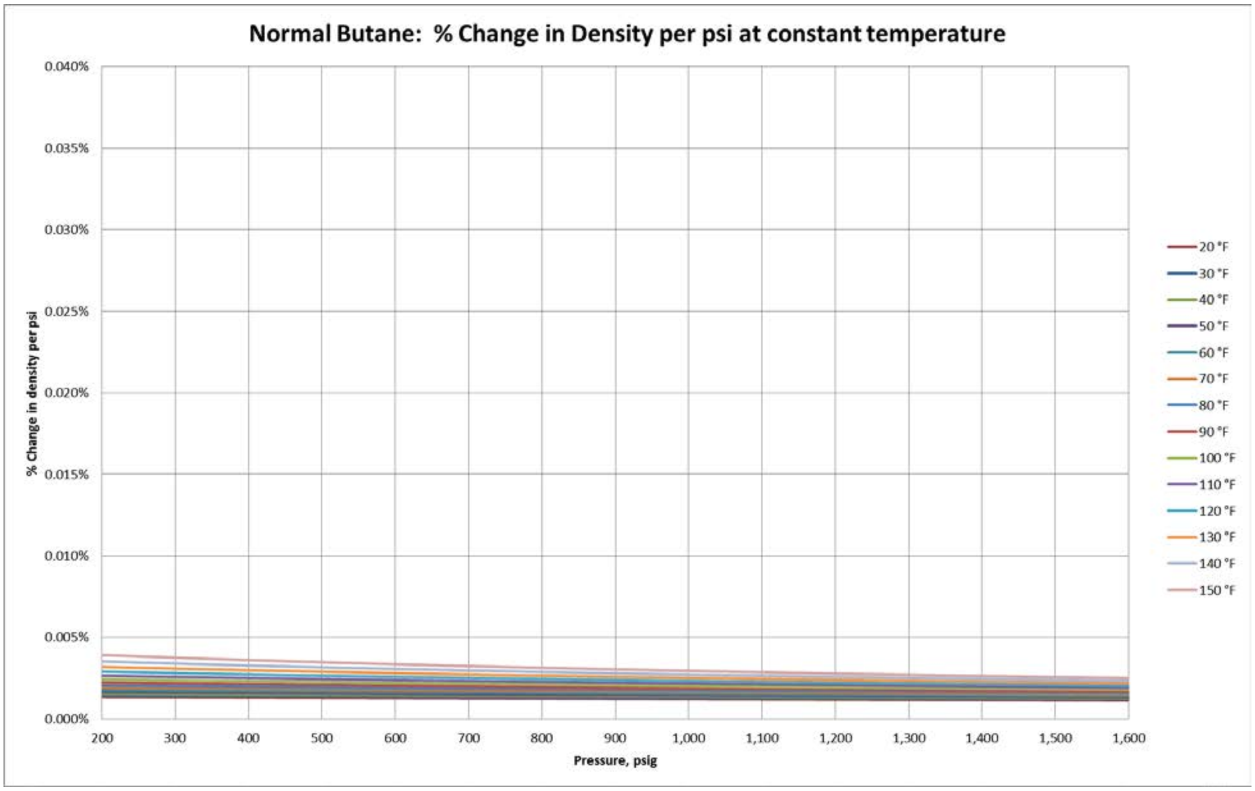
Normal Butane: % Change in Density per psi at constant temperature
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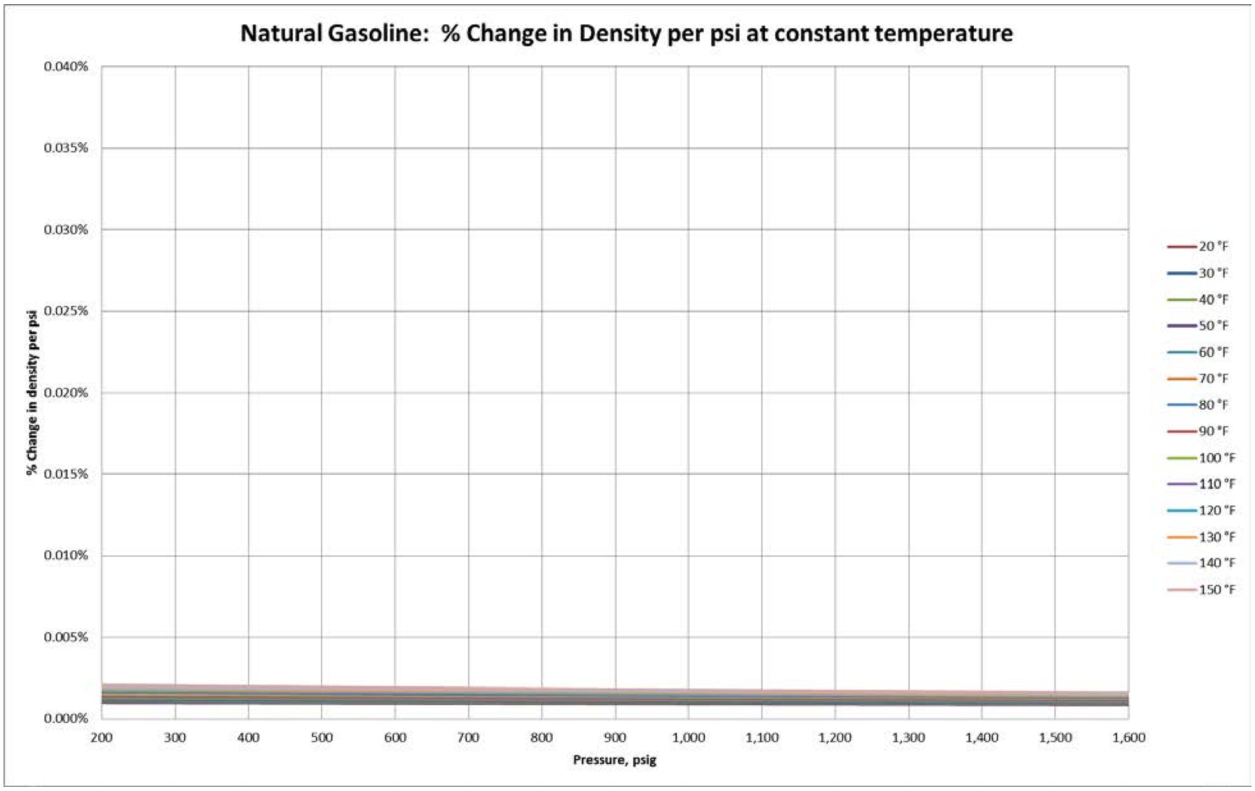
Natural Gasoline: % Change in Density per psi at constant temperature
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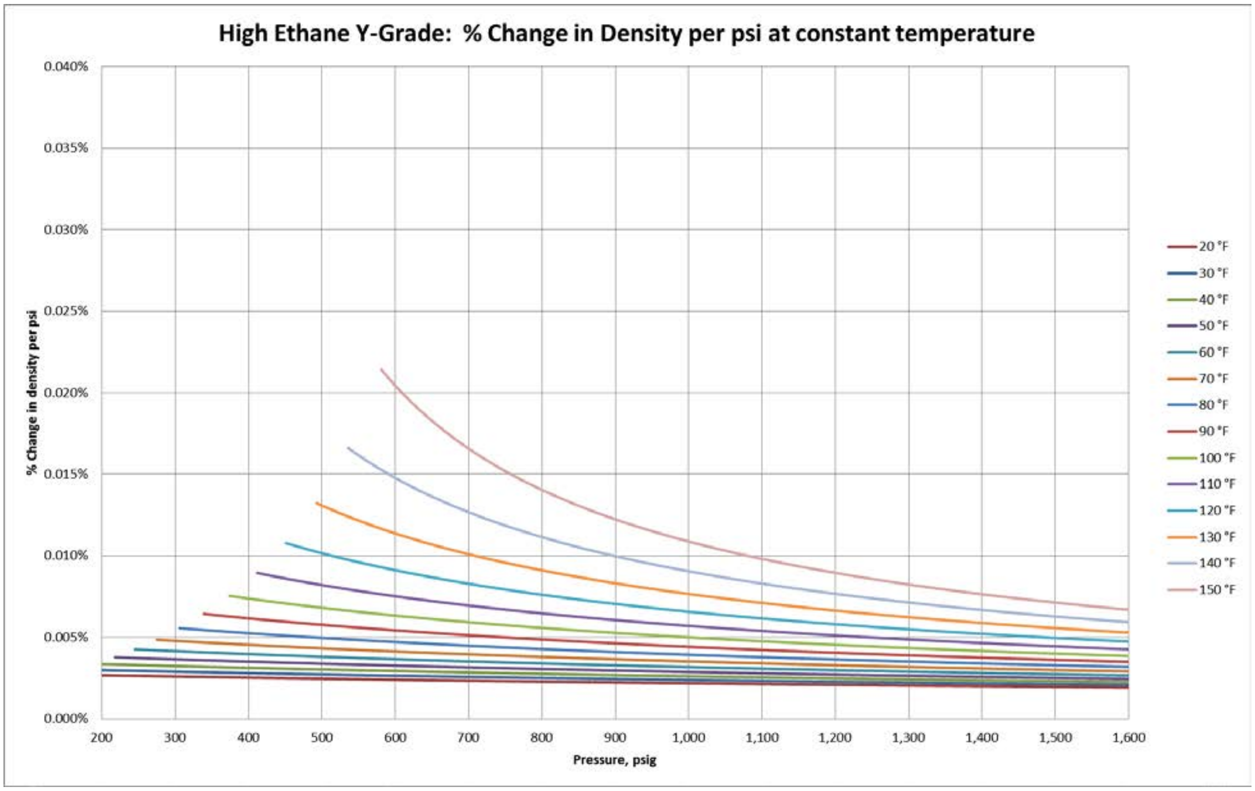
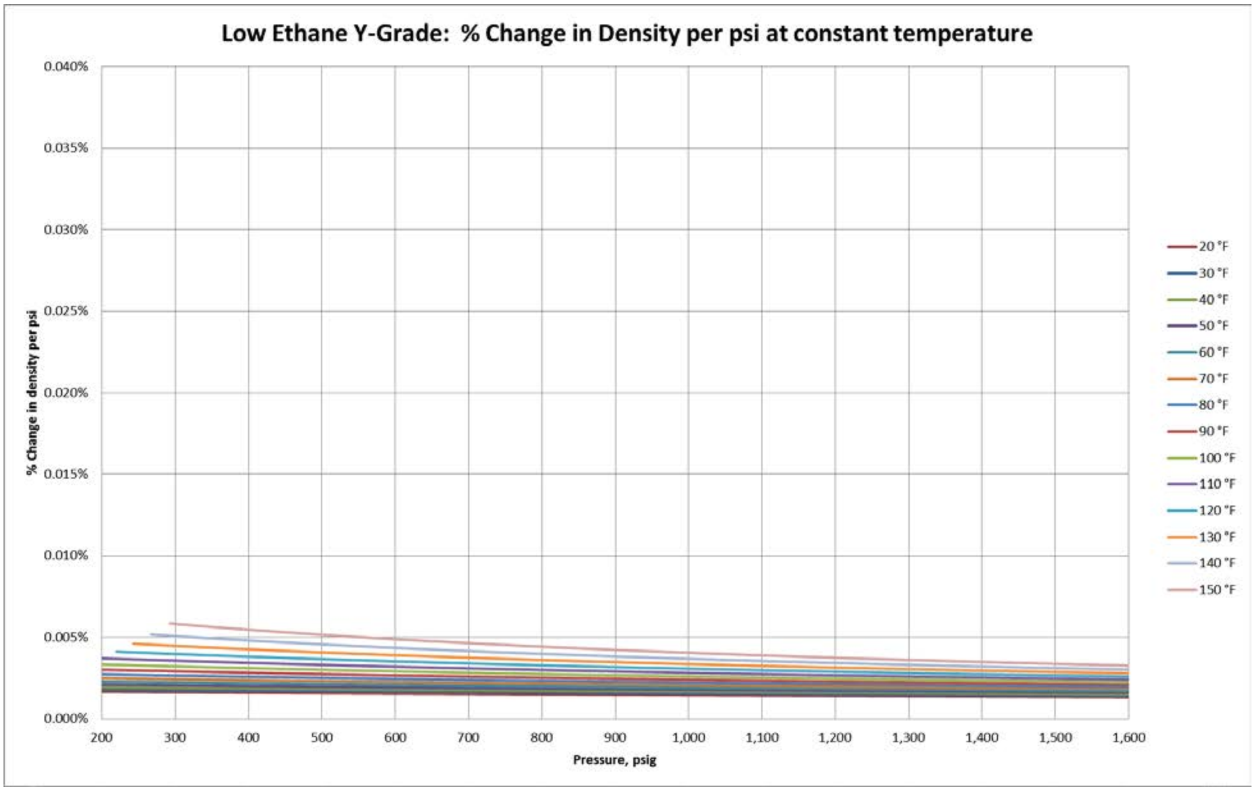

High Ethane Y-Grade: % Change in Density per psi at constant temperature


Low Ethane Y-Grade: % Change in Density per psi at constant temperature

## A.4 Composition Matrix

The following compositions were selected for these examples. Users may choose to evaluate the sensitivity of the fluid density to temperature or pressure for the actual composition.

**Table A.3—Composition Matrix**

| **Component** | **Ethane** | **80-20 EP** | **Ethylene** | **Propane** | **Propylene** | **Propylene mix** | **Isobutane** | **Butane mix** | **Normal butane** | **Natural gasoline** | **High-ethane Y-grade** | **Low-ethane Y-grade** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Methane** | 2.50 % | 1.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 1.15 % | 0.42 % |
| **Ethane** | 95.00 % | 80.00 % | 0.00 % | 5.00 % | 0.00 % | 1.00 % | 0.00 % | 1.00 % | 0.00 % | 0.00 % | 45.56 % | 18.06 % |
| **Ethylene** | 0.00 % | 0.00 % | 100.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % |
| **Propane** | 2.50 % | 19.00 % | 0.00 % | 92.00 % | 0.00 % | 33.00 % | 1.00 % | 3.00 % | 0.00 % | 0.50 % | 31.46 % | 33.51 % |
| **Propylene** | 0.00 % | 0.00 % | 0.00 % | 1.00 % | 100.00 % | 65.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % |
| **Isobutane** | 0.00 % | 0.00 % | 0.00 % | 1.50 % | 0.00 % | 1.00 % | 98.00 % | 20.00 % | 2.00 % | 0.00 % | 3.72 % | 5.86 % |
| **Normal butane** | 0.00 % | 0.00 % | 0.00 % | 0.50 % | 0.00 % | 0.00 % | 1.00 % | 50.00 % | 97.00 % | 2.50 % | 10.18 % | 17.27 % |
| **Isopentane** | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 16.00 % | 1.00 % | 29.00 % | 2.36 % | 5.17 % |
| **Normal pentane** | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 8.00 % | 0.00 % | 21.00 % | 2.42 % | 6.29 % |
| **Hexane** | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 2.00 % | 0.00 % | 47.00 % | 3.13 % | 13.42 % |
| **Nitrogen** | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % |
| **$CO_2$** | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.00 % | 0.02 % | 0.00 % |
| **Total weight (%)** | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

# Annex B
(normative)

# Test Equipment—Pycnometer Calibration and Proving

## B.1 General

The objective of this annex is to describe the design requirements and performance requirements for the test equipment to be used in the methods given in Annex C and Annex D.

Various equipment is required during both the calibration of a pycnometer and the proving of a density meter using the pycnometer. These include a flow-through pressure pycnometer (4.1.25), an electronic weigh scale, certified test weights, and temperature- and pressure-measuring devices.

Additional equipment is also needed to calibrate the pycnometer, including various-sized glass beakers, a vacuum pump, pressure-calibration device, and a water cushion cylinder, all of which are detailed in Annex C.

## B.2 Flow-through Pycnometer Design Considerations

Use a pycnometer with a flow-through design. Evaluate the selected pycnometer for sensitivity to the sample system flow rate, vapor exclusion, liquid and particulate accumulation, and atmospheric water condensation.

The pycnometer shall be designed and constructed to meet the accuracy requirements of Annex C, as well as those for safety, ease of operation, and cleaning. The following shall be considered when determining the size, design, and construction of a pycnometer:

The pressure rating of the pycnometer shall meet or exceed the higher of:

- the highest pressure rating of the piping, pipeline, or meter station; and
- the combination of maximum operating pressure plus the greatest pressure increase resulting from thermal expansion of the pycnometer contents between sampling and emptying.

The pycnometer shall be constructed, inspected, and tested in accordance with the applicable piping code or pressure vessel code (such as ASME B31.3). In accordance with the applicable code, hydrostatically test the pycnometer to a pressure to 1.5 times the maximum allowable working pressure.

Equip the pycnometer with an over-pressure safety device, such as a rupture disk. The relief device should be fitted, set to operate and give full relief at a pressure no greater than that specified in the applicable piping or pressure vessel code.

Due to the delicate nature of the rupture disk, this type of over-pressure device should never be dismantled without good reason. The actual dismantling, cleaning, and maintenance procedures will depend on the design of the pycnometer, and reference should be made to the manufacturer's recommendations.

The materials used to construct a pycnometer need to be compatible with the fluid being measured. Typically, a pycnometer is double-walled and constructed of stainless steel.

A single-walled pycnometer shall not be used for light hydrocarbons.

The entire pycnometer assembly shall be manufactured of materials that do not corrode in service.

The ratio of the pycnometer tare weight to the mass of the contents should be kept as low as possible to minimize weighing errors. This necessitates a minimum internal volume of at least 500 $cm^3$. A volume of 1,000 $cm^3$ is recommended. The pycnometer shall be of a size that can be safely handled and accurately weighed when filled with water.

Both the internal and external surfaces should be polished to facilitate cleaning. Valve and rupture disk assemblies should be designed so that they cannot trap liquids or other contaminants that would introduce weighing errors.

A bubble-tight shut-off valve should be fitted at inlet and outlet of the pycnometer, and it is recommended that the valve bodies form an integral part of the pycnometer. The valves should be designed to give a fast and positive shut-off, have zero leakage and good resistance to abrasive particulate materials, and be easy to disassemble and clean. It is desirable that the valve components be changeable without causing a change in internal volume that would require the pycnometer to be recalibrated. Plug or ball valves of DN8 to DN15 (NPS ¼ to NPS ½) nominal bore are recommended. Note that the flow rate through the pycnometer can be adversely affected by the use of valves that have smaller bore than the associated tubing and fittings.

When ball valves are used on a pycnometer, use vented ball valves and orient the vent inward toward the pycnometer when the valve is in the closed position.

A user may choose to install male quick-connect-type fittings onto the outer ends of the valve bodies for ease of operation. The installation of threaded valve or tubing connections may be difficult to clean and prone to wear. Female quick-connect-type connections on the hoses, tubing, or rigid pipe should not be of the self-shut-off type, but should be full-flow fittings so as to maximize the fluid flow rate through the pycnometer.

A pycnometer that does not have integral valves should be engraved or etched with valve alignment marks so that any movement of the valve relative to the pycnometer body can be easily detected. If movement occurs, the volume calibration will be invalidated.

When handling a pycnometer with non-integral valves, take particular care to ensure that the valves are not moved relative to the pycnometer body (tightened or loosened); otherwise, the volume calibration shall be invalidated.

For a pycnometer fitted with tapered plug valves, avoid applying excessive torque to the valve to minimize damage to the valve seats.

To determine the pycnometer volume at operating conditions, ensure the pycnometer volume is determined and certified by a laboratory using equipment traceable to a NMI. The determination and certification shall include:

— the volume to within ±0.005 % at 95 % confidence level at declared datum conditions and other conditions in Annex C, Section C.1.2;

— the steel temperature and pressure coefficients of expansion needed to calculate the volume at sampling conditions.

In accordance with this standard, the pycnometer volume and weight shall be determined prior to first use, then recertified at regular intervals not to exceed two years. Any modification, including changing a valve, requires the pycnometer to be recertified.

To minimize hysteresis effects, determine these data only after the pycnometer has been pressurized to the highest pressure to which its volume is to be determined.

To protect the pycnometer from damage, it is recommended that a portable carrying case be used. It should be of robust construction, not pressure tight, and fitted with lifting handles and secure locking devices to hold the lid in place.

Maintenance procedures should be performed in accordance with the manufacturer's recommendations.

## B.3 Electronic Weigh Scale

The electronic weigh scale used with a pycnometer in laboratory calibrations and density meter provings shall have a:

- range or scale capacity of approximately 125 % of the maximum fluid-filled pycnometer weight, typically 0 g to 5000 g;
- minimum accuracy equal to the lesser of either:
  - ±0.02 % of the test fluid weight;
  - ±0.02 % of the air-filled weight of the pycnometer.
- resolution better than or equal to 1 part in 10,000 (typically 0.01 g) of either:
  - the test fluid weight;
  - the air-filled weight of the pycnometer.

The weigh scale accuracy shall be certified traceable to NMI standards. The weigh scale (electronic) should be recertified at a two-year maximum interval.

Verify the weigh scale at the time of use for either laboratory calibration or density meter proving with certified apparent mass standards (test weights) to assure accuracy and to avoid weighing errors due to local gravitational forces.

Selection of the type of weigh scale should take into account the fluid- or air-filled mass of the pycnometer, the precision of the scale, and environmental conditions.

Mount the scale on a level, stable, vibration-free surface. If the scale is not equipped with an internal level, use an appropriate level to verify that the scale pan is horizontal.

Provide an air shield to minimize the effect of air currents on the weigh scale measurements.

A pycnometer holding tray is recommended for centering and stabilizing the pycnometer during weighing.

## B.4 Certified Test Weights

Certified test weights (apparent mass standards) that conform to ASTM E617 Class 0, 1, 2 or 3, OIML R111-1 Class $E_1$, $E_2$, or $F_1$, and are traceable to a NMI (4.1.23) test weight standard shall be used to calibrate or verify the weigh scale.

Annex J shows a certificate for typical secondary apparent mass standards traceable to NIST.

Test weights shall be stored and handled in such a manner as to prevent damage and surface contamination, which generally requires storage in a felt-lined box and handling with gloves. Recertify test weights if damaged or if suspected of being in error.

Recertify test weights at intervals no longer than every two years.

## B.5 Temperature Instrumentation

Measure the temperatures with a portable device traceable to a NMI (4.1.23) and accurate to 0.05 °C (0.1 °F) or better. The temperature instrument shall be recertified at a one-year maximum interval. Electronic devices are preferred because of their readability.

To eliminate biases caused by different temperature-measuring devices at all temperature measurement points, verify that each device measures the same temperature within 0.05 °C (0.1 °F) at a temperature near the test temperature, or use the same device, after it has reached temperature stability. A differential temperature device is preferred where the difference in temperature between two points is specified.

## B.6 Pressure Instrumentation

Measure pressures with a device traceable to a NMI and accurate to 0.05 % of reading or better for the laboratory, and 0.10 % of reading or better in the field. The pressure instrument shall be recertified at a one-year maximum interval. Electronic devices are preferred because of their readability. Resolution should be 0.1 psi or better. In some situations, a differential-pressure device may be required to assure that the density deviation due to pressure is within the design criteria. Pressure differences shall not exceed 3.5 kPa (0.5 psi).

## B.7 Pycnometer Ball Valve Considerations

Inlet and outlet connections on a pycnometer may be equipped with ball valves. Some ball valves are manufactured to include a small vent port in the ball. The pressure rating of the valve depends on the orientation of the vent port. Additionally, these valves can be installed so that the vent port is turned inward toward the pycnometer, or can be installed with the vent port turned outward. The position of the vent port affects the volume contained in the pycnometer. The user should evaluate the effect of the vent port orientation on pycnometer density determination. Calculations have shown that the error is on the order of 3 parts in 100,000 if the vent port is contaminated with fluid of the same density of water when the pycnometer contains fluid of a relative density of 0.500. The orientation of the ball in the valve should be constrained so that it remains consistent throughout the life of the pycnometer calibration.

# Annex C

(normative)

# Pycnometer Calibration—Laboratory Method

## C.1 Objective of Tests

### C.1.1 General

The objective of the pycnometer calibration is to determine the following unique values:

a) pycnometer air-filled weight ($W_a$);

b) pycnometer evacuated weight ($W_o$);

c) pycnometer base volume (PBV);

d) the coefficient of cubical expansion due to temperature on the pycnometer ($E_t$);

e) the coefficient of cubical expansion due to internal pressure on the pycnometer ($E_p$).

An acceptable test is determined by the repeatability of the test results for three consecutive runs.

A run consists of one evacuated weight ($W_o$), one air-filled weight ($W_a$) at atmospheric pressure, and determinations of the pycnometer volume at a datum temperature and at multiple test pressures ($PV_p$).

The pycnometer volumes at test pressures ($PV_p$) include:

— one low-pressure test at or less than 689 kPa (100 psi);

— one high-pressure test at nominally 5 % more than the maximum expected operating pressure but less than the lower of the maximum rated pressure of the pycnometer or the rupture disk burst pressure;

— two or more pressures evenly distributed between the high and the low pressures.

If the pressure rating of the piping system in which the pycnometer is used is less than ANSI 600, the number of calibration pressures per run can be reduced to three: low, intermediate, and high.

The pycnometer should be restricted to proving at pressures less than the high-pressure test.

### C.1.2 Repeatability Tolerance

To establish the volume of the pycnometer at operating conditions, the following parameters should be determined and certified:

— the temperature and pressure coefficients needed to calculate the volume at sampling conditions;

— determination and certification completed before the pycnometer is first used and thereafter at regular intervals. To minimize hysteresis effects, these data should be determined only after the pycnometer has been pressurized to the highest pressure to which its volume is to be determined.

An acceptable calibration of the pycnometer results from performing three consecutive sequences of tests [items a) through e) below] for which each parameter repeats within 0.02 %:

a) the pycnometer evacuated weight ($W_o$);

b) the pycnometer air-filled weight ($W_a$);

c) the pycnometer volume ($PV_p$) at the datum temperature and a pressure of 689 kPa (100 psia) or less;

d) the pycnometer volume ($PV_p$) at the datum temperature and near the maximum operating pressure;

e) the pycnometer volume ($PV_p$) at the datum temperature and a pressure or pressures evenly distributed between the two pressures specified in items c) and d).

Based on the empirical data, calculate the pycnometer volume at the test temperature and pressure ($PV_{tp}$) using the following equation:

$$PV_{tp} = \left[PBV + E_p\left(P_f - P_d\right)\right] \times \left[1 + E_t\left(T_f - T_d\right)\right] \qquad \text{C.1}$$

The $PV_{tp}$ for each sequence shall agree with the average $PV_{tp}$ from all sequences within ±0.05 %.

The nominal $E_t$ values may be used for calibrations, provided that the manufacturer has confirmed a linear relationship for thermal expansion of the pycnometer. If the entities wish to confirm the nominal $E_t$ value, use the test method discussed in this Annex.

## C.2 Test Equipment

The test equipment required for laboratory calibration of a pycnometer is listed in Table C.1.

The water reservoir, water trap, and the water cushion cylinder shall be of such a capacity to allow a minimum of three consecutive calibration runs to be performed on one pycnometer, without the need to re-fill, stabilize, or empty of any of the equipment.

**Table C.1—Test Equipment for Laboratory Calibration of a Pycnometer**

| | Specifications | | | |
|---|---|---|---|---|
| **Instrument** | **Range** | **Accuracy** | **Capacity** | **Comment** |
| Analytical balance with air shield | 0 to 5000 g | ±0.01 g | | |
| Stainless steel test weights | 50 to 5000 g | ASTM E617<br>(class 0, 1, 2, or 3) | | |
| Digital thermometer | As needed | ±0.05 °C (±0.1 ºF) | | |
| Glass thermometer | As needed | ±0.05 °C (±0.1 ºF) | | |
| Vacuum gauge<br>(bourdon tube preferred) | 30 to -30 in Hg | | | 5 in Hg increments or better |
| Pressure indicating device<br>(a second device may be needed to provide sufficient resolution) | 0 to 21,000 kPa<br>(0 to 3000 psi) | 0.05 % of reading | | Transmitter with digital display preferred |
| Pressure calibration device | 0 to 21,000 kPa<br>(0 to 3000 psi) | 0.025 % of reading | | Deadweight tester preferred |
| Distilled water reservoir<br>(clear glass container) | | | 20 L (5 gal.) | |
| Water trap (clear glass beaker) | | | 7,000 $\text{cm}^3$ | |
| Water cushion cylinder | | | 250 $\text{cm}^3$ | MAWP of 21,000 kPa (3000 psi.) |
| Vacuum pump | | | 90 L/min<br>(4.5 gpm) | 1 mm Hg from ultimate vacuum |
| Stainless steel and clear vacuum tubing (OD) | | | | ≥ 6 mm (0.250 in.) |
| **Optional Equipment (for Determination of $E_t$)** | | | | |
| Temperature bath | 22 °C (40 °F) minimum between test temperatures | stability of ± 0.05 °C (0.1 ºF) | | |
| Gear pump | 0 to 23 L/min<br>(0 to 6 gpm) | | | |
| Flow meter | 0 to 23 L/min<br>(0 to 6 gpm) | | | |

## C.3 Clean the Pycnometer and Check the Test Equipment

Thoroughly clean the pycnometer and calibrate or check all test equipment in accordance with the following procedure:

a) Wash the inside of the pycnometer with an appropriate solvent, and then with acetone to remove any residual solvent.

b) Rinse the inside of the pycnometer with distilled water, then wash with acetone to remove any residual water.

c) Dry the inside of the pycnometer thoroughly by purging with dry nitrogen, then evacuate it with a vacuum pump for at least 10 minutes to remove water vapor. Close the inlet valve (it is unlikely that the pycnometer will be fully evacuated).

d) Wash the outside of the pycnometer with distilled water, then rinse with acetone. Blow-dry the outside of the pycnometer.

e) Ensure that the pressure devices have been certified in accordance with Annex B, Section B.6 and inspect them for damage.

f) Ensure that the temperature devices have been certified in accordance with Annex B, Section B.5 and verify the accuracy of the temperature devices against a certified reference temperature measurement device to assure agreement within 0.1 °C (0.2 °F).

g) Verify the weigh scale with the ASTM E617 apparent mass standards and calibrate if necessary.

## C.4 Deaerate the Water Reservoir

Fill the water reservoir and deaerate the water. Steps a) through e) illustrate one procedure, of many, used to fill and deaerate the water reservoir. The method is the choice of the calibration laboratory.

a) Set up the test apparatus as shown in Figure C.1.

b) Close Valve A and pull a vacuum on the system. The water will be displaced from the water supply container to the 20 L (5 gal) water reservoir.

c) When enough water has been displaced, turn off the vacuum pump.

d) Set up the test apparatus as shown in Figure C.2. At this time, place the pycnometer to be calibrated in close proximity to the water reservoir.

e) With Valve A closed, deaerate the distilled water by pulling a vacuum on the water reservoir until no air bubbles remain (typically, this takes 12 or more hours). Close Valve F.

f) Before proceeding with the calibration, assure that the temperatures of the water reservoir and the pycnometer have stabilized. The water reservoir does not need to be stabilized to room temperature, but the water temperature should approximate the room temperature.

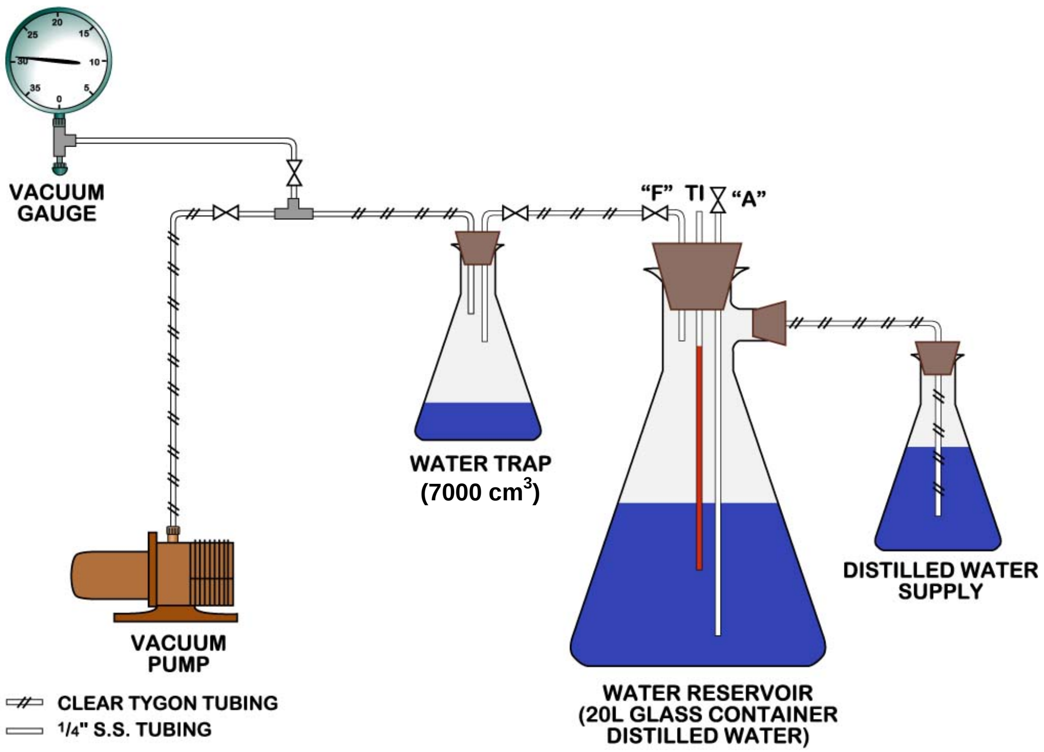


Figure C.1—Vacuum Filling the Water Reservoir (Laboratory Calibration) (optional procedure)

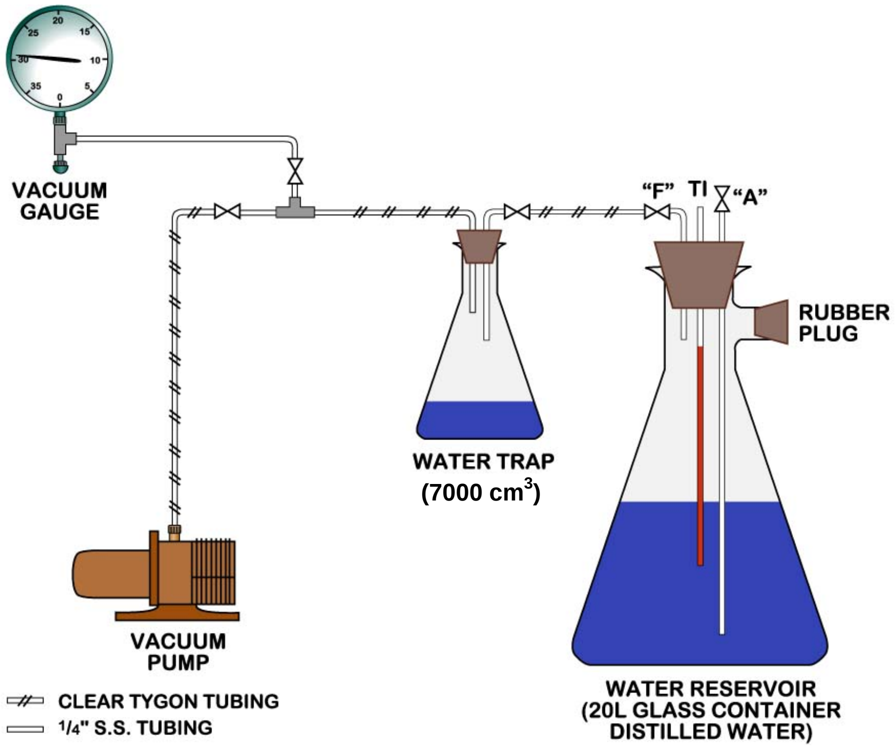


Figure C.2—Deaerating the Water Reservoir (Laboratory Calibration)

## C.5 Determine the Evacuated and Air-Filled Weight

Determine the pycnometer evacuated weight ($W_o$) and air-filled weight ($W_a$) in accordance with the following procedure:

a) Evacuate the pycnometer with the vacuum pump to a pressure approaching near vacuum of 3.1 kPa (29 in. Hg or 0.45 psia) for at least two minutes, as shown in Figure C.3.

b) Close the outlet valve on the pycnometer and the inlet valve on the vacuum tubing to the water trap.

c) Disconnect the pycnometer from the vacuum tubing.

d) Place the evacuated pycnometer on the weigh scale and record the evacuated weight ($W_o$) to the nearest 0.01 g.

e) Repeat the steps described in steps a) through d) above until two successive weighings for $W_o$ agree within 0.02 %. Record the last $W_o$ reading.

f) With the outlet valve closed, open the inlet valve and allow air to enter. After 30 seconds, close the inlet valve and weigh the pycnometer, and record the air-filled weight ($W_a$) to the nearest 0.01 g.

g) Repeat step f) until two successive weighings for $W_a$ agree within 0.02 %. Record the last $W_a$ reading.

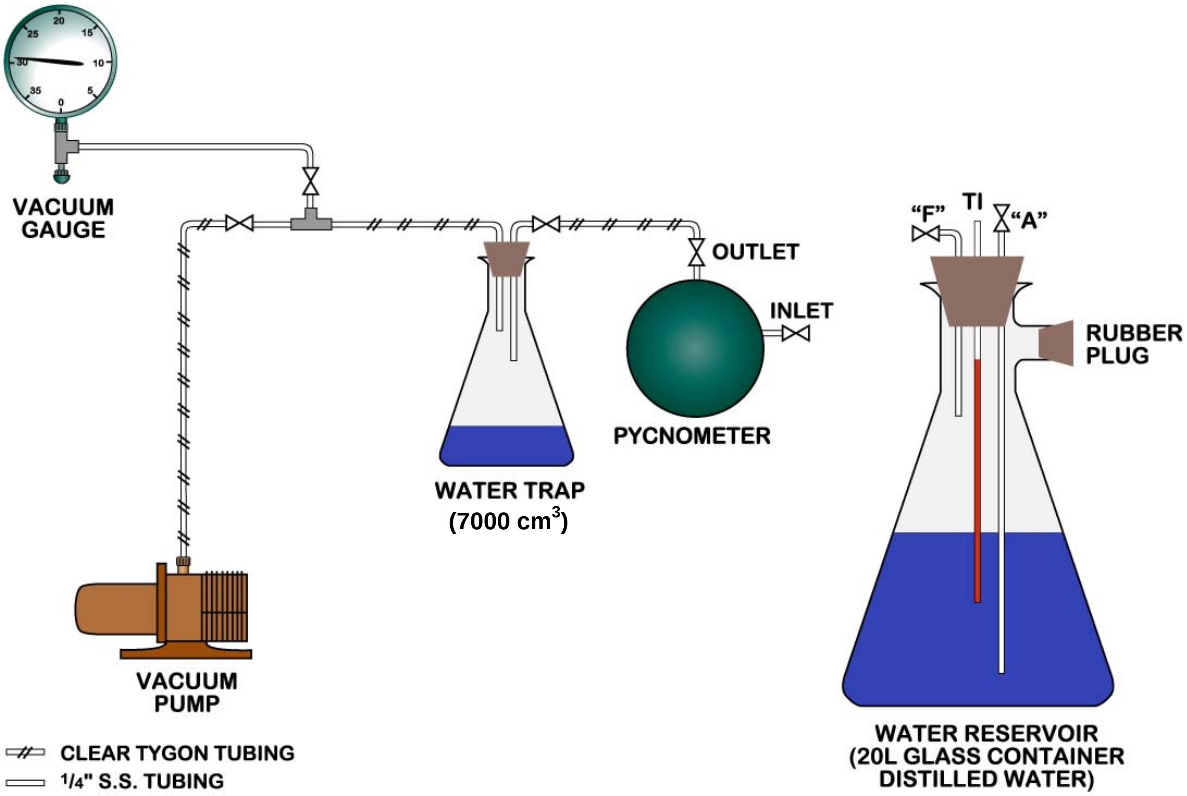


**Figure C.3—Vacuum Emptying the Pycnometer**

## C.6 Vacuum Fill the Pycnometer

Vacuum fill the pycnometer in accordance with the following procedure:

a) Install the pycnometer on the test apparatus, as shown in Figure C.4.

b) Evacuate air from the pycnometer and all stainless steel and vacuum tubing through Valves A and D to approach near vacuum of 3.1 kPa (29 in. Hg or 0.45 psia) for at least two minutes. Make sure that Valves B and F are closed.

c) Open Valve F and fill the pycnometer with distilled water from the water reservoir. When a full flow of water is observed entering the water trap, close the pycnometer outlet valve and Valve A. Open Valve B.

d) Pressurize the system to approximately 700 kPa (100 psi) below the burst pressure of the rupture disk. Check for leakage.

e) Open Valve C.

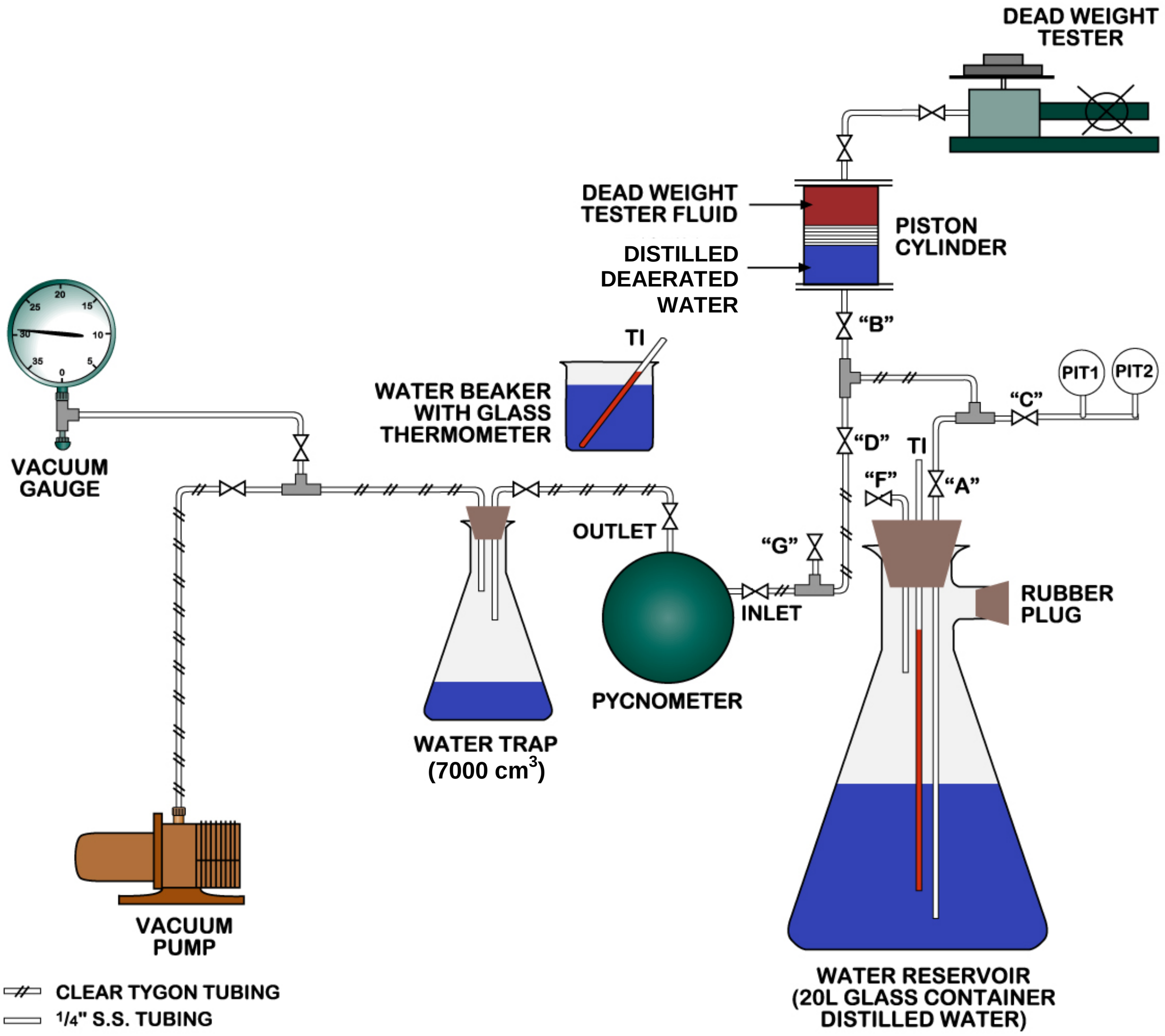


**Figure C.4—Pycnometer Calibration Test Apparatus**

## C.7 Calibrate Using the Water-Weigh Method

Verify the pycnometer water-filled weight using the water-weigh method in accordance with the following procedure:

a) Close the pycnometer outlet valve.

b) Using the deadweight tester as shown in Figure C.4, apply pressure to the pycnometer and close the pycnometer inlet valve. Monitor the supply tubing pressure for a short time to ensure that it has not changed. If it has changed, open the pycnometer inlet valve and repeat this step.

c) When the pressure is correct, close Valve D.

d) Record the water reservoir temperature, as indicated by the digital thermometer, to the nearest 0.05 °C (0.1 °F).

e) Remove the pycnometer and wash both the inlet- and outlet-valve openings with acetone to remove excess water. Blow-dry the openings with nitrogen. Wash the outside of the pycnometer with acetone. Blow-dry the outside of the pycnometer.

f) Place the water-filled pycnometer on the weigh scale and record the fluid-filled weight $(W_f)$ to the nearest 0.01 g.

g) Connect the test tubing and the pycnometer on the test apparatus as shown in Figure C.5. Open Valve G.

h) Evacuate air between Valve D and the pycnometer inlet valve through Valve G for five minutes. Close Valve B. Open Valves A and D. After a full flow of water enters the water trap, close Valves G and A. Open Valve B.

i) Open the pycnometer inlet valve.

j) Reinstall the pycnometer on the test apparatus, as shown in Figure C.4.

k) Open Valve F and fill the pycnometer with distilled water from the water reservoir. When a full flow of water is observed entering the water trap, close the pycnometer outlet valve and Valve A. Open Valve B.

l) Record the room air temperature to the nearest 0.05 °C (0.1 °F).

m) Record the temperature of the water reservoir. This temperature shall be within ±0.5 °C (1.0 °F) of the temperature initially recorded for this run.

n) Repeat the steps described in steps a) through l) until a test weight $(W_f)$ has been determined at each of the test pressures. This constitutes one run.

o) Empty the water from the pycnometer.

p) Repeat the steps described in C.3, steps b) through d); C.5; C.6; and C.7, steps a) through l). (This completes the second run.)

q) Repeat the steps described in C.3, steps b) through d); C.5; C.6; and C.7, steps a) through l). (This completes the third run.) Note that each run consists of one test at high pressure, one test at low pressure, and one or two tests at an intermediate pressure, as shown in C.1.1.

r) Calculate the run-to-run repeatability for each of the $W_o$, $W_a$, and $W_f$ weights.

s) If three consecutive calibration runs do not meet the tolerances in C.1.2, additional calibration runs are necessary until three consecutive runs meet the required tolerances.

t) Determine the weight of the field-connection-type fittings.

u) If field-connection-type fittings are to be used, the calibration certificate shall state the pycnometer $W_o$ and $W_a$ weights without fittings and the $W_{fo}$ and $W_{fa}$ weights with field-connection-type fittings.

Note that the pycnometer is not typically emptied between calibration runs.

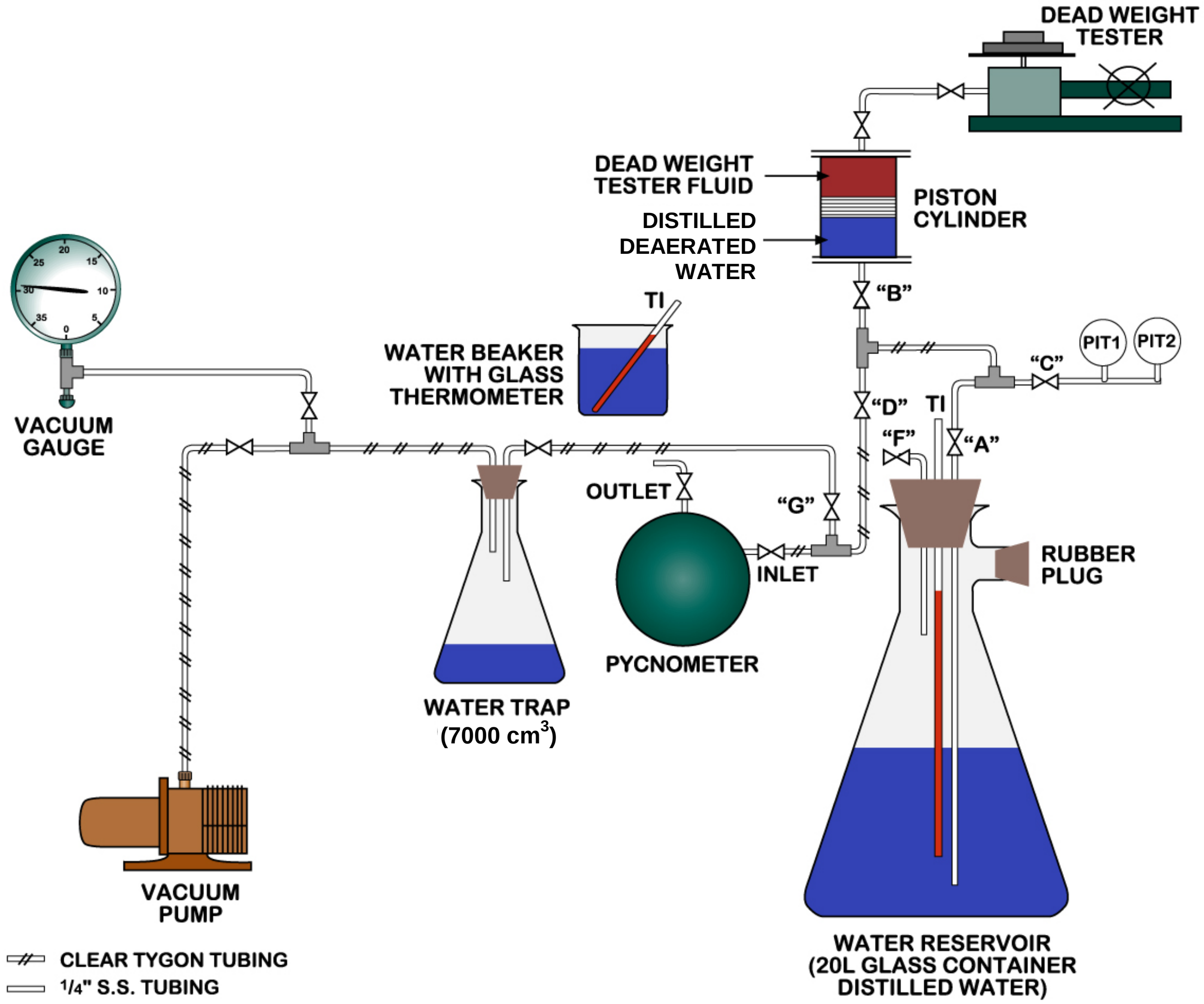


**Figure C.5—Reinstallation of Test Tubing**

## C.8 Calculate the Test Results

Establish the test results for:

a) the pycnometer air-filled weight ($W_a$) as the average of the three successful test runs reported to the nearest 0.01 g;

b) the pycnometer evacuated weight ($W_o$) as the average of the three successful test runs reported to the nearest 0.01 g;

c) the pycnometer base volume ($PBV$) as the average of the three successful test runs reported to at least five significant digits. $PBV$ is calculated using the following equation:

$$PBV = \frac{PV_{tp}}{[1+E_t(T_f - T_d)]} \qquad \text{C.2}$$

d) the coefficient of cubical expansion due to temperature on the pycnometer ($E_t$) as specified by the manufacturer for the material of construction (see Figure C.6);

e) the coefficient of cubical expansion due to internal pressure on the pycnometer ($E_p$) as the average of the three successful test runs reported to at least six decimal places. $E_p$ is calculated as the linear regression of the $PV_p$ and test pressure.

f) $$PV_{tp} = \left[PBV + E_p\left(P_f - P_d\right)\right] \times \left[1 + E_t\left(T_f - T_d\right)\right] \qquad \text{C.3}$$

## C.9 Pycnometer Certificate

A pycnometer certificate shall document the test results and include the following information and data, and meet or exceed the discrimination level. Additional results may be reported as needed. The format of the certificate and the order within each section is the choice of the user.

— Heading of certificate shall contain the following information and be located at the top of the report:

**Table C.2—Pycnometer Certificate Heading**

| Heading Information | Explanation | Discrimination and Units |
|---|---|---|
| Certifying company | Name | Alphanumeric |
| Location | Location of certifying facility | Alphanumeric |
| Date | Date certified | **SI**: YYYY-MM-DD<br>**USC**: MM-DD-YYYY |
| Certificate number | Unique number | Alphanumeric |
| Customer | | |
| Owner | | |
| Pycnometer serial no. | | Alphanumeric |
| Pycnometer manufacturer | | |
| Material of construction | | |
| Maximum working gauge pressure | | **SI**: XXXX kPa(g)<br>**USC**: XXXX psig |
| Pressure relief setting (gauge pressure) | Rupture disk pressure | **SI**: XXXX kPa(g)<br>**USC**: XXXX psig |

— Report the pycnometer weights and volume:

**Table C.3—Pycnometer Weights and Volume**

| Heading Information | Explanation | Discrimination and Units |
|---|---|---|
| Certified evacuated weight (without fittings) | $W_o$ | XXXX.XX g |
| Certified air-filled weight (without fittings) | $W_a$ | XXXX.XX g |
| Certified evacuated weight (with fittings) | $W_{fo}$ (with fittings) if so equipped | XXXX.XX g |
| Certified air-filled weight (with fittings) | $W_{fa}$ (with fittings) if so equipped | XXXX.XX g |
| Pressure coefficient of expansion | $E_p$ | SI: X.XXX E-03 $\text{cm}^3$/kPa<br>USC: X.XXX E-03 $\text{cm}^3$/psi |
| Temperature cubical coefficient | $E_t$ | SI: X.X E-05 °C<br>USC: X.XX E-05 °F |
| Datum absolute pressure | $P_d$ | SI: X.XXX kPa<br>USC: X.XXX psia |
| Datum temperature | $T_d$ | SI: X.XX °C<br>USC: X.X °F |
| Pycnometer base volume | $PBV$ at datum, base, and/or vacuum | Units: $\text{cm}^3$<br>Discrimination: XXXX.XX |

— Report each device used to calibrate the pycnometer, such as but not limited to: thermometer(s), pressure gauge(s), certified test weights, dead weight tester, scale, test stand, pressure recorder:

**Table C.4—Pycnometer Report Calibration Devices**

| Heading Information | Explanation | Discrimination and Units |
|---|---|---|
| Type | | |
| Manufacturer | | |
| Model | | |
| Serial number | | |
| Range(s) | | |
| Resolution | as applicable | |
| Accuracy | as applicable | |
| Elevation | if applicable | |
| NIST Class | if applicable | |

— Report the details of each test run for each weighing:

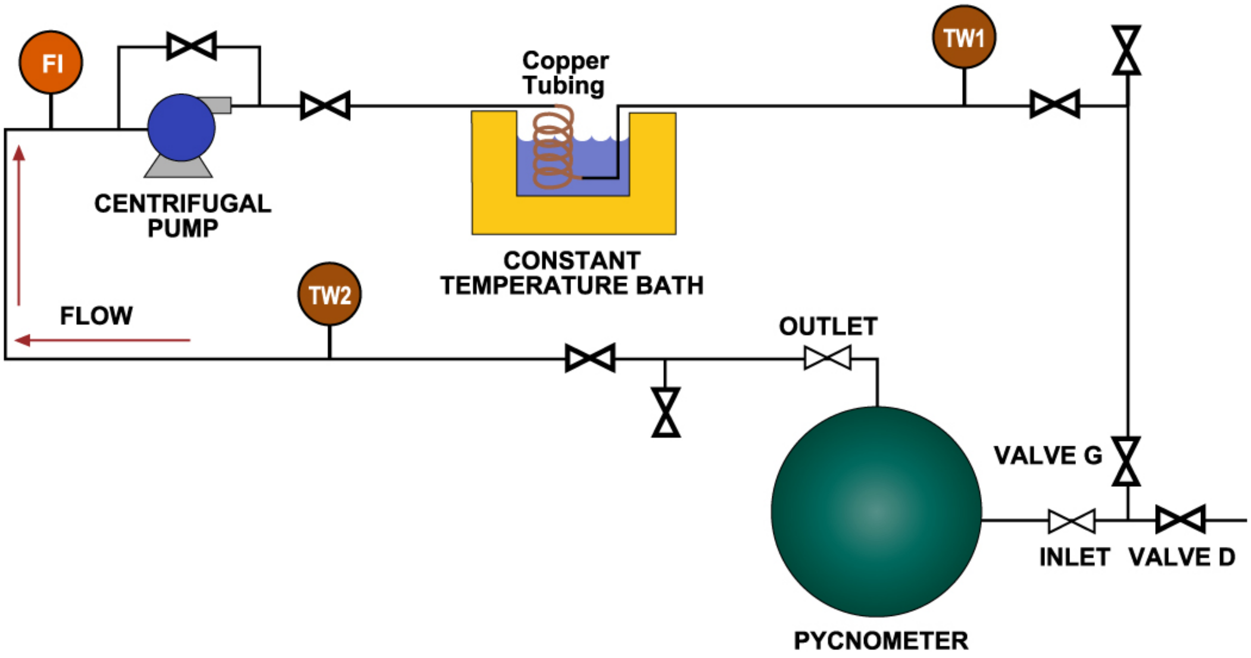
**Table C.5—Pycnometer Report Test Run Data**

| Heading Information | Explanation | Discrimination and Units |
|---|---|---|
| Weighing | 1, 2, 3, 4, etc. | |
| Gauge pressure | | SI: XXXX kPa(g)<br>USC: XXXX psig |
| Test group | A, B, etc. | |
| Average $PV_p$ | | XXX.XX $cm^3$ |
| Repeatability | | X.XXX % |

## C.10 Determination of the Thermal Expansion Factor ($E_t$)

The pycnometer thermal expansion factor ($E_t$) shall be supplied by the manufacturer. However, if the nominal $E_t$ cannot be substantiated by the manufacturer, tests may be conducted to determine the thermal expansion of the pycnometer (see Figure C.6). Conduct a minimum of two temperature tests at least 22.0 °C (40 °F) apart.

Calibration and calculation procedures are purposely not included for the $E_t$ determination test. The $E_t$ for any pycnometer should not change as long as the materials used remain consistent in their thermal expansion properties.



NOTE All flowing tubing, all valves, and the pycnometer shall be insulated to maintain a stable temperature.

Figure C.6—Optional $E_t$ Test Apparatus

# Annex D
(normative)

# Density Meter Proving—Pycnometer Method

## D.1 Purpose

The following describes the equipment, procedure, and calculations for proving density meters using pressure pycnometers.

## D.2 Introduction

This procedure captures a representative sample of the fluid flowing in the density meter and determines the density of the sampled fluid. The accuracy of the proving system is vitally important in obtaining a successful pycnometer proving. To achieve this accuracy, all test equipment shall be calibrated or verified prior to use.

During proving, the density deviation between the sample point, density meter, and pycnometer shall not exceed 0.05 %.

There are many possible configurations in which pycnometers may be used (refer to 10.10.5, which illustrates various installation configurations). One possible system allows the liquid that has flowed through the pycnometer to return to the pipeline. When thermal stability and its resulting repeatability cannot be achieved using the preferred installations shown in 10.10.5, it may be necessary to divert flow to a safe drain or flare system in order to achieve an adequate flow through the density meter and pycnometers.

If the density varies by more than 0.05 % over the period of time needed to fully stabilize the pycnometer, it is not likely that a prover repeatability of 0.05 % will be obtained for three consecutive proving runs. For this situation, the entities may agree to take one or both of the following approaches:

a) Average the results of several provings.

b) Increase the repeatability tolerance.

The accuracy of the measurement may suffer as a result of this practical approach.

## D.3 Description of Apparatus

### D.3.1 General

A flow-through pressure pycnometer, a weigh scale, test weights, and temperature- and pressure-measuring devices are required to perform a pycnometer proving of a density meter.

A flow-through pressure pycnometer is a vessel whose pycnometer base volume (PBV) and evacuated weight ($W_o$) are precisely known and have been determined and certified in accordance with Annex C.

The evacuated weight ($W_o$), temperature ($E_t$) and pressure ($E_p$) coefficients, and pycnometer base volume (PBV) for the pycnometer are quoted on its calibration certificate. These values are unique to each pycnometer, and care should be taken to ensure that the correct and current calibration data are used.

### D.3.2 Preparation for Use of the Electronic Scale

Place the scale on a level, stable, vibration-free surface. The scale shall be level in both horizontal axes prior to use. After energizing the weigh scale, allow sufficient time for the scale to reach temperature stability. Follow the manufacturer’s recommendations.

Before first use or once per day, whichever is less frequent, scales shall be verified with certified test weights (apparent mass standards) and calibrated when found outside of the tolerance specified by the scale manufacturer. This will assure accuracy and avoid weighing errors due to local gravitational forces. If this verification finds the scale exceeding the tolerance, consider whether previous provings may be in error.

A single verification may be acceptable if multiple provings are performed within the same day/shift and:

- the scale is not moved;
- the scale remains energized;
- the scale remains in a temperature-stabilized environment.

It is essential that the scale be energized and stabilized before calibration or adjustment in accordance with the manufacturer’s instructions.

Verification of the scale is required when the weigh scale is relocated or when power is lost during the procedure.

The effect of air currents on the scale’s measurement shall be negated. This may require the use of an air shield or other controls.

Use a pycnometer holding tray for centering and stabilizing the pycnometer during weighing and providing a repeatable location for the pycnometer.

Certified test weights shall conform to the accuracy requirements of Annex J.

### D.3.3 Temperature Determination

Temperature determination shall be made with a device accurate to 0.1 °C (0.2 °F) and traceable to a NMI. Electronic devices are preferred because of their resolution and stability.

To eliminate biases caused by different temperature-measuring devices at all temperature-measurement points, verify that each device measures the same temperature at near the test temperature, or use the same device after it has reached temperature stability. A differential temperature device is preferred where the difference in temperature between two points is specified.

Determine that the difference in fluid temperature at the volume meter, density meter, and the pycnometer is not greater than the sensitivity tolerance for the fluid. To achieve this, temperature shall be measured at the following positions:

- at the outlet of the volume meter;
- at the inlet or outlet of the density meter;
- at the inlet or outlet of the pycnometer.

### D.3.4 Pressure Determination

Pressure determination shall be made with a device accurate to 6.9 kPa (1 psi) and traceable to a NMI. Electronic devices are preferred because of their resolution and stability. A differential-pressure device is preferred where the difference in pressure between two points is specified.

Determine that the difference in fluid pressure at the volume meter, density meter, and pycnometer is not greater than the sensitivity tolerance for the fluid. To achieve this, pressure may have to be measured at the following positions:

— at the outlet of the volume meter;

— at the inlet and outlet of the density meter;

— at the inlet and outlet of the pycnometer.

## D.4 Proving Density Meters

### D.4.1 General

Proving density meters using a pycnometer requires capturing a representative sample in a pycnometer. A representative sample requires replication of the operating temperature and pressure conditions at the density meter. When the temperature and pressure have stabilized across the density meter and pycnometer, the valves on the pycnometer are closed to capture the sample, and the density meter reading is recorded at this time to be compared with the density determined by the pycnometer.

The pycnometer is installed in parallel or in series with the density meter to be proved. If necessary, a regulating device shall be installed downstream of the pycnometer assembly in such a way as to maintain stable temperature and pressure in the pycnometer within the sensitivity tolerance required by the fluid. The flow rate through the pycnometer should be monitored and controlled to capture a representative sample. The pycnometer and its piping may require insulation to ensure that the sample remains at the density meter operating conditions. Use caution when there is a significant pressure drop downstream of the pycnometer; this may cause a temperature drop in the pycnometer due to auto-refrigeration.

For most applications, the pycnometer is installed in series with the density meter. For some applications, such as when there is insufficient pressure drop to ensure thermal stability when flowing through the meter, density meter, and the pycnometer, the pycnometer is installed in parallel with the density meter. It is critical that the flowing temperature and pressure be maintained within the specified tolerances of 0.1 °C (0.2 °F) and 6.9 kPa (1 psi) or as indicated in Annex A.

**CAUTION Ensure that a rupture disk is part of the pycnometer assembly. When the pycnometer is full, and until it is emptied, rigorous temperature control should be maintained to avoid a pressure buildup.**

### D.4.2 Method

#### D.4.2.1 Overview

The pycnometer may be installed either in series with the density meter or in a parallel slipstream. Irrespective of the configuration used, it is essential that the sample trapped in the pycnometer be at the same temperature and pressure as that in the density transducer. Determine that the difference in fluid temperature at the volume meter, density meter, and pycnometer is not greater than the sensitivity tolerance for the fluid. To achieve this, measure the temperature at the following positions:

— at the outlet of the volume meter;

— at the inlet and outlet of the density meter;

— at the inlet and outlet of the pycnometer.

It is also important to ensure that at no time is flow through the density transducer reduced to such an extent or increased to such an extent that the density reading is affected.

The inlet and outlet of the pycnometer assembly should be connected using tubing (usually stainless steel) that has a nominal diameter of 12 mm (½ in.) or greater. The length should be kept as short as practical, and the tubing should be thermally insulated to minimize heat loss. High-pressure hoses may be used, provided that the hoses are compatible with the process fluids, temperature, and pressure. The sequence of connections is shown below:

1) Couple the pycnometer unit to the density measurement system and flush the connecting piping.

2) Close the outlet valves.

3) Open the inlet valves, checking the system for leaks.

4) When a flow indicator is used, throttle the outlet as necessary to provide sufficient flow.

5) Flow the product until the inlet and outlet temperature are less than 0.1 °C (0.2 °F) difference (unless the sensitivity of the fluid to temperature or pressure allows or requires a different tolerance).

The flow should be adjusted so that there is no accumulation of gas, no solid particles, no product separation, and no water drop-out in the pycnometer. The pressure differential across the pycnometer should be sufficient to achieve thermal equilibrium with the line temperature within a reasonable time period, but not so great as to allow gas breakout to occur. Maintain this flow until the temperature of the pycnometer and the density transducer are within the limits defined above or in Annex A.

#### D.4.2.2 Density Stability/System Stability

Pycnometer proving of density meters should be carried out only when conditions are reasonably stable. A rapid and large variation in density will make it difficult to achieve proving repeatability criteria.

#### D.4.2.3 Fluid Behavior

Fluid behavior, along with its impact on the performance of the pycnometer, should be evaluated. Errors may be introduced during filling, operation, or emptying as a result of the following factors:

a) polymerization;

b) liquid–liquid separation, including lubricating oil or glycol adhering to the inside of the pycnometer;

c) auto-refrigeration, its effect on the time required to reach temperature stability, and the possibility of hydrate formation.

To eliminate auto-refrigeration, the pycnometer and its piping may be preloaded with an inert gas at a pressure sufficient to prevent the phenomenon.

### D.4.3 Proving procedure

#### D.4.3.1 General

The sections below outline the proving of a density meter installed as shown in Section 11.

### D.4.3.2 Cleaning the Pycnometer

The pycnometer should be thoroughly washed with a suitable solvent prior to use. Cleaning and drying instructions are shown below.

**CAUTION Some solvents are toxic, flammable, or both. Take precautions as specified by local regulations.**

The following procedure shall be performed to clean the pycnometer:

1) Wash the inside of the pycnometer with a suitable cleaning agent(s) that completely evaporates to remove any residue.

2) Dry the inside of the pycnometer thoroughly by purging with clean, dry air or nitrogen for several minutes to evaporate or displace the cleaning agent(s).

3) Wash the outside of the pycnometer with distilled water. Rinse with a cleaning agent that evaporates completely. Dry the outside of the pycnometer with filtered dry air or nitrogen.

Particular care should be taken to ensure that no hydrocarbon, water, or contaminant is trapped in the valve ends or valve retaining assemblies. This is not normally required for volatile products, such as LPG or NGL.

All cleaning agents and solvents should be chosen to be compatible with valve components; consult the manufacturer's guide.

### D.4.3.3 Calibrating and Checking Test Equipment

The following procedure shall be performed to calibrate and check the test equipment:

a) Verify the scale at zero, within 500 g of the maximum weight of the fluid-filled pycnometer weight, and a point midway between these values using the certified test weights. Calibrate the weigh scale, if required, using the certified test weights (Annex J).

b) Verify the operation of the temperature and pressure devices.

## D.4.4 Verify the Pycnometer Evacuated Weight ($W_o$)

The procedure involves a comparison of the evacuated weight of the pycnometer with the evacuated weight on the certificate. This can be accomplished either by measuring the tare weight of the evacuated pycnometer or calculating the evacuated weight by weighing the air-filled tare weight and subtracting the calculated weight of the contained air.

For the second method, weigh the empty pycnometer with the valves open. The tare weight should not differ from the certified weight quoted on the pycnometer calibration certificate by more than 0.02 %.

If the tare weight is found to be greater than that quoted on the calibration certificate, the cleaning procedure has been insufficiently thorough. If the tare weight has decreased, damage or missing components should be suspected.

After cleaning and reassembly of the pycnometer, and only if using the original hardware, the tare weight should be verified. If the pycnometer volume or tare weight has changed by more than 0.02 %, a recalibration is required. Complete recalibration is required if replacement parts are used when reassembling.

The field $W_o$ without fittings shall be calculated using the following equation:

$$Field\ W_o = Field\ W_a - \rho_A \times PBV \qquad \text{D.1a}$$

Where:

$W_o$ = weight of pycnometer with all air evacuated (without fittings)

$W_a$ = weight of air-filled pycnometer (without fittings)

$PBV$ = pycnometer base volume, pycnometer volume at datum pressure and datum temperature

Compare the field $W_o$ with the certificate $W_o$. If the difference exceeds 0.02 %, the pycnometer shall not be used.

The field $W_{fo}$ (with fittings) shall be calculated using the following equation:

$$Field\ W_{fo} = Field\ W_{fa} - \rho_A \times PBV \qquad \text{D.1b}$$

Where:

$W_{fo}$ = weight of pycnometer with all air evacuated (with fittings)

$W_{fa}$ = weight of air-filled pycnometer (with fittings)

$PBV$ = pycnometer base volume, pycnometer volume at datum pressure and datum temperature

Compare the field $W_{fo}$ with the certificate $W_{fo}$. If the difference exceeds 0.02 %, the pycnometer shall not be used.

The procedure in steps a) through g) below shall be performed to verify the pycnometer evacuated weight. This value may be verified with ($W_{fo}$) or without ($W_o$) the pycnometer fittings.

The calibration certificate may state two evacuated weights that may be identified as $W_o$ and further described as weights "with" and "without" fittings. The values on the calibration certificate may be stated as follows:

- evacuated weight ($W_o$);
- evacuated weight with fittings ($W_{fo}$);
- the fittings used to determine "weight with fittings" are the fittings supplied and sent with the pycnometer to the calibration laboratory.

a) Place the air-filled pycnometer on the weigh scale and record the scale's reading. If weighing without fittings, use b); if weighing with fittings, use c).

b) Compare the field $W_o$ and verify that it does not differ from the certificate value by more than 0.02 %.

c) Compare the field $W_{fo}$ and verify that it does not differ from the certificate value by more than 0.02 %.

d) If the field $W_o$ or $W_{fo}$ differ from the certificate value by more than 0.02 %, verify the calculations, recheck the scale, or both.

e) If the field $W_o$ has increased more than 0.02 % from the certificate value, the pycnometer has been insufficiently cleaned and dried. Continue to clean the pycnometer until the $W_o$ variance is less than or equal to 0.02 %.

f) If the field $W_{fo}$ has increased more than 0.02 % from the certificate value, the pycnometer has either been insufficiently cleaned and dried, or the fittings' weight is incorrect. Continue to clean the pycnometer until the $W_{fo}$ variance is less than or equal to 0.02 %. If it is suspected that the fittings' value is the cause of the variance greater than 0.02 %, the fittings should be removed, inspected, and reweighed. The field $W_o$ should then be verified against the certificate value. The fittings should then be reattached to the pycnometer and the $W_{fo}$ can then be verified.

g) If the field $W_o$ or $W_{fo}$ has decreased by more than 0.02 % from the certificate value, either the pycnometer has been damaged or the fittings' weight is incorrect. Remove the fittings to verify possible damage. If the pycnometer is damaged, it shall not be used.

### D.4.5 Installing the Pycnometer

The following procedure shall be performed to install the pycnometer or pycnometers:

1) Install the pycnometer in series with the density meter or in a parallel slipstream. Allow the product to enter the upstream pycnometer valves first. With the downstream valve closed, allow the pressure to build slowly until the flowing pressure is reached. At this point, open the downstream valve and allow fluid to flow through the pycnometer.

2) When the pycnometer is filled with fluid, slowly close the bypass valve to initiate flow, and continue until fully closed.

3) Use a double-wall vacuum sphere pycnometer, which may not require the use of additional insulating devices.

NOTE Insulating the pycnometer and/or its connections can speed temperature stabilization and prevent water condensation on the exterior surfaces.

Connecting lines should be of material, pressure rating, and length to suit the application and installation and, for normal usage, a minimum internal diameter of 12.7 mm (0.5 in.) is recommended. Narrower bore lines may be needed for ease of handling on high-pressure systems carrying low-viscosity products. Smooth-bore lines should be used and fitted with female quick-fit connectors capable of mating securely with the male connections on the pycnometers.

### D.4.6 Verifying Density Deviation and Stability

The following procedure shall be performed to verify density deviation and stability:

a) Observe the output of the density meter for several minutes to verify steady-state density conditions.

b) When temperature and pressure differences between the density meter and the pycnometer or pycnometers have stayed within the criteria given in 10.10.3 and D.4.2.1 for a sufficient period of time, record the following field data:

    1) density (density meter output);

    2) density meter temperature;

    3) pycnometer temperature;

    4) density meter pressure;

    5) pycnometer pressure.

c) Partially open the pycnometer bypass valve, immediately close the pycnometer outlet valve, then close the inlet valve.

d) Remove the pycnometer from the sample system piping and check for leakage. Any leakage from a pycnometer shall void the test.

### D.4.7 Determining the Fluid-filled Weight

The following procedure shall be performed to determine the pycnometer fluid-filled weight ($W_f$) without fittings or ($W_{ff}$) with fittings:

To prevent operation of the rupture disk, the time required for removing the pycnometer, weighing, re-installing, or emptying it in a safe location should be kept to a minimum.

a) Remove the pycnometer from the proving connections.

b) Remove any additional insulation.

c) If necessary, wash both valve openings and the outside of the pycnometer. Blow dry with nitrogen. Repeat, if necessary, until the outside of the pycnometer is completely dried.

d) Place the pycnometer on the weigh scale and record the weight. It should be weighed to the nearest 0.01 % of the liquid weight, taking care in handling to avoid contaminating the clean surfaces. Two successive weight checks should agree to within 0.02 g.

### D.4.8 Calculating the Density Meter Correction Factor

The following procedure shall be performed to calculate the density meter correction factor:

a) Calculate the density meter correction factor (DMF) in accordance with the instructions given in D.4.10.

b) Repeat the steps described in D.4.4, D.4.5, D.4.6, and D.4.7 above to obtain the second consecutive DMF.

c) Repeat the steps described in D.4.4, D.4.5, D.4.6, and D.4.7 above to obtain the third consecutive DMF.

d) Calculate the repeatability. A successful proving requires that the DMFs for three consecutive proving runs not differ by more than 0.05 %.

e) When three successful consecutive provings have been performed, calculate the average DMF.

f) For applications in which the density meter's output is adjusted, other than by the use of a DMF, an additional proving run shall be performed to confirm that the adjusted density meter's output does not differ from the new test's result by more than 0.05 %. However, it is the user’s option to run a separate verification proving run if so desired.

### D.4.9 Emptying the Pycnometer

The following procedure shall be performed to empty the pycnometer or pycnometers.

For some applications, the steps described in items b) and c) below may be waived if agreed upon by the entities involved.

a) Empty the pycnometer in a safe location by either venting or flaring the contents.

b) Clean the pycnometer in accordance with D.4.3.2.

c) Verify the pycnometer evacuated weight ($W_o$) using the procedures described in D.4.4. If the pycnometer evacuated weight differs from the certificate value by more than 0.02 %, one should consider additional cleaning procedures to achieve the criteria or the test results are invalid.

d) When the pycnometer is empty, it is recommended that the pycnometer be stored in its carrying case for protection, and the valve stems should be loosened to avoid distortion of the valve seats.

Safety considerations demand that, after satisfactory confirmation of the tare weight, the pycnometer is completely purged with nitrogen to expel all the air in readiness for validating the density transducer. When sampling high-vapor-pressure liquids, it may be necessary to pre-pressurize the pycnometer with nitrogen to prevent expansion chilling when connecting to the system.

**CAUTION Before making pipe connections, ensure that the pipes are in good condition. The connections should be properly made and any restraining or safety device properly used.**

## D.4.10 Calculation Procedures

### D.4.10.1 General

The steps described in this subsection outline the appropriate calculation procedures for proving density meters by the use of pycnometers.

From the pycnometer certificate, obtain the following data:

a) the pycnometer air-filled weight ($W_a$) without fittings or ($W_{fa}$) with fittings;

b) the pycnometer evacuated weight ($W_o$) without fittings or ($W_{fo}$) with fittings;

c) the pycnometer base volume ($PBV$);

d) the coefficient of cubical expansion due to temperature on the pycnometer ($E_t$);

e) the coefficient of cubical expansion due to pressure on the pycnometer ($E_p$);

f) the datum pressure of the pycnometer ($P_d$);

g) the datum temperature ($T_d$).

If the pycnometer fluid-filled weight ($W_f$) was determined with the fittings attached, use the certified values for ($W_{fo}$) and ($W_{fa}$) with fittings for calculation purposes.

In addition, obtain the following data:

h) the elevation of the weigh scale above sea level ($H$);

i) the density of the reference test weights ($\rho_{TWr}$);

j) the density of the field test weights ($\rho_{TWf}$);

k) the existing density meter factor (DMF).

A minimum of three consecutive proving runs is required; obtain the following data for each proving run:

l) the density meter's density reading;

m) the pycnometer air-filled weight ($W_a$);

n) the pycnometer fluid-filled weight ($W_f$);

o) the flowing pressure at test ($P_f$);

p) the flowing temperature at test ($T_f$).

### D.4.10.2 Calculate Air Density

For proving of density meters by pycnometers, the dry air density may be calculated using equations D.2 for USC units or D.3 for SI units:

$$\rho_A = 0.0012\left[1 - \frac{(0.032 \times H)}{1000}\right] \qquad \text{D.2}$$

$$\rho_A = 0.0012\left[1 - \frac{(0.105 \times H)}{1000}\right] \qquad \text{D.3}$$

For a given proving location, the air density is constant. As a result, the air density need only be calculated once.

### D.4.10.3 Calculate Pycnometer Flowing Volume ($PV_{tp}$)

The $PV_{tp}$ shall be calculated using one of the following equations:

When $P_f$ is in absolute pressure units:

$$PV_{tp} = \left[PBV + E_p\left(P_f - P_d\right)\right] \times \left[1 + E_t\left(T_f - T_d\right)\right] \qquad \text{D.4}$$

When $P_f$ is in gauge pressure units:

$$PV_{tp} = \left[PBV + E_p P_f\right] \times \left[1 + E_t\left(T_f - T_d\right)\right] \qquad \text{D.5}$$

Where:

$W_a$ = weight of air-filled pycnometer (without fittings)

$W_o$ = weight of pycnometer with all air evacuated (without fittings)

$PBV$ = pycnometer base volume, pycnometer volume at datum pressure and datum temperature

$E_t$ = coefficient of cubical expansion due to temperature on the pycnometer

$E_p$ = coefficient of cubical expansion due to pressure on the pycnometer

$P_d$ = datum pressure of pycnometer (absolute pressure: 14.696 psia or 101.325 kPa), (gauge pressure: 0 psig or 0 kPa)

$T_d$ = datum temperature (0.0 °F or –17.78 °C)

$P_f$ = pressure at flowing conditions (during test)

$T_f$ = temperature at flowing conditions (during test)

### D.4.10.4 Calculate Apparent Mass of Fluid ($AM_{fl}$)

The apparent mass of the fluid ($AM_{fl}$) shall be calculated using the following equation:

$$AM_{fl} = W_f - W_o \qquad \text{D.6}$$

Where:

$W_o$ = weight of pycnometer with all air evacuated (without fittings)

$W_f$ = weight of fluid-filled pycnometer (without fittings)

### D.4.10.5 Correct for Air Buoyancy on Test Weights ($C_{bw}$)

In order that the weighings can be corrected for air buoyancy, the elevation ($H$) has to be known for the test site.

The $C_{bw}$ for field provings shall be calculated using the following equation:

$$C_{bw} = 1 - \frac{\rho_A}{\rho_{TWF}} \qquad \text{D.7}$$

Where:

$\rho_{\text{TWF}}$ = density of the field test weights

A constant value for $C_{bw}$ may be used for a specific site and test equipment.

### D.4.10.6 Determine Mass of Fluid ($M_{fl}$)

The mass of the fluid ($M_{fl}$) shall be calculated using the following equation:

$$M_{fl} = \left(W_f - W_o\right) \times C_{bw} \qquad \text{D.8}$$

Where:

$W_f$ = weight of fluid-filled pycnometer (without fittings)

$W_o$ = weight of pycnometer with all air evacuated (without fittings)

$C_{bw}$ = correction for air buoyancy on weighing

### D.4.10.7 Determine Density at Test Conditions ($\rho_{ftp}$)

The value for $\rho_{ftp}$ shall be calculated using the following equation:

$$\rho_{ftp} = \frac{M_{fl}}{PV_{tp}} \qquad \text{D.9}$$

Where:

$M_{fl}$ = mass of fluid

$PV_{tp}$ = pycnometer volume at test temperature and test pressure

If necessary, convert the density to the appropriate units. Refer to Annex G.

### D.4.10.8 Determine Density Meter Factor (DMF)

#### D.4.10.8.1 General

The DMF shall be calculated using the following equation, with $\rho_{ftp}$ in the same units as the density meter's reading:

$$DMF = \frac{\rho_{ftp}}{test\ density} \qquad \text{D.10}$$

Where:

$\rho_{ftp}$ = density of fluid at test temperature and test pressure

#### D.4.10.8.2 Determine Results of Second and Third Proving Runs

Repeat the calculations in D.4.10.3 to D.4.10.8 for the second proving run.

Repeat the calculations in D.4.10.3 to D.4.10.8 for the third proving run.

#### D.4.10.8.3 Determine Repeatability of Results

The repeatability of the results can be calculated using the following equation:

$$\% = \frac{Maximum\ DMF - Minimum\ DMF}{Minimum\ DMF} \times 100 \qquad \text{D.11}$$

Where:

DMF = density meter factor

For a successful test, the DMFs for three successive proving runs shall not differ by more than 0.05 %.

### D.4.10.9 Calculate New DMF

The average DMF value shall be calculated using the following equation:

$$DMF_{average} = \frac{(DMF_{Run\ 1} + DMF_{Run\ 2} + DMF_{Run\ 3})}{3} \qquad \text{D.12}$$

Where:

DMF = density meter factor

The method of applying the average DMF to the custody transfer quantities depends on the secondary equipment that converts the density meter's raw output to engineering units, the mass flow integrating equipment, and the accounting policies of the operator. The equipment manufacturers should be consulted to ensure the correct application of the proving results.

All entities should agree on the method by which the average DMF is to be applied to the custody transfer quantities prior to commencement of movements. The average DMF should be applied in the flow computer as shown in Figure 18, and the resultant density used in any subsequent calculation process is a Factored Density value.

At a minimum, the density meter proving report shall include the following information and/or data. The units and discrimination level required are shown in addition.

### D.4.10.10 Density Meter Proving Report

The heading of the report shall contain the following information and be located at the top of the report:

**Table D.1—Proving Report Heading**

| Heading Information | Explanation | Discrimination Level |
|---|---|---|
| Company | Name of facility owner | Alphanumeric |
| Location | Location of facility | Alphanumeric |
| Proving date | Date proving was accomplished | **SI**: YYYY-MM-DD<br>**USC**: MM-DD-YYYY |

Data required to identify the density meter that is being proved:

**Table D.2—Proving Report Density Meter Data**

| Heading Information | Explanation | Discrimination Level |
|---|---|---|
| Density meter model | — | Alphanumeric |
| Density meter serial number | — | Alphanumeric |
| Density meter location/identification | Local designation/identification of density meter being proved | Alphanumeric |
| Density meter product | Product flowing through pycnometer during prove | Alphanumeric |

Data required to identify/calculate various factors utilized in the field calibration process or by the field calibration scale:

**Table D.3—Proving Report Field Calibration Data**

| Heading Information | Explanation | Discrimination Level |
|---|---|---|
| Density of field test weights ($\rho_{\mathrm{TWf}}$) | g/cm$^3$ @ 20 °C | Numeric (x.xx) |
| Elevation above sea level at test site ($H$) | Height above sea level | Numeric (x.xxx.0) |
| Air density at test site ($\rho_{\mathrm{A}}$) | g/cm$^3$ | Numeric (0.xxxxx) |
| Correction for air buoyancy on weighing ($C_{bw}$) | — | Numeric (0.xxxxxx) |

Data required to identify the pycnometer being used in the proving process:

**Table D.4—Proving Report Pycnometer Identification Data**

| Heading Information | Explanation | Units/Discrimination Level |
|---|---|---|
| Pycnometer serial no.: | | Alphanumeric |
| Pycnometer certificate calibration no.: | | Numeric |
| Pycnometer certification date: | | SI: YYYY-MM-DD<br>USC: MM-DD-YYYY |
| Pycnometer base volume | $PBV$ | Units: $cm^3$<br>Discrimination: XXXX.XX |
| Certified evacuated weight (without fittings) | $W_o$ | Units: g<br>Discrimination: XXXX.XX |
| Certified air-filled weight (without fittings) | $W_a$ | Units: g<br>Discrimination: XXXX.XX |
| Certified evacuated weight (with fittings) | $W_{fo}$ | Units: g<br>Discrimination: XXXX.XX |
| Certified air-filled weight (with fittings) | $W_{fa}$ | Units: g<br>Discrimination: XXXX.XX |
| Coefficient of cubical expansion due to pressure on pycnometer | $E_p$ | Units:<br>SI: $cm^3$/kPa<br>USC: $cm^3$/psi<br>Discrimination:<br>SI: X.XXX E-03<br>USC: X.XXX E-03 |
| Coefficient of cubical expansion due to temperature on pycnometer | $E_t$ | Units:<br>SI: 1/°C<br>USC: 1/°F<br>Discrimination:<br>SI: X.X E-05<br>USC: X.XX E-05 |
| Datum pressure of pycnometer<br>(absolute pressure: 14.696 psia or 101.325 kPa)<br>(gauge pressure: 0 psig or 0 kPa) | $P_d$ | Units:<br>SI: kPa<br>USC: psi<br>Discrimination:<br>SI: X.XXX<br>USC: X.XXX |
| Datum temperature of pycnometer<br>(0.0 °F or –17.78 °C) | $T_d$ | Units:<br>SI: °C<br>USC: °F<br>Discrimination:<br>SI: X.XX<br>USC: X.X |

Data required to calculate the density meter factor during the proving process:

— The preferred units to be utilized in developing the density meter factor (DMF) are SI units.

— Utilizing the SI system, the nominal units for density expression are $kg/m^3$. However, it is normal practice in North America to use $g/cm^3$.

— It is recommended that the USC units of $lb/ft^3$ not be used to express flowing density in the determination of the density meter factor.

## Table D.5—Proving Report Proving Data and Calculations

| | | | **Run 1** | **Run 2** | **Run 3** |
|---|---|---|---|---|---|
| **Flowing Conditions** | | | | | |
| 1 | Flowing density ($\rho_{ftp}$ with existing DCF) | kg/m$^3$<br>g/cm$^3$<br>lb/ft$^3$ | x.x<br>x.xxxx<br>x.xxx | x.x<br>x.xxxx<br>x.xxx | x.x<br>x.xxxx<br>x.xxx |
| 2 | Density meter temperature | °C<br>°F | x.x<br>x.x | x.x<br>x.x | x.x<br>x.x |
| 3 | Density meter gauge pressure | kPa<br>psig | x<br>x | x<br>x | x<br>x |
| 4 | Pycnometer temperature at flowing conditions, $T_f$ | °C<br>°F | x.x<br>x.x | x.x<br>x.x | x.x<br>x.x |
| 5 | Pycnometer pressure at flowing conditions (gauge), $P_f$ | kPa<br>psig | x<br>x | x<br>x | x<br>x |
| **Pycnometer Volume** | | | | | |
| 6 | Serial number | | VIP160 | VIP160 | VIP160 |
| 7 | Pycnometer base volume, pycnometer volume at datum pressure and datum temperature | cm$^3$ | x.xx | x.xx | x.xx |
| 8 | $E_p$ x $P_f$ | cm$^3$ | x.xx | x.xx | x.xx |
| 9 | $PV_p$ = line 7 + line 8 | cm$^3$ | x.xx | x.xx | x.xx |
| 10 | $C_{tsp} = 1 + [(E_t \times (T_f - T_d)]$ | | 1.xxxxx | 1.xxxxx | 1.xxxxx |
| 11 | $PV_{tp}$ = line 9 x line 10 | cm$^3$ | x.xx | x.xx | x.xx |
| **Mass of Fluid** | | | | | |
| 12 | Weight of fluid-filled pycnometer (without fittings), $W_f$ | g | x.xx | x.xx | x.xx |
| 13 | Weight of air-filled pycnometer (without fittings), $W_a$ | g | x.xx | x.xx | x.xx |
| 14 | Weight of air, $\rho_A$ x $PBV$ | g | 1.xxxxx | 1.xxxxx | 1.xxxxx |
| 15 | Weight of pycnometer with all air evacuated (without fittings), $W_o$ = (line 13–line 14) | g | x.xx | x.xx | x.xx |
| 16 | Mass ($M_{fl}$) = (line 12–line 15) x $C_{bw}$ | g | x.xx | x.xx | x.xx |
| **Density of Fluid** | | | | | |
| 17 | $\rho_{ftp}$ = line 16 / line 11 | g/cm$^3$ | x.xxxx | x.xxxx | x.xxxx |
| 18 | Test density = line 17 x 1000<br>Test density = line 17 x 62.428 | kg/m$^3$<br>lb/ft$^3$ | x.x<br>x.xx | x.x<br>x.xx | x.x<br>x.xx |
| 19 | DMF = line 18 / line 1 | | x.xxxxx | x.xxxxx | x.xxxxx |
| **Results** | | | | | Runs 1–3 |
| 20 | Repeatability (must not be > 0.05 %) | % | | | x.xxx |
| 21 | Average DMF | | | | x.xxxxx |
| 22 | Previous DMF | | | | x.xxxx |
| 23 | Density deviation (test vs. flowing) | kg/m$^3$<br>g/cm$^3$<br>lb/ft$^3$ | x.xxxx | x.xxxx | x.xxxx |
| 24 | MF deviation (test vs. flowing) | % | | | x.xxxx |
| 25 | New DMF (line 21 x line 22) | | | | x.xxxx |
| Comments: | | | | | |

# Annex E
(informative)

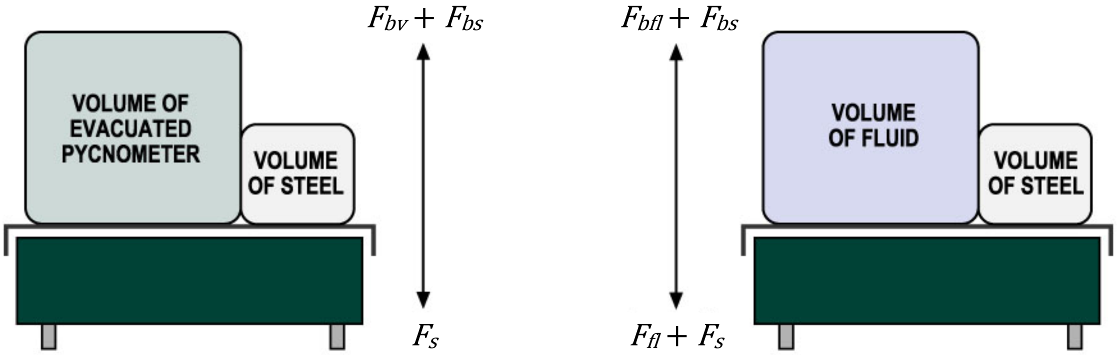
# Derivation of Air Buoyancy Equation

## E.1 Derivation of Equation for $C_{bw}$

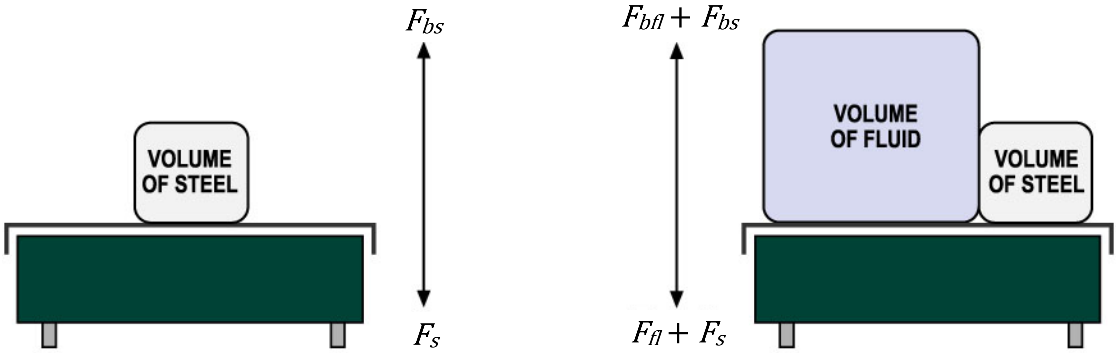
### E.1.1 General

The derivation of the $C_{bw}$ equation has been written for qualified technical personnel with a background in physics.

To derive the equation to correct for the air buoyancy on all weighings, assume the use of a perfect electronic balance.



**Using Evacuated Weight $W_O$**



**Using Air-Filled Weight $W_a$**

Figure E.1—Net Forces on Pycnometer

As shown in Figure E.1, the net forces may be calculated as follows:

By definition:

$$M = \rho_{ftp} \times PV_{tp} \tag{E.1}$$

$$PV_{tp} = \frac{M}{\rho_{ftp}} \tag{E.2}$$

For both the apparent mass standard and the fluid:

$$Net\ Force = Force\ due\ to\ gravity - Buoyant\ force\ of\ air \tag{E.3}$$

Since the electronic balance is perfect, no corrections are needed for the balance:

$$(Net\ Force)_{tw} = (Net\ Force)_{fl} \tag{E.4}$$

## E.1.2 Using the Pycnometer Evacuated Weight ($W_o$)

The fluid's net force is calculated as follows:

$$(Net\ Force)_{fl} = Net\ force_{fluid\text{-}filled\ pycnometer} - Net\ force_{evaculted\ pycnometer} \tag{E.5}$$

Or:

$$(Net\ Force)_{fl} = (F_{fl} + F_{1pyc}) - F_{2pyc} \tag{E.6}$$

Where:

$F_{fl} + F_{1pyc}$ = total forces exerted on the fluid-filled pycnometer

$F_{2pyc}$ = total forces exerted on an evacuated pycnometer

The forces on the fluid combined with the forces exerted on the steel shell of the pycnometer are expressed as follows:

$$(F_{fl} + F_{1pyc}) = (F_{fl} - F_{bfl}) + (F_{s} - F_{bs}) \tag{E.7}$$

Although the pycnometer is evacuated, the internal volume is displacing air, and therefore has a buoyancy force for the evacuated volume. The forces on the steel shell of the pycnometer and the buoyancy force exerted on the evacuated volume are expressed as follows:

$$F_{2pyc} = F_s - (F_{bs} + F_{bv}) \tag{E.8}$$

Substituting:

$$(Net\ force)_{fl} = [(F_{fl} - F_{bfl}) + (F_s - F_{bs})] - [F_s - (F_{bs} + F_{bv})] \tag{E.9}$$

Reducing the equation yields the following:

$$(Net\ force)_{fl} = (F_{fl} - F_{bfl}) + F_{bv} \qquad \text{E.10}$$

And:

$$F_{bfl} = \frac{(\rho_A PV_{tp})}{\left(\frac{g_l}{g_c}\right)} \qquad \text{E.11}$$

And:

$$F_{bv} = \frac{(\rho_A PV_t)}{\left(\frac{g_l}{g_c}\right)} \qquad \text{E.12}$$

Assuming that the pycnometer volume does not change significantly between an evacuated and a fluid-filled state:

$$PV_{tp} = PV_t \qquad \text{E.13}$$

And:

$$F_{bfl} = F_{bv} \qquad \text{E.14}$$

Reducing the net force equation yields the following:

$$(Net\ force)_{fl} = F_{fl} \qquad \text{E.15}$$

Remembering that the scale is perfect:

$$(Net\ force)_{tw} = (Net\ force)_{fl} \qquad \text{E.16}$$

Since the test weights have both gravitational and buoyancy forces exerted on them:

$$F_{fl} = F_{tw} - F_{btw} \qquad \text{E.17}$$

For the mass standard, the gravitational forces are expressed as follows:

$$F_{tw} = \frac{(\rho_{TWf} V_{tw})}{\left(\frac{g_l}{g_c}\right)} \qquad \text{E.18}$$

For the fluid, the gravitational forces are expressed as follows:

$$F_{fl} = \frac{(\rho_{ftp} PV_{tp})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.19}$$

The air buoyancy forces are expressed as follows:

$$F_{btw} = \frac{(\rho_A V_{tw})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.20}$$

Substituting into the equation for net force:

$$\left(\frac{g_l}{g_c}\right)\left(\rho_{TWf} V_{tw} - \rho_A V_{tw}\right) = \left(\frac{g_l}{g_c}\right)\left(\rho_{ftp} PV_{tp}\right) \tag{E.21}$$

By definition:

$$V_{tw} = \frac{M_{tw}}{\rho_{TWf}} \tag{E.22}$$

$$PV_{tp} = \frac{M_{fl}}{\rho_{ftp}} \tag{E.23}$$

$$M_{tw} = \rho_{TWf} \times V_{tw} \tag{E.24}$$

$$M_{fl} = \rho_{ftp} \times PV_{tp} \tag{E.25}$$

Again substituting into the equation for net force and then reducing:

$$M_{fl} = M_{tw}\left[1 - \left(\frac{\rho_A}{\rho_{TWf}}\right)\right] \tag{E.26}$$

The mass value of the apparent mass standard can be calculated by the following equation (in accordance with NIST procedures):

$$M_{tw} = AM_{tw}\left[\frac{1 - \left(\dfrac{0.0012}{\rho_{TWr}}\right)}{1 - \left(\dfrac{0.0012}{\rho_{TWf}}\right)}\right] \tag{E.27}$$

NOTE The apparent mass of an object is equal to the mass of just enough reference material of a specified density ($\rho_{TWr}$) that will produce a balance reading equal to that produced by the object if the measurements are done in air. NIST specifies that the reference material density be taken at 20 °C in air with a density of 0.0012 g/cm$^3$ at 20 °C. The original basis for reporting apparent mass was apparent mass versus brass. The apparent mass versus a density of 8.0 g/cm$^3$ ($\rho_{TWr}$ = 8.0) is the more recent definition, and is used extensively throughout the world. The use of apparent mass versus 8.0 g/cm$^3$ is encouraged over apparent mass versus brass.

Substituting:

$$M_{fl} = AM_{tw}\left[\frac{1-\left(\dfrac{0.0012}{\rho_{TWr}}\right)}{1-\left(\dfrac{0.0012}{\rho_{TWf}}\right)}\right]\times\left[1-\left(\frac{\rho_A}{\rho_{TWf}}\right)\right] \tag{E.28}$$

From the previous section:

$$Mass = Apparent\ mass \times Air\ buoyancy\ correction \tag{E.29}$$

$$C_{bw} = \left[\frac{1-\left(\dfrac{0.0012}{\rho_{TWr}}\right)}{1-\left(\dfrac{0.0012}{\rho_{TWf}}\right)}\right]\times\left[1-\left(\frac{\rho_A}{\rho_{TWf}}\right)\right] \tag{E.30}$$

For the $W_o$ application, the $C_{bw}$ equation corrects only for the buoyancy of the additional test weights required to determine the difference between the $W_f$ and $W_o$ values.

### E.1.3 Example Calculation

For the purposes of example calculations, assume the balance has been calibrated with a set of apparent mass standards where the field test weight has a density of 7.84 g/cm$^3$ at 20 °C and the reference test weight has a density of 8.0 g/cm$^3$ at 20 °C, and air has a density of 0.00118 g/cm$^3$. When a fluid-filled pycnometer is placed on the balance, it indicates a scale reading of 2000 g. The evacuated weight of the pycnometer indicates a scale reading of 1000.0 g. The air-filled weight of the pycnometer indicates a scale reading of 1001.18 g. The $PV_{tp}$ value for the pycnometer is 1000.00 cm$^3$.

Solving for the mass of the fluid:

$$M_{fl} = 1000\left[\frac{1-\left(\dfrac{0.0012}{8.0}\right)}{1-\left(\dfrac{0.0012}{7.84}\right)}\right]\times\left[1-\left(\frac{0.00118}{7.84}\right)\right] \\ = 999.85\ \text{g} \tag{E.31}$$

## E.2 Using the Pycnometer Air-Filled Weight ($W_a$)

### E.2.1 General

A similar derivation can be performed for open beakers, glass pycnometers, or flow-through pycnometers when $W_a$ is used to define the fluid's net force:

$$(Net\ force)_{fl} = Net\ force_{fluid\text{-}filled\ pycnometer} - Net\ force_{air\text{-}filled\ pycnometer} \tag{E.32}$$

The net force of the fluid-filled pycnometer is expressed as follows:

$$(Net\ force)_{fl} = (F_{fl} + F_{1pyc}) - F_{3pyc} \tag{E.33}$$

The net force of the air-filled pycnometer is expressed as follows:

$$(F_{fl} + F_{1pyc}) = (F_{fl} - F_{bfl}) + (F_s - F_{bs}) \tag{E.34}$$

Since the pycnometer is air-filled, the internal volume is not displacing air, and therefore has no buoyancy force:

$$F_{3pyc} = F_s - F_{bs} \tag{E.35}$$

Substituting:

$$(Net\ force)_{fl} = \left[(F_{fl} - F_{bfl}) + (F_s - F_{bs})\right] - \left(F_s - F_{bs}\right) \tag{E.36}$$

Reducing the equation yields the following:

$$(Net\ force)_{fl} = F_{fl} - F_{bfl} \tag{E.37}$$

And:

$$F_{bfl} = \frac{(\rho_A P V_{tp})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.38}$$

Remembering that the scale is perfect:

$$(Net\ force)_{tw} = (Net\ force)_{fl} \tag{E.39}$$

$$F_{tw} - F_{btw} = F_{fl} - F_{bfl} \tag{E.40}$$

For the mass standard, the gravitational forces are expressed as follows:

$$F_{tw} = \frac{(\rho_{TWf} V_{tw})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.41}$$

And the air buoyancy forces are expressed as follows:

$$F_{btw} = \frac{(\rho_A V_{tw})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.42}$$

For the fluid, the gravitational forces are expressed as follows:

$$F_{fl} = \frac{(\rho_{ftp} P V_{tp})}{\left(\dfrac{g_l}{g_c}\right)} \tag{E.43}$$

And the air buoyancy forces are expressed as follows:

$$F_{bfl} = \frac{(\rho_A PV_{tp})}{\left(\frac{g_l}{g_c}\right)} \tag{E.44}$$

Substituting into the equation for net force:

$$\left(\frac{g_l}{g_c}\right)\left(\rho_{TWf} V_{tw} - \rho_A V_{tw}\right) = \left(\frac{g_l}{g_c}\right)\left(\rho_{ftp} PV_{tp} - \rho_A PV_{tp}\right) \tag{E.45}$$

By definition:

$$V_{tw} = \frac{M_{tw}}{\rho_{TWf}} \tag{E.46}$$

$$PV_{tp} = \frac{M_{fl}}{\rho_{ftp}} \tag{E.47}$$

$$M_{tw} = \rho_{TWf} \times V_{tw} \tag{E.48}$$

$$M_{fl} = \rho_{ftp} \times PV_{tp} \tag{E.49}$$

Again, substituting into the equation for net force and then reducing:

$$M_{tw}\left[1 - \frac{\rho_A}{\rho_{TWf}}\right] = M_{fl}\left[1 - \frac{\rho_A}{\rho_{ftp}}\right] \tag{E.50}$$

Solving for the mass of the fluid:

$$M_{fl} = M_{tw}\left[\frac{1 - \left(\frac{\rho_A}{\rho_{TWf}}\right)}{1 - \left(\frac{\rho_A}{\rho_{ftp}}\right)}\right] \tag{E.51}$$

The mass value of the apparent mass standard can be calculated as follows:

$$M_{tw} = AM_{tw}\left[\frac{1 - \left(\frac{0.0012}{\rho_{TWr}}\right)}{1 - \left(\frac{0.0012}{\rho_{TWf}}\right)}\right] \tag{E.52}$$

Substituting:

$$M_{fl} = AM_{tw} \left[ \frac{1 - \left( \dfrac{0.0012}{\rho_{TWr}} \right)}{1 - \left( \dfrac{0.0012}{\rho_{TWf}} \right)} \right] \times \left[ \frac{1 - \left( \dfrac{\rho_A}{\rho_{TWf}} \right)}{1 - \left( \dfrac{\rho_A}{\rho_{ftp}} \right)} \right] \qquad \text{E.53}$$

From the previous section:

$$Mass = Apparent\ mass \times Air\ buoyancy\ correction \qquad \text{E.54}$$

Therefore, for air-filled weight calculations:

$$C_{bw} = \left[ \frac{1 - \left( \dfrac{0.0012}{\rho_{TWr}} \right)}{1 - \left( \dfrac{0.0012}{\rho_{TWf}} \right)} \right] \times \left[ \frac{1 - \left( \dfrac{\rho_A}{\rho_{TWf}} \right)}{1 - \left( \dfrac{\rho_A}{\rho_{ftp}} \right)} \right] \qquad \text{E.55}$$

And:

$$\rho_{ftp} = \frac{\left( W_f - W_a \right)}{PV_{tp}} \qquad \text{E.56}$$

## E.2.2 Example Calculation

For the purposes of example calculations, assume the balance has been calibrated with a set of apparent mass standards where the field test weight has a density of 7.84 g/cm$^3$ at 20 °C and the reference test weight has a density of 8.0 g/cm$^3$ at 20 °C, and air has a density of 0.00118 g/cm$^3$. When a fluid-filled pycnometer is placed on the balance, it indicates a scale reading of 2000 g. The evacuated weight of the pycnometer indicates a scale reading of 1000.0 g. The air-filled weight of the pycnometer indicates a scale reading of 1001.18 g. The $PV_{tp}$ value for the pycnometer is 1000.00 cm$^3$.

Solving for the mass of the fluid:

$$M_{fl} = 998.82 \left[ \frac{1 - \left( \dfrac{0.0012}{8.0} \right)}{1 - \left( \dfrac{0.0012}{7.84} \right)} \right] \times \left[ \frac{1 - \left( \dfrac{0.00118}{7.84} \right)}{1 - \left( \dfrac{0.00118}{\left( \dfrac{998.82}{1000.0} \right)} \right)} \right] \qquad \text{E.57}$$

$$= 999.85\ \text{g}$$

# Annex F
(informative)

# Reference Fluids (Air and Water)

## F.1 Properties of Air

Use the properties of air to determine the correct mass of an object.

The earth's atmosphere is composed of air. Air is a mixture of different gases, approximately 78 % nitrogen and 21 % oxygen, with traces of water vapor, carbon dioxide, argon, and various other components.

The earth’s surface is in effect at the bottom of a sea of air, and a buoyant force equal to the weight of the air displaced by an object acts upward on it. The air buoyancy factor is a correction made to the calculated base density to account for the difference between the density in a vacuum and the density in air. The air buoyancy factor is subtracted from the base density before the density is multiplied by the volume to calculate the mass.

To demonstrate this effect, a glass balloon is placed on one end of an equal arm balance. When the air surrounding the balloon is removed, the buoyant force is removed, and the balance tilts. Figure F.1 demonstrates the buoyant effects of the atmosphere.

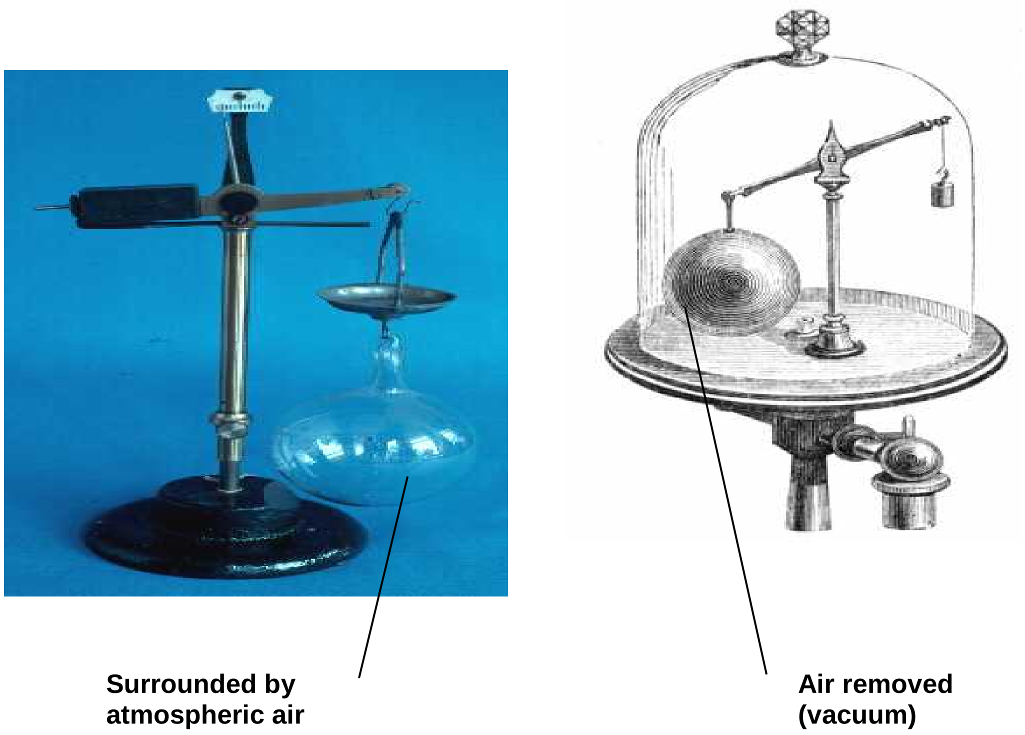


Figure F.1—Buoyancy Illustration

## F.2 Apparent Mass to Mass Values

### F.2.1 General

All hydrocarbon and other petroleum-related fluid densities are based on mass or weight in a vacuum. Air buoyancy corrections are therefore required for all calibrations of density meters, laboratory calibrations of pycnometers, and field verification of pycnometers.

In practical field and laboratory weighings, calculate the mass of an object from its apparent mass using the following equation:

$$Mass = Apparent\ mass \times Air\ buoyancy\ \ correction \qquad \text{F.1}$$

Although it is recognized that a more explicit treatment may be performed, the precision of this equation is sufficient for the limits of practical field and commercial laboratory determinations.

### F.2.2 Correction for Air Buoyancy on Weighings ($C_{bw}$)

The mass of a test fluid shall be calculated using a pycnometer by the following equation:

$$M_{fl} = (W_f - W_o)(C_{bw}) \qquad \text{F.2}$$

Where:

$M_{fl}$ = mass of fluid

$W_f$ = weight of fluid-filled pycnometer (without fittings)

$W_o$ = weight of pycnometer with all air evacuated (without fittings)

$C_{bw}$ = correction for air buoyancy on weighing

The following formula shall be used for laboratory calibration of pycnometers:

$$C_{bw} = \left[\frac{1-(0.0012/\rho_{TWr})}{1-(0.0012/\rho_{TWF})}\right]\left[1-(\rho_A/\rho_{TWF})\right] \qquad \text{F.3}$$

Where:

$C_{bw}$ = correction for air buoyancy on weighing

$\rho_{TWr}$ = density of reference test weights

$\rho_{TWF}$ = density of field test weights

$\rho_A$ = density of dry air

Keeping in mind the practicality of field conditions, the formula becomes the following for proving and verification tests:

$$C_{bw} = 1-(\rho_A/\rho_{TWF}) \qquad \text{F.4}$$

Where:

$C_{bw}$ = correction for air buoyancy on weighing

$\rho_A$ = density of dry air

$\rho_{TWF}$ = density of field test weights

NOTE The apparent mass of an object is equal to the mass of just enough reference material of a specified density ($\rho_{TWr}$) that will produce a balance reading equal to that produced by the object if the measurements are done in air. NIST specifies that the reference material density be taken at 20 °C in air with a density of 0.0012 g/cm$^3$ at 20 °C. The original basis for reporting apparent mass was apparent mass versus brass. The apparent mass versus a density of 8.0 g/cm$^3$ ($\rho_{TWr}$ = 8.0) is the more recent definition, and is used extensively throughout the world. The use of apparent mass versus 8.0 g/cm$^3$ is encouraged over apparent mass versus brass.

### F.2.3 Air Density Calculation for the Air Buoyancy Determination

Determine the density of air to calculate the air buoyancy effect on an object. Use the following to determine the density of dry air:

a) calculation of air density in SI units:

$$\rho_A = 0.001223068\left[1 - \left(\frac{0.1049869\,h}{1000}\right)\right] \times \left[\frac{519.67}{(1.8T_\mathrm{f} + 491.67)}\right] \tag{F.5}$$

b) calculation of air density in USC units:

$$\rho_A = 0.001223068\left[1 - \left(\frac{0.032\,h}{1000}\right)\right] \times \left[\frac{519.67}{(T_f + 459.67)}\right] \tag{F.6}$$

Where:

$\rho_A$ = density of dry air, in g/cm$^3$

$H$ = elevation above sea level, in m (SI); in ft (USC)

$T_f$ = test temperature, in ºC (SI); in ºF (USC).

NOTE The density of air as calculated in equations F.5 and F.6 is a dry air density. Calculations have shown that the use of non-zero relative humidities has negligible effect on air buoyancy calculations. The density at 760 mmHg atmospheric pressure, 0 % relative humidity, 0 elevation, and 15.5555555 °C (60 °F) is consistent with the latest International Committee of Weights and Measures (CIPM) 81/91 Air Density Executable File, which is available from NIST at http://ts.nist.gov/ts/htdocs/230/235/labmetrologypage.htm.

### F.2.4 Properties of Water

Mass divided by density is equal to volume; therefore, the density of distilled water has to be known to determine the volume of the pycnometer. Refer to API *MPMS* Chapter 11.4.1 for water density values.

# Annex G
(informative)

# Conversion Factors

## G.1 Density Conversion Factors

### G.1.1 General

A compilation of conversion factors is included as an aid to the user of this standard. API *MPMS* Chapters 11.5.1 [5], 11.5.2 [6], 11.5.3 [7], and 15 [8] have precedence over this annex. Densities of hydrocarbons are expressed in terms of absolute density, relative density, and degrees API. Different density units can be used in quantitative calculations; therefore, it is important to have knowledge of the appropriate compensation and conversion factors.

### G.1.2 Explaining Density

**Density:** the mass of liquid per unit volume at 15 °C and 101.325 kPa with the standard unit of measurement being kilograms per cubic meter. It is usually expressed in kg/m$^3$, but can be expressed in other units, such as lb/ft$^3$. When reporting density, the units of measurement, together with the reference temperature, shall be explicitly stated.

**Density (degrees API):** a special function of relative density 15 °C/15 °C (60 °F/60 °F). If a hydrocarbon's API gravity is greater than 10, it is less dense than water; if less than 10, it has a greater density than water. Although mathematically, API gravity has no units, it is nevertheless referred to as being in "degrees." API gravity was designed so that most values would fall between 10 and 70 API gravity degrees. The measuring scale is calibrated in degrees API.

## G.2 Density Units

### G.2.1 General

On-line density measurement units are expressed in either SI (International System of Units) or in USC (United States Customary Units).

### G.2.2 SI (International System of Units):

a) absolute density [kilograms per cubic meter (kg/m$^3$)]

b) absolute density [grams per milliliter (g/mL)]

c) absolute density [grams per cubic centimeter (g/cm$^3$)]

NOTE Grams per cubic centimeter are numerically equivalent to grams per milliliter. The unit of measure "g/mL" is preferred.

### G.2.3 USC (United States Customary Units):

a) absolute density [pounds mass per gallon (lbm/gal)]

b) relative density (dimensionless ratio value)

c) API gravity (°API)

## G.3 Density Conversion Factors

### G.3.1 Base Units

The conversion factors from USC to SI units for density are based on the following values, as per IEEE/ASTM SI 10 2002:

1 pound (avoirdupois) (lb) = **0.45359237** kilogram (kg)

1 gallon (U.S.) = **231** $in^3$

1 cubic inch ($in^3$) = **1.6387064E-05** cubic meters ($m^3$)

NOTE The conversion factors set in **boldface** are exact.

### G.3.2 SI Liquid Density Units

kilograms per cubic meter ($kg/m^3$)

grams per milliliter (g/mL)

grams per cubic centimeter ($g/cm^3$)

### G.3.3 USC Liquid Density Units

pounds per cubic foot ($lb/ft^3$)

pounds per U.S. gallon (lb/gal)

relative density (RD)

degrees API (°API)

**Table G.1—Density Conversion Factors (SI units to SI units)**

| To convert from | To | Multiply by |
|---|---|---|
| grams per milliliter (g/mL) | grams per cubic centimeter ($g/cm^3$) | **1.0** |
| grams per milliliter (g/mL) | kilograms per cubic meter ($kg/m^3$) | **1000** |
| grams per cubic centimeter ($g/cm^3$) | grams per milliliter (g/mL) | **1.0** |
| grams per cubic centimeter ($g/cm^3$) | kilograms per cubic meter ($kg/m^3$) | **1000** |
| kilograms per cubic meter ($kg/m^3$) | grams per milliliter (g/mL) | **0.001** |
| kilograms per cubic meter ($kg/m^3$) | grams per cubic centimeter ($g/cm^3$) | **0.001** |

## Table G.2—Density Conversion Factors (SI units to USC units)

| To convert from | To | Multiply by |
|---|---|---|
| kilograms (kg) | pounds (lb) | 2.204623 |
| grams per milliliter (g/mL) | pounds per U.S. gallon (lb/gal) | 8.345404 |
| grams per cubic centimeter (g/cm$^3$) | pounds per U.S. gallon (lb/gal) | 8.345404 |
| kilograms per cubic meter (kg/m$^3$) | pounds per U.S. gallon (lb/gal) | 0.008345404 |
| kilograms per cubic meter (kg/m$^3$) | pounds per barrel (lb/Bbl) | 0.3505070 |
| kilograms per cubic meter (kg/m$^3$) | pounds per cubic foot (lb/ft$^3$) | 0.06242796 |
| kilograms per cubic meter (kg/m$^3$) | pounds per 1000 cubic feet (lb/1,000 ft$^3$) | 62.42796 |

## Table G.3—Density Conversion Factors (USC units to SI Units)

| To convert from | To | Multiply by |
|---|---|---|
| pounds (lb) | kilograms (kg) | **0.45359237** |
| pounds per U.S. gallon (lb/gal) | grams per milliliter (g/mL) | 0.1198264 |
| pounds per U.S. gallon (lb/gal) | grams per cubic centimeter (g/cm$^3$) | 0.1198264 |
| pounds per U.S. gallon (lb/gal) | kilograms per cubic meter (kg/m$^3$) | 119.8264 |
| pounds per barrel (lb/Bbl) | kilograms per cubic meter (kg/m$^3$) | 2.85301 |
| pounds per cubic foot (lb/ft$^3$) | kilograms per cubic meter (kg/m$^3$) | 16.01846 |
| pounds per 1000 cubic feet (lb/1000 ft$^3$) | kilograms per cubic meter (kg/m$^3$) | 0.01601846 |

NOTE Conversion factors shown in bold are exact values.

## Table G.4—Density Conversion Factors (USC Units to USC Units—lb/gal and RD)

| To convert from | To | Multiply by |
|---|---|---|
| pounds per U.S. gallon (lb/gal) | relative density (RD 60 °F/ 60 °F) | 0.1199443 |
| relative density (RD 60 °F/60 °F) | pounds per U.S. gallon (lb/gal) | 8.3372 |

**Table G.5—Density Conversion Factors (USC Units to USC Units – lb/gal, RD and °API)**

| To convert from | To | Use this calculation formula |
|---|---|---|
| pounds per U.S. gallon ($lb/gal$) @ 60 °F | degrees API ($°API$) @ 60 °F | $^{\circ}API\ @60\ ^{\circ}\mathrm{F} = \frac{1179.7138}{lb\,/\,gal} - 131.5$ |
| Relative Density ($RD$) @ 60 °F | degrees API ($°API$) @ 60 °F | $^{\circ}API\ @\ 60\ ^{\circ}\mathrm{F} = \frac{141.5}{RD\ @\ 60\ ^{\circ}\mathrm{F}\,/\,60\ ^{\circ}\mathrm{F}} - 131.5$ |
| degrees API ($°API$) @ 60 °F | Relative Density ($RD$) @ 60 °F | $RD\ @\ 60\ ^{\circ}\mathrm{F}\,/\,60\ ^{\circ}\mathrm{F} = \frac{141.5}{^{\circ}API\ @\ 60\ ^{\circ}\mathrm{F} + 131.5}$ |
| degrees API ($°API$) @ 60 °F | pounds per U.S. gallon ($lb/gal$) @ 60 °F | $lb\,/\,gal\ @\ 60\ ^{\circ}\mathrm{F} = \left(\frac{141.5}{^{\circ}API + 131.5}\right) \mathrm{x}\ 8.3372$ |

## G.4 Temperature Conversion Factors

### G.4.1 General

The reference density temperature conversions of SI to USC, and USC to SI, are not normally required for liquid custody transfer measurement. One exception involves hydrocarbon products, which are exchanged across an international border where there are different reference temperature values. For SI units, 15.00 °C or 20.00 °C are commonly used, whereas in USC units, 60.0 °F is the reference temperature for liquid hydrocarbon fluids.

Temperature units are expressed in either SI (International System of Units), or in USC (United States Customary Units).

### G.4.2 Base Units

The conversion factors for temperature are based on the following values, as per IEEE/ASTM SI 10-2002.

The SI unit of thermodynamic temperature is the Kelvin (K). Use this unit to express thermodynamic temperature and temperature intervals. Wide use is also made of the degree Celsius (°C), which is equal to the unit Kelvin. Degree Celsius is a special name for expressing Celsius temperature and temperature intervals. Celsius temperature $t$ (which replaced centigrade temperature) is related to thermodynamic temperature $T$ by the equation:

$$t = T - T_o, \text{ where } T_o = 273.15K \text{ by definition.}$$

## G.5 Temperature Units

### G.5.1 SI (International System of Units)

a) degrees Celsius (°C)

b) Kelvin (K)

### G.5.2 USC (United States Customary Units)

a) degrees Fahrenheit (°F)

b) degrees Rankine (°R)

**Table G.6—Temperature Conversion Units (SI and USC)**

| To convert from | To | Use this calculation formula |
|---|---|---|
| degrees Celsius (°C) | Kelvin (K) | K = °C + 273.15 |
| degrees Celsius (°C) | degrees Fahrenheit (°F) | °F = 1.8 °C +32 |
| degrees Celsius (°C) | degrees Rankine (°R) | °R = 1.8 (°C + 273.15) |
| Kelvin (K) | degrees Celsius (°C) | °C = K – 273.15 |
| Kelvin (K) | degrees Fahrenheit (°F) | °F = 1.8 K – 459.67 |
| Kelvin (K) | degrees Rankine (°R) | °R = 1.8 K |
| degrees Fahrenheit (°F) | degrees Celsius (°C) | °C = (°F – 32) / 1.8 |
| degrees Fahrenheit (°F) | Kelvin (K) | K = (°F + 459.67) / 1.8 |
| degrees Fahrenheit (°F) | degrees Rankine (°R) | °R = °F + 459.67 |
| degrees Rankine (°R) | degrees Celsius (°C) | °C = °R /1.8 – 273.15 |
| degrees Rankine (°R) | Kelvin (K) | K = °R / 1.8 |
| degrees Rankine (°R) | degrees Fahrenheit (°F) | °F = °R – 459.67 |

## G.6 Pressure Conversion Factors

### G.6.1 Base Units

The conversion factors for pressure are based on the following values, as per IEEE/ASTM SI 10 2002.

### G.6.2 SI (International System of Units)

pascal (Pa)

absolute pressure [kilopascals kPa (abs), bar (abs)]

gauge pressure [kilopascals (kPa (gauge), bar (gauge)]

differential pressure (kPa)

### G.6.3 USC (United States Customary Units)

absolute pressure [pounds per square inch (psia)]

gauge pressure [pounds per square inch (psig)]

differential pressure [pounds per square inch (psi)]

differential pressure (also abbreviated as psid)

### Table G.7—Pressure Conversion Units (SI and USC)

| To convert from | To | Uses this calculation formula |
|---|---|---|
| kPa(1) | kPa (gauge) | kPa (gauge) = kPa – Patm(7) |
| kPa | bar | bar = kPa / 100 |
| kPa(1) | bar (gauge) | bar (gauge) = (kPa – Patm) /100 |
| kPa(1) | psia | psia = kPa x 0.1450377 |
| kPa(1) | psig | psig = (kPa x 0.1450377) – Patm |
| kPa (gauge)(2) | kPa | kPa = kPa (gauge) + Patm |
| kPa (gauge)(2) | bar (abs) | bar (abs) = (kPa (gauge) + Patm) / 100 |
| kPa (gauge)(2) | psia | psia = (kPa (gauge) x 0.1450377) + Patm |
| kPa (gauge)(2) | psig | psig = kPa (gauge) x 0.1450377 |
| bar (abs)(3) | kPa (gauge) | kPa (gauge) = (bar (abs) x 100) – Patm |
| bar (abs)(3) | bar (gauge) | bar (gauge) = bar (abs) – Patm |
| bar (abs)(3) | psia | psia = bar (abs) x 14.50377 |
| bar (abs)(3) | psig | psig = (bar (abs) x 14.50377) – Patm |
| bar (gauge)(4) | kPa (abs) | kPa = (bar (gauge) x 100) + Patm |
| bar (gauge) | kPa | kPa = bar (gauge) x 100 |
| bar (gauge)(4) | bar (abs) | bar (abs) = bar (gauge) + Patm |
| bar (gauge)(4) | psia | psia = (bar (gauge) x 14.50377) + Patm |
| bar (gauge)(4) | psig | psig = bar (gauge) x 0.1450377 |
| psia(5) | kPa (gauge) | kPa (gauge) = (psia / 0.1450377) – Patm |
| psia(5) | bar (abs) | bar (abs) = psia / 14.50377 |
| psia(5) | bar (gauge) | bar (gauge) = (psia / 14.50377) – Patm |
| psia(5) | psig | psig = psia – Patm |
| psig(6) | kPa (abs) | kPa (abs) = (psig / 0.1450377) + Patm |
| psi | kPa | kPa = psi / 0.1450377 |
| psig(6) | bar (abs) | bar (abs) = (psig + Patm) / 14.50377 |
| psi | bar | bar = psi / 14.50377 |
| psig(6) | psia | psia = psig + Patm |

(1) kilopascals absolute pressure

(2) kilopascals gauge pressure

(3) bar absolute pressure

(4) bar gauge pressure

(5) pounds per square inch absolute pressure

(6) pounds per square gauge pressure

(7) Atmospheric pressure (Patm) is commonly assumed to be 101.325 kPa (1.01325 bar, 14.696 psia) at sea level; the value 101.325 kPa (abs) or 14.696 psia are normally used as the standard reference pressure.

# G.7 Viscosity Conversion

## G.7.1 General

The viscosity of a fluid does not determine the density of that fluid, but a temperature change will affect both the density and the viscosity of the fluid. Viscosity has an impact on equipment performance, so it is beneficial to have a basic understanding of the different units of viscosity.

## G.7.2 Viscosity Definitions

Viscosity is the measure of a material's resistance to flow. Viscosity is a result of the internal friction of the material's molecules. Materials with a high viscosity do not flow readily; materials with a low viscosity are more fluid.

a) viscosity: the internal resistance of a fluid to flow.

b) dynamic (absolute) viscosity: the ratio between the applied shear stress and the velocity gradient. It is a measure of the resistance to flow of the liquid.

c) kinematic viscosity: the ratio between the dynamic viscosity and the density of the liquid at the temperature of viscosity measured. It is a measure of the resistance to flow of a liquid under gravity.

## G.7.3 SI (International System of Units)

### G.7.3.1 Dynamic (Absolute) Viscosity

pascal seconds (Pa · s)

millipascal seconds (mPa · s)

centipoise (cP)

### G.7.3.2 Kinematic Viscosity

meter squared per second ($m^2/s$)

centistoke (cSt)—equal to the dynamic viscosity in cP divided by the density in grams per milliliter (g/mL)

## G.7.4 USC (United States Customary Units)

### G.7.4.1 Dynamic (Absolute) Viscosity

pound per foot second (lb/(ft · sec))

pascal seconds (Pa · s)

centipoise (cP)

### G.7.4.2 Kinematic Viscosity

foot squared per second ($ft^2/s$)

centistoke (cSt)

### Table G.8—Dynamic (Absolute) Viscosity Conversion Units (SI and USC)

| To convert from | To | Multiply by |
|---|---|---|
| Pa · s | mPa · s | 1.0 E+03 |
| Pa · s | cP | 1.0 E+03 |
| Pa · s | lb/(ft · sec) | 6.719689 E-01 |
| mPa · s | Pa · s | 1.0 E-03 |
| mPa · s | cP | 1.0 E+00 |
| mPa · s | lb/(ft · sec) | 6.71969 E-04 |
| cP | Pa · s | 1.0 E-03 |
| cP | mPa · s | 1.0 E+00 |
| cP | lb/(ft · sec) | 6.719689 E-04 |
| lb/(ft · sec) | Pa · s | 1.488164 E+00 |
| lb/(ft · sec) | mPa · s | 1.488164 E+03 |
| lb/(ft · sec) | cP | 1.488164 E+03 |

### Table G.9—Kinematic Viscosity Conversion Units (SI and USC)

| To convert from | To | Multiply by |
|---|---|---|
| $m^2/s$ | cSt | 1.0 E+06 |
| $m^2/s$ | $ft^2/s$ | 1.076391 E+01 |
| cSt | $m^2/s$ | 1.0 E-06 |
| cSt | $ft^2/s$ | 1.076391 E-05 |
| $ft^2/s$ | $m^2/s$ | 9.290304 E-02 |
| $ft^2/s$ | cSt | 9.290304 E+04 |

# Annex H
(normative)

# Offline Density Meter Factor Determination for Crude Oils and Viscous Fluids

## H.1 Density Meter Calibration Based on Composite Sample

### H.1.1 General

For any crude oil or viscous fluid that is measured volumetrically at a vapor pressure below atmospheric and where density is determined using an on-line density meter, the following method should be used to determine a new density meter factor (DMF). This method may be used for a light refined product stream that is similarly measured; however, a pycnometer proving could provide a result with lower uncertainty.

### H.1.2 Purpose—Composite Sample

The purpose of this method is to validate the use of the flow-weighted average density on the QTR. This method requires that a density be determined according to an industry-standard test method from a composite sample obtained in accordance with API *MPMS* Chapter 8.2/ASTM D4177. This method also requires the flow computer to display the DMF; to calculate a flow-weighted average factored density from the on-line density meter at base conditions; or, if the density results are at flowing conditions, to also calculate a flow-weighted average temperature and pressure at the density meter. The use of factored density requires the DMF to be backed out before calculating the new DMF. This procedure assumes the temperature and pressure instruments associated with the density meter have been verified.

### H.1.3 Procedure—Composite Sample

The procedure is as follows:

1) Obtain a composite sample in accordance with API *MPMS* Chapter 8.2/ASTM D4177 and determine the density of the composite sample at reference conditions in accordance with an industry standard test method (see 11.4.2).

2) Obtain the flow-weighted average factored density from the quantity transaction record (QTR).

3) Obtain or calculate as required the absolute density or relative density for both 1 and 2 at the same reference temperature and pressure.

4) If the QTR density from the previous step is within 0.003 relative density or 3 kg/m$^3$ (0.5 °API) of the laboratory result, the density meter performance is validated, the DMF is not changed, and this procedure is complete.

5) If the QTR density is not within 0.003 relative density or 3 kg/m$^3$ (0.5 °API) of the laboratory result, repeat steps 1 through 3 on a new aliquot from the composite sample.

    a) If three or more replicates repeat within the uncertainty of the density test method as compared to the average of the results (see equation H.1), average the results to calculate the new DMF.

    b) If three or more sequences do not repeat within the uncertainty of the density test method, evaluate the composite sample, its analytical test method, and/or the on-line density meter operation.

6) Divide the composite sample density by the QTR density to determine the new DMF.

   a) To calculate the new DMF, calculate the unfactored density from the factored density from the QTR divided by the existing DMF.

   b) Use the composite sample density from the previous step and divide by the unfactored density to determine the new DMF.

   c) Implement the new DMF.

$$(\rho_i - \rho_{avg}) \leq \rho_{tr} \tag{H.1}$$

Where:

$\rho_i$ = density test result

$\rho_{avg}$ = average of all density test results

$\rho_{tr}$ = uncertainty of the density test method

### H.1.4 Density Meter Factor from Composite Sample

The method of applying the average DMF to the custody transfer quantities depends on the secondary equipment that converts the density meter's raw output to engineering units, the mass flow integrating equipment, and the accounting policies of the operator. The DMF shall be applied in accordance with Section 12 and Figure 18 of this document. All entities should agree on the method by which the DMF is to be applied to the custody transfer quantities.

For subsequent batches, repeat steps 1 through 5 in H.1.3 to validate the DMF and track how DMF is affected by other operating conditions, such as pressure, product, or crude grades. If this validation method results in a DMF that would subsequently move the total calculated GSV quantity of the batch by more than 0.05 %, the QTR would need to be recalculated using the density determined from the composite sample.

The tracking of DMF may show that separate DMFs may be necessary based on fluid properties.

This method shall be used on each batch, and a log of the on-line density, composite density, and resultant DMF shall be retained for trending of performance results.

## H.2 Density Meter Factor Based on Spot Sample

### H.2.1 General

For any crude oil or viscous fluid that is measured volumetrically where density is determined using an on-line density meter, the following method should be used to determine a new density meter factor (DMF). This method may be used for a light refined product stream that is similarly measured; however, a pycnometer proving could provide a result with lower uncertainty.

### H.2.2 Purpose—Spot Sample

The purpose of this method is to validate an instantaneous density reading. This method requires that a density be determined according to an industry-standard test method from a spot sample obtained in accordance with API *MPMS* Chapter 8.1/ASTM D4057 or API *MPMS* Chapter 8.5/ASTM D8009. This method also requires the flow computer to display the DMF; to report an instantaneous unfactored or factored density from the on-line density meter at base conditions; or, if the density results are at flowing conditions, to report the instantaneous temperature and pressure at the density meter.

### H.2.3 Frequency

The method should be performed at a defined frequency based on one or more of the following:

1) batch;
2) periodically—daily, weekly, bi-weekly, monthly;
3) throughput.

### H.2.4 Procedure—Spot Sample

The procedure is as follows:

1) Read and record the instantaneous factored density from the flow computer and, at the same time, obtain a spot sample as close as practical to the density meter in accordance with API *MPMS* Chapter 8.1/ASTM D4057 or API *MPMS* Chapter 8.5/ASTM D8009.
2) Determine the density of the spot sample at reference conditions in accordance with an industry-standard test method (see 11.4.2).
3) Obtain or calculate as required the absolute density or relative density for both 1 and 2 at the same reference temperature and pressure.
4) If the density from the previous step is within 0.003 relative density or 3 kg/m$^3$ (0.5 °API) of the laboratory result, the density meter performance is validated, the DMF is not changed, and this procedure is complete.
5) If the density is not within 0.003 relative density or 3 kg/m$^3$ (0.5 °API) of the laboratory result, repeat steps 1 through 4 on a new spot sample.
    a) If three or more replicates repeat within the uncertainty of the density test method of the average of the results (see equation H.1), average the results to calculate the new DMF.
    b) If five test sequences fail to repeat within the uncertainty of the test method used, consider further evaluation of the on-line density meter operation, the sampling process, or the analytical test method.

### H.2.5 Density Meter Factor from Spot Sample

The method of applying the average DMF to the custody transfer quantities depends on the secondary equipment that converts the density meter's raw output to engineering units, the mass flow integrating equipment, and the accounting policies of the operator. The DMF shall be applied in accordance with Section 12 and Figure 18 of this document. All entities should agree on the method by which the DMF is to be applied to the custody transfer quantities.

For subsequent batches or other defined frequency in H.2.3, repeat steps 1 through 5 in H.2.4 to validate the DMF and track how DMF is affected by other operating conditions, such as pressure, product, or crude grades. If this validation method results in a DMF that would subsequently move the total calculated GSV quantity of the batch by more than 0.05 % then the QTR would need to be recalculated using the density determined from the sample.

Tracking may show that separate DMFs may be necessary based on fluid properties.

This method shall be used on each batch or other defined frequency in H.2.3. A log of the on-line density, composite density, and resultant DMF should be retained for trending of performance results.

## H.3 Verification Based on a Sample

This method compares a density determined from a sample to the density determined using an on-line density meter result at the same reference conditions to verify the density meter performance. For a composite sample, follow the method in H.1. For a spot sample, follow the method in H.2.

If the comparison of results is within 0.3 % of the QTR density (typically 3 kg/m$^3$ or 0.5 °API), the DMF in service is verified and no change is made. Refer to Step 6 in method H.1, or step 5 in method H.2. However, if the comparison of results is outside of 0.3 %, perform either H.1 or H.2 as appropriate to calculate and implement a new DMF.

This method shall be used on each batch or other defined frequency in H.2.3. A log of the on-line density, composite or spot density, and the resultant DMF should be retained for trending of performance results.

Record the results of the verification test for tracking and analysis.

# Annex I

(normative)

## Density Used in Volume Calculation

When density is used as an input to volume calculation at reference conditions, various steps are taken to convert from flowing conditions to reference conditions. To convert the factored density to density at reference temperature, refer to the calculations described in API *MPMS* Chapter 9.1/ASTM D1298, API *MPMS* Chapter 9.3/ASTM D6822, and API *MPMS* Chapter 11.1/adjunct to ASTM D1250.

Density shall be converted from flowing conditions to reference conditions before its use in subsequent calculations. Refer to API *MPMS* Chapter 9.1/ASTM D1298, API *MPMS* Chapter 9.3/ASTM D6822, and API *MPMS* Chapter 11.1 for the various calculation procedures.

For light hydrocarbons, such as NGL and LPG, refer to API *MPMS* Chapter 9.2/ASTM D1657 to convert density from flowing conditions to reference conditions before its use in subsequent calculations. Refer to API *MPMS* Chapter 11.2.4/GPA TP-27 for the calculation procedures to address the effect of temperature on density, and to API *MPMS* Chapter 11.2.2 for the calculation procedures to address the effect of pressure on density. Refer to API *MPMS* Chapter 11.2.5/GPA TP-15 for the methodology of calculating the equilibrium vapor pressure of light hydrocarbons that are required when applying pressure correction to the density.

# Annex J
(informative)

# Concepts of Mass and Weight

## J.1 Mass and Apparent Mass Values—Definitions

In the field of measurement, considerable ambiguity exists with respect to the definitions of mass, apparent mass, and weight. The following definitions are presented to enable the user of this standard to understand more clearly the relationship of these terms.

**Weight** is defined as the net force that is created by a particular mass in the presence of local gravitational acceleration and local atmospheric buoyancy. Typically, this is the nominal value indicated by a scale, or balance, in a particular location and environment. It should be interpreted in accordance with local gravitational acceleration and local atmospheric air density, which causes a resulting buoyant force acting to reduce the weight indications for the "weighed" object. In most situations, the net force is a combination of the earth’s gravity and the buoyancy of the fluid surrounding the object. As simply stated in Newton's first law: $F = ma$. The term $F$ represents weight (buoyancy having been properly accounted for in weighing); $m$ is the associated mass; and $a$ is the local acceleration, or gravitational acceleration at the location in which the weight determination is made.

**Weighing** is defined as measuring the net force acting on an object’s mass.

**Mass** is the quantity of matter a body contains. This quantity is measured by the body's acceleration under a given force, or by a force exerted on it by a particular gravitational field. This means that if we can only deduce mass by means of a nominal weight measurement, it is imperative that we know the local gravitational field acting on it, as well as all buoyancy effects created by the local atmosphere on the weighed material.

For terrestrial measurements, gravitational acceleration of a local field varies according to density gradients associated with the surrounding material, which are affected by other matter in the vicinity, as well as the material's distance from the center of the earth. Because the earth is non-spherical, varying geographic locations produce differing gravitational accelerations.

Another key factor is the local ambient atmosphere density, whose effective mass also affects local gravitation acceleration. In addition, the atmospheric density affects the buoyancy of immersed objects; this also affects the weight indicated by a scale for material that is being weighed in atmosphere. It is to be expected that density gradients associated with geographic areas involving petroleum production substantially differ from typical geological density gradients, owing to the lower density of petroleum products in the immediate vicinity as compared with typical geological mineral densities. Mass is defined in terms of a standard mass; therefore, the mass of an object is simply a multiple of the mass standard. The mass of an object remains constant regardless of its location. Thus, the mass of an object does not vary as it is moved from one part of the earth to another, although the net forces acting on the mass may change. If the net forces change, the weight of the object will vary from location to location. The weight of an object having a specific mass will vary when placed in different acceleration fields, such as the gravitational field of a planet. For example, at the earth's surface, a 1.0 kg mass weighs about 2.2 lb, but on Mars, the same kilogram mass might weigh only about 0.8 lb, and on Jupiter, it might weigh 5.5 lb, because of the different gravitational fields on each planet.

**Apparent mass** is defined as the weight of an object in air, compared with a mass standard. A mass measurement by weighing is performed in air, as are virtually all mass reference standards’ calibrations. Thus, when two objects are compared in mass, each object is subjected to two principal opposing forces:

— a lifting force equal to the mass of air displaced by the object times the force of gravity;

— a downward force equal to the mass of the object times the force of gravity.

Since all mass reference standards' calibrations are made in air and are performed by comparing an unknown standard with a known primary standard, the mass of the unknown standard is frequently reported as the mass the standard would appear to have when compared with a reference standard at 20 °C in air with a density of 0.0012 g/cm$^3$. Whenever apparent mass is used, it is necessary to specify the density of the (normally hypothetical) reference standard against which the unknown standard is being compared. This statement of the density of the reference standard, called "reference density," is necessary because the apparent mass value depends in part on the volume of the reference standard. A reference density of 8.0 g/cm$^3$ is normally used to report the apparent mass of a standard or object. This is referred to as the apparent mass versus 8.0 g/cm$^3$ at 20 °C in normal air (0.0012 g/cm$^3$). In the past, the apparent mass was reported against the density of normal brass at 20 °C. This is referred to as the apparent mass versus 8.3909 g/cm$^3$ at 20 °C in normal air.

## J.2 Mass and Apparent Mass Standards

By international agreement, the international mass standard is the International Prototype Kilogram, a platinum-iridium standard (90 % platinum and 10 % iridium) that is kept at the International Bureau of Weights and Measures in Sevres, France. The primary mass standard for the United States, which has been compared with the International Prototype Kilogram, is the U.S. Prototype Kilogram 20, a platinum-iridium standard kept at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

Mass standards are precise standards whose volume, density, cubical coefficient of thermal expansion, and mass have been determined by NIST. Mass standards are used for highly accurate measurements in scientific research laboratories, but are impractical for precise commercial measurements.

Apparent mass standards are precise standards whose density and apparent mass have been determined by a high-precision commercial laboratory, as compared with their primary standards. Apparent mass standards are calibrated by primary mass or primary apparent mass standards, which, in turn, have been certified by a national metrology institute (such as NIST in the U.S.). Apparent mass standards are used by all states and by commercial laboratories as their primary standards for precise weighings.

The NIST Classification of Mass and Laboratory Weights (mass and apparent mass standards) is based on tolerances from the true value. ASTM E617 (class 0, 1, 2, or 3) weights are apparent mass standards appropriate for use in density measurement under this standard.

Figure J.1 contains an example of a test weight certificate.

**Report of Mass Values**
**One-Piece Metric Mass Standards**

**Calibration Company Ltd.**
**123 Test Equipment Lane**
**Denver CO, 99999**

**Certificate No.:** RM12345
**Date of Certification:** January 5, 2011

**Test Weight Set Description:** Calco S/S Metric Weight Set
**Test Weight Set Identifier:** 1249687SS001
**Material:** 316 Stainless Steel
**Assumed Density @ 20 °C:** 7,950 kg/m$^3$
**Range of Test Weights:** 100 g to 50 mg

Tested with reference standards traceable to the National Institute of Standards and Technology through NIST Test Number 822/228509, April 11, 2010.

Calibrated to ASTM E617-97 Class 1 tolerances.

The calibration of these weights is based on apparent mass vs. material of density 8,000 kg/m$^3$.

**Certification performed by:** ______________________

Jane W. Technician

| Nominal Value | Serial Number | Corrections (mg) | Tolerance (±mg) | Uncertainty (±mg) |
|---|---|---|---|---|
| 100 g | A999 | –0.0242 | 0.250 | 0.0703 |
| 50 g | A998 | +0.0282 | 0.120 | 0.0346 |
| 20 g | A997 | +0.0104 | 0.074 | 0.0177 |
| 10 g | A996 | –0.0314 | 0.050 | 0.0115 |
| 5 g | A995 | –0.0021 | 0.034 | 0.0108 |
| 2 g | A994 | +0.0267 | 0.034 | 0.0076 |
| 1 g | A993 | +0.0177 | 0.034 | 0.0075 |
| 500 mg | B500 | +0.0009 | 0.010 | 0.0024 |
| 200 mg | B499 | +0.0011 | 0.010 | 0.0024 |
| 100 mg | B498 | +0.0076 | 0.010 | 0.0024 |
| 50 mg | B497 | –0.0035 | 0.010 | 0.0024 |

Correction is defined as the difference between the mass value of a weight and its nominal value. A positive correction indicates that the mass value is greater than the nominal value by the amount of the correction.

**Figure J.1—Example Report of Mass Values**

## J.3 Weighing

Analytical balances, or weigh scales, are vertical force comparators. In other words, they measure the net force acting on an unknown object, compared with the net force acting on a known object (an apparent mass standard). By definition, they are influenced by external vertical forces.

The principal vertical forces that influence the weighing instrument’s performance are local gravity, air buoyancy, air currents, vibration, and attitude. Lesser forces, such as electrostatic and magnetic forces, are beyond practical field and laboratory accuracy levels.

The influence of air currents on the analytical balance can be controlled by the use of a draft shield.

The influence of vibration and attitude can be controlled by mounting the analytical balance on a level, stable surface that is free from vibration.

By calibrating in air an analytical balance to a known apparent mass standard, the balance is prepared to read the apparent mass of any object whose density is equal to the apparent mass standard’s reference density. This calibration method also corrects for the effect of local gravitational forces so long as the balance is not moved to a different location.

The influence of air buoyancy forces on an object can be calculated if the object’s density or volume is known. If the apparent mass standard’s density is greater than the object’s density, the buoyancy correction shall be greater than 1. If the apparent mass standard’s density is less than the object’s density, the buoyancy correction shall be less than 1. The buoyancy correction equation is given in Annex E.

## J.4 Apparent Mass to Mass Values

All hydrocarbon and other petroleum-related fluid densities are based on mass or weight in a vacuum. Use air buoyancy corrections for all calibrations of density meters, laboratory calibrations of pycnometers, and field verification of pycnometers. Refer to Annex E for a discussion of air buoyancy.

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