

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First Edition, supersedes API MPMS Chapter 14.6, *Continuous Density Measurement*, Second Edition, which is withdrawn.

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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*

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 E₁, E₂, F₁, F₂, M₁, M₁₋₂, M₂, M₂₋₃, and M₃, 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:

$$^{\circ}\text{API} = \frac{141.5}{\text{RD}_{(60\text{ }^{\circ}\text{F}/60\text{ }^{\circ}\text{F})}} - 131.5 \quad 1$$

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.

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	--	--

⁴ The SI designated volume unit is mL; however, this standard uses cm³.

Symbol	Definition	Units	
		USC	SI
F_{bfl}	buoyancy force on fluid	lbf	N
F_{bs}	buoyancy force on steel of pycnometer	lbf	N
F_{btw}	buoyancy force on test weights	lbf	N
F_{bv}	buoyancy force on evacuated pycnometer volume	lbf	N
F_{fl}	gravitational force on fluid	lbf	N
F_s	gravitational force on steel of pycnometer	lbf	N
F_{tw}	gravitational force on test weights	lbf	N
F_{1pyc}	total forces on steel of pycnometer when fluid-filled	lbf	N
F_{2pyc}	total forces on steel of pycnometer when evacuated ⁵	lbf	N
F_{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, 32.17405(lbm · ft)/(lbf · s ²) or 1(kg · m)/(N · s ²)	--	--
g_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

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_{tw}	mass of test weights	g	g
OD	outside diameter	in	mm
P_b	pressure, base	psi	kPa
P_d	datum pressure of pycnometer (absolute pressure: 14.696 psia or 101.325 kPa) (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	--	--
<i>S</i>	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)	--	--
<i>V</i>	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
ρ	density	g/cm ³	kg/m ³
ρ_A	density of dry air	g/cm ³	kg/m ³
ρ_{ftp}	density of fluid at test temperature and test pressure	g/cm ³	kg/m ³
ρ_{in}	indicated density	g/cm ³	kg/m ³
ρ_m	density at the meter run	g/cm ³	kg/m ³
ρ_p	density of the probe material	g/cm ³	kg/m ³
ρ_{tp}	density compensated for thermal and pressure effects on sensor (unfactored density)	g/cm ³	kg/m ³
ρ_{te}	density compensated for thermal effects on sensor	g/cm ³	kg/m ³
ρ_{TWf}	density of field test weights	g/cm ³	kg/m ³
ρ_{TWr}	density of reference test weights	g/cm ³	kg/m ³
τ	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:

- 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.

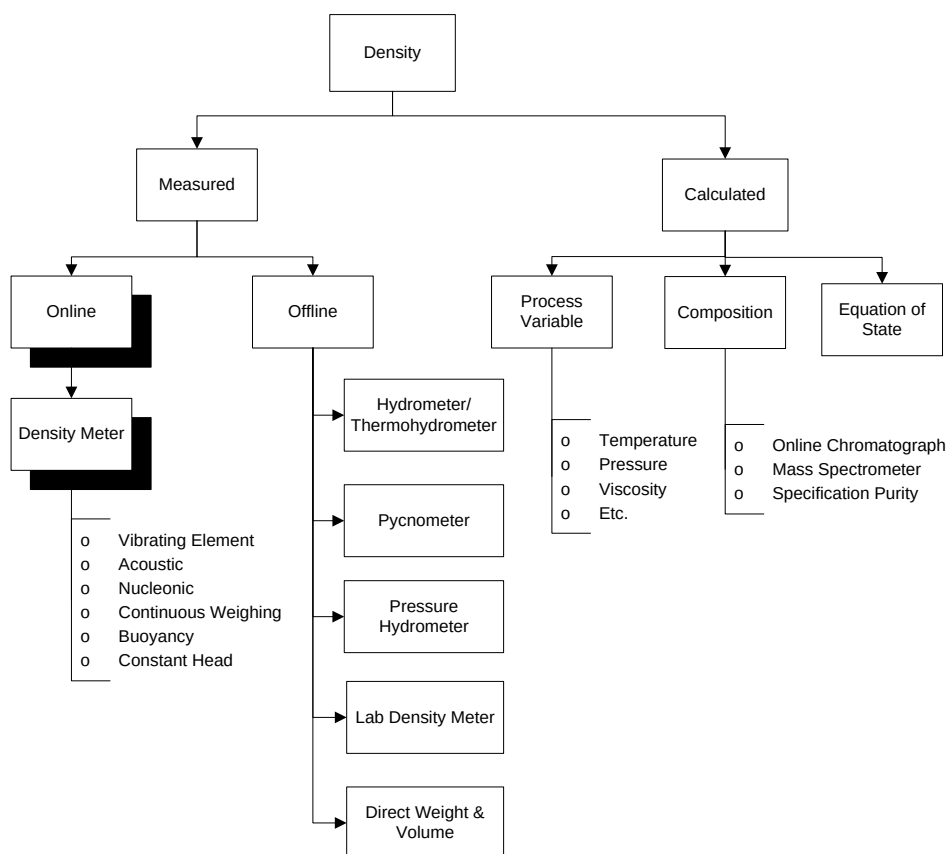


Figure 1—Density Determination Methods

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.

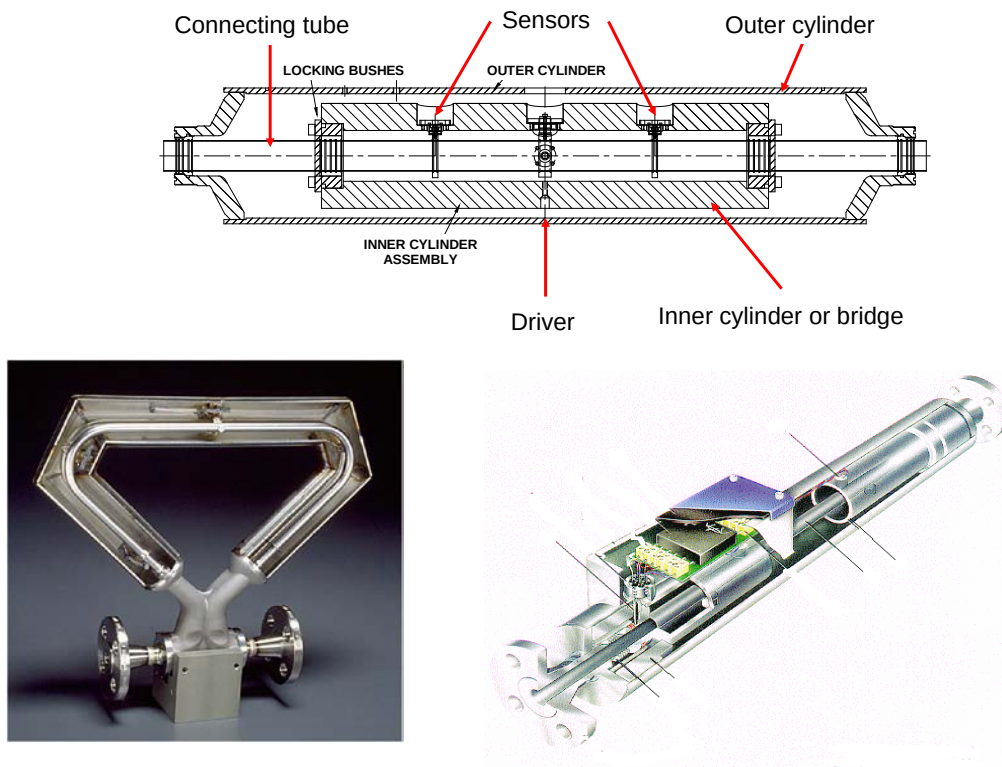


Figure 2—Vibrating-element Density Meters

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:

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

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, τ . 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:

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

Where:

ρ = density of the fluid (raw)

τ = 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.

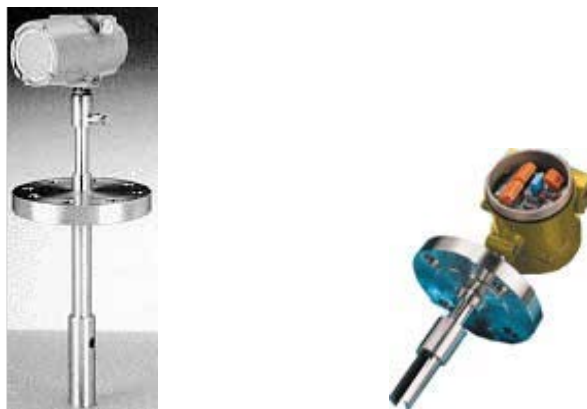


Figure 3—Vibrating-element (Insertion) Density Meters

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 CO₂ and CO₂ 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.

- The uncertainty of the density reading should be better than 0.10 % of the true density.
- The selected density meter shall have a minimum repeatability of ± 0.05 % over the range of design operating conditions.
- 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.
- 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).
- Install the meter in accordance with the criteria given in Section 10, as well as the manufacturer's recommendations.
- 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/m³ crude oil of approximately 0.01 %, for 600 kg/m³ natural gasoline of approximately 0.03 %, and for 500 kg/m³ 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 CO₂ 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:

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

Where:

ρ_{te} = density compensated for thermal effects on sensor

ρ = 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:

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

Where:

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

ρ_{te} = density compensated for thermal effects on sensor

p = flowing gauge pressure at the density meter

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

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

K_{20A} , K_{20B} , K_{21A} , K_{21B} = 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 CO₂;
- 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 (ΔP) 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 ΔP is too low, the velocity through the density meter will not provide a representative sample and temperature equilibrium will not be achieved. If the ΔP 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:

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

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/cm²)

ρ = density of probe material (kg/m^3)

In U.S. customary units:

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

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)

ρ = 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.

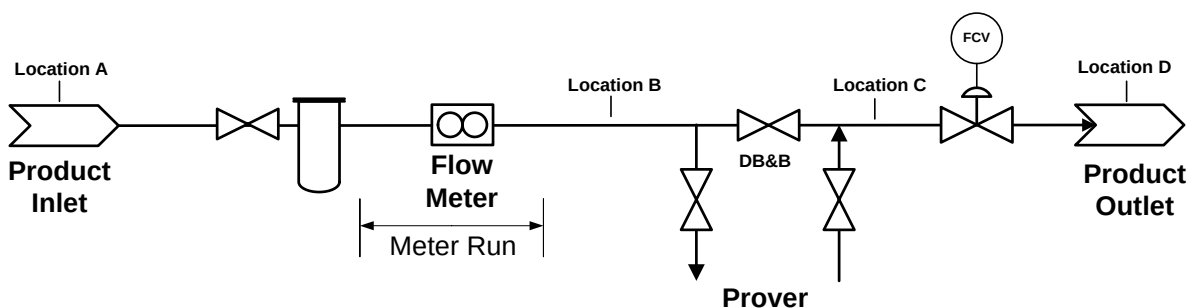


Figure 5—Volume Measurement

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.

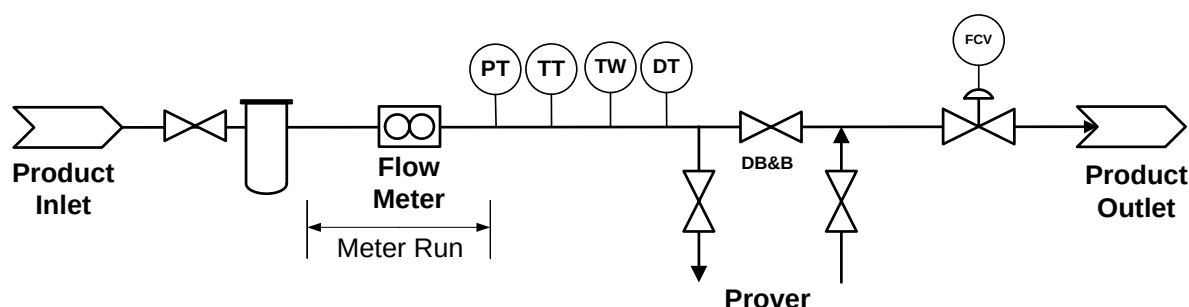


Figure 6—Inferred Mass Flow Measurement

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.