Preparation and Testing of Foamed Cement Formulations at Atmospheric Pressure

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1 Scope

This standard defines the test methods including the generation of unfoamed base and their corresponding foamed cement slurries at atmospheric pressure. These procedures are developed for foaming cement slurries with air, at atmospheric conditions, which could mimic a foam quality experienced with nitrogen at downhole conditions; they may be modified to accommodate other gases such as nitrogen. Slurries that are foamed with nitrogen, and their properties, will also be discussed within this standard as they are relevant to the scope of the standard.

This standard does not address testing at pressures above atmospheric conditions, nor does this standard include or consider the effects of nitrogen solubility in the nitrogen fraction calculations.

2 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. However, not all documents listed may apply to your specific needs. The body of the standard should be referred to for how these documents are specifically applied. For a list of other standards associated with this standard, see the Bibliography.

API Recommended Practice 10B-2, *Recommended Practice for Testing Well Cements*

API Recommended Practice 10B-3, *Recommended Practice on Testing of Deepwater Well Cement Formulations*

3 Terms, Definitions, and Symbols

3.1 Terms and Definitions

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

3.1.1
additive
Material added to a cement slurry to modify or enhance some desired property.

3.1.2
batch mixing
Process of mixing and holding a volume of cement slurry prior to placement in the wellbore.

3.1.3
cement
Portland cement
Material formed by the grinding of clinker, generally consisting of hydraulic calcium silicates and aluminates and usually containing one or more of the forms of calcium sulfate added during grinding.

3.1.4
compatibility
Capacity to form a fluid mixture that does not undergo undesirable chemical and/or physical reactions.

3.1.5
compressive strength
Strength of a set cement sample measured by the force required to cause it to fail in compression, expressed as force per unit area.

3.1.6
consistometer
Device used to measure the thickening time of a cement slurry at specified temperature and pressure.

NOTE An atmospheric consistometer can be used to condition fluids prior to testing and for determining the thickening time of arctic slurries.

3.1.7
foamed cement
Cement slurry containing a stable gas fraction (typically nitrogen) well dispersed and entrained within the slurry.

3.1.8
free fluid
Colored or colorless liquid that has separated from a cement slurry when standing in a static condition.

3.1.9
nitrogen fraction
Volume percent nitrogen within a volume of foamed cement slurry, commonly referred to as foam quality.

NOTE In the laboratory the nitrogen fraction will typically be created with air. Nitrogen fraction is a function of temperature and pressure and thus can vary widely during job placement.

3.1.10
relative density
specific gravity
Ratio of the mass of a substance to the mass of an equal volume of a standard substance at a reference temperature.

NOTE The standard substance is typically water; the reference temperature is typically 4 °C (39 °F) for a relative density or specific gravity of 1.00.

3.1.11
sedimentation
Separation and settling of solids in a cement slurry.

3.1.12
slurry stability test
Test to determine the degree of sedimentation and/or free fluid development in a cement slurry.

3.1.13
sonic strength
Compressive strength of a cement sample obtained by measuring the velocity of sound through the cement and computing the strength using a correlation to compressive strength measurements.

3.1.14
static fluid loss test
Test to determine filtrate lost from a cement slurry when placed against a 45 µm (325 mesh) screen at 6900 kPa (1000 psi) differential pressure.

3.1.15
thickening time
Time elapsed from the initial application of pressure and temperature to the time at which the slurry reaches a consistency deemed sufficient to make it unpumpable (e.g. 70 Bc or 100 Bc).

NOTE The results of a thickening-time test provide an indication of the length of time a cement slurry can remain pumpable under the test conditions.

3.1.16

unfoamed base cement slurry

Cement slurry utilized to create a foamed cement that does not contain the surfactant(s), or gas fraction of the foamed cement slurry.

3.1.17

unfoamed base cement slurry with surfactants

Cement slurry utilized to create a foamed cement that does contain the surfactant(s), utilized to create the foamed cement slurry.

3.1.18

unstable foamed cement

Foamed cement that fails to maintain the evenly and well dispersed nitrogen (or gas) fraction following foam generation.

NOTE In the laboratory the nitrogen fraction will typically be created with air; a foamed cement that cannot be foamed to the desired nitrogen (or gas) fraction may remain stable but may not be fit for purpose and should be redesigned.

3.2 Symbols

d_{rel}	relative density of the set cement segment
m_{a}	mass of additive(s) without surfactants
m_{airf}	foamed cement segment weight in air
m_{BWOS}	mass of unfoamed base cement slurry with no surfactant(s)
m_{BWS}	mass of unfoamed base cement slurry with surfactant(s) to be placed in the blending container
m_{c}	cement mass
m_{s}	mass of surfactant(s)
m_{w}	mix water mass
m_{waterf}	foamed cement segment weight in water
m_{wfb}	mass of water to fill blender (used to determine blender volume)
$V_{\mathrm{ad.abs}}$	solid additive volume
V_{bc}	blending container volume
V_{BWOS}	slurry volume without surfactant(s)
V_{BWS}	unfoamed base cement slurry volume with surfactant(s)
$V_{\mathrm{c.abs}}$	cement volume
V_{w}	mix water volume
$v_{\mathrm{ad.abs}}$	solid additive absolute volume
$v_{\mathrm{c.abs}}$	cement absolute volume
w_{s}	mass fraction of surfactant(s) expressed as a percentage
φ_{N2A}	nitrogen fraction required to achieve the design downhole density at estimated downhole conditions of pressure and temperature in the well at atmospheric conditions expressed as a percentage
φ_{N2L}	nitrogen fraction in the lab
ρ_{BWOS}	base cement slurry density without surfactant(s)
ρ_{BWS}	density of the unfoamed base cement slurry with surfactant(s)
ρ_{FA}	atmospheric foamed cement slurry density calculated with the required nitrogen fraction to achieve the design downhole density (at estimated downhole conditions of pressure and temperature in the well)

ρ_{FD}	targeted in situ downhole density of the foamed cement slurry
ρ_{N2D}	downhole density of nitrogen at the estimated pressure and temperature in the well (expressed in grams per centimeter or kilograms per cubic meter; can be obtained from Annex A)
ρ_{set}	density of set cement segment
ρ_{Water}	density of water

4 Sampling

4.1 General

Samples of the water, cement material or cement blend, and additives (solid or liquid) used for mixing are required to test a foamed cement slurry. These samples shall be obtained in accordance with API 10B-2. Appropriate sampling equipment and methods should be used to obtain samples. Wellsite, or representative samples, should be used to ensure the test materials match as closely as possible to those used for job execution.

4.2 Method

Applicable sampling techniques for the fluids and materials used in foamed cementing operations can be found within API 10B-2.

5 Slurry Calculations

5.1 Introduction

The maximum nitrogen fraction calculations are based on the properties of nitrogen at anticipated in situ downhole conditions. Nitrogen fraction calculations can be performed using the equations and tables contained in this standard, or by the use of a numerical foamed cement simulator. Small, but acceptable, differences in nitrogen fraction results may occur due to variations in compressibility factors (Z nitrogen) between the tables within this standard and those used by numerical simulators.

Laboratory preparation and testing are performed based on the results of these calculations using air (instead of nitrogen). At atmospheric conditions, the differences between cement foamed with nitrogen or air are not significant.

5.2 Calculation of Base Cement Slurry Composition With and Without Surfactant(s)

The base cement slurry for preparing a foamed cement slurry contains surfactant(s) that cannot be added to the base cement slurry for initial mixing. This requires calculation of the relative mass percentage (mass fraction) of the surfactant(s) in the foamed cement slurry. This is done by taking the total mass of the surfactant(s) and dividing by the total mass of the base cement slurry. For these calculations, “additives” are considered as all additives added to mix the initial base cement slurry and exclude the surfactant(s) used for foaming the system.

The mass fraction of surfactant(s), w_S, expressed as a percentage, can be calculated according to Equation (1):

$$w_s = \frac{m_s}{m_c + m_a + m_s + m_w} \times 100 \tag{1}$$

where

w_S is the mass fraction of surfactant(s) expressed as a percentage;

m_S is the mass of surfactant(s) expressed in grams;

m_C is the cement mass expressed in grams;

m_a is the additive(s) mass without surfactants expressed in grams; and

m_w is the mix water mass expressed in grams.

NOTE Mass fraction for other components of the foamed cement (such as cement and water) can be calculated by Equation (1) and replacing the numerator, mass of surfactant(s), m_s, by the mass of the foamed cement component (such as cement and water).

If desired, the base cement slurry density without surfactant(s), ρ_{BWOS}, can be calculated in grams per cubic centimeter according to Equation (2):

$$\rho_{BWOS} = \frac{m_c + m_a + m_w}{(m_c \times v_{c.abs}) + (m_a \times v_{ad.abs}) + V_w} \quad (2)$$

where

ρ_{BWOS} is the base cement slurry density without surfactant(s) expressed in grams per cubic centimeter;

m_c is the cement mass expressed in grams;

m_a is the additive(s) mass without surfactants expressed in grams;

m_w is the mix water mass expressed in grams;

$v_{c.abs}$ is the cement absolute volume expressed in cubic centimeters per gram;

$v_{ad.abs}$ is the solid additive absolute volume expressed in cubic centimeters per gram; and

V_w is the mix water volume expressed in cubic centimeters.

NOTE 1 Mass and volume calculations are described in API 10B-2.

NOTE 2 Mass fraction and density can be calculated using homogeneous metric (SI) or U.S. customary (USC) units.

5.3 Determination of Slurry Volume and Mass

5.3.1 General

Determine the volume of unfoamed base cement slurry to be used. The total volume of unfoamed base cement slurry shall include the volume of surfactant(s) to be added to the base cement slurry. The surfactant(s) is (are) added after the initial mixing of the base cement slurry.

During the job design process the maximum nitrogen fraction in the annulus following cement placement (in situ) shall be determined for each foamed cement job and is typically determined with computer-aided foamed cement job design tools. The maximum nitrogen fraction should be agreed by the user and the provider of the foamed cement before testing begins. This maximum nitrogen fraction shall be utilized during testing to evaluate the stability of the foamed cement slurry as specified in 8.3.

Nitrogen is a real gas; therefore, not only does the volume of nitrogen change with pressure and temperature but also its density. Pre-calculated nitrogen densities are also provided in tables within Annex A. The nitrogen density can be calculated using the equations in Annex B, which include the compressibility factor (Z nitrogen). Nitrogen compressibility factors are provided within Annex C, Table C.1 (for SI units) and Table C.2 (for USC units).

Once the pressure and temperature are determined for laboratory testing, the appropriate atmospheric nitrogen fraction can be determined utilizing the nitrogen density tables in Annex A and the equations as specified in 5.3.

NOTE Refer to Annex D for example calculations.

5.3.2 Atmospheric Nitrogen Fraction to Achieve the Design Density Calculated with the Downhole N_2 Density at the Estimated Pressure and Temperature in the Well

Utilizing the design downhole density and the estimated pressure and temperature in the well, the laboratory nitrogen fraction φ_{N2A} (i.e. volume fraction of gas) is calculated according to Equation (3):

$$\varphi_{N2A} = \frac{\rho_{BWS} - \rho_{FD}}{\rho_{BWS} - \rho_{N2D}} \times 100 \tag{3}$$

where

φ_{N2A} is the nitrogen fraction required to achieve the designed downhole density at estimated downhole conditions of pressure and temperature in the well at atmospheric conditions expressed as a percentage

ρ_{BWS} is the density of the unfoamed base cement slurry with surfactant(s), expressed in kilograms per cubic meter at downhole conditions;

ρ_{FD} is the targeted in situ (downhole) density of the foamed cement slurry, expressed in kilograms per cubic meter; and

ρ_{N2D} is the downhole density of nitrogen at the estimated pressure and temperature in the well, expressed in kilograms per cubic meter, obtained from Annex A.

Stability and compressive strength testing of the foamed cement shall be conducted at the nitrogen fraction (expressed as a percentage) required to achieve the designed downhole density at estimated downhole conditions of pressure and temperature in the well at atmospheric conditions.

NOTE 1 To facilitate the use of the tables in Annex A, the density terms according to Equation (3) can be expressed in units of kg/m^3 or lbm/gal; if the density is expressed in kg/m^3, to express the density in g/cm^3 divide the value by 1000.

NOTE 2 The atmospheric laboratory prepared density will vary from the target in situ (downhole) density (see 5.3.7).

5.3.3 Calculation of Atmospheric Foamed Cement Slurry Density Utilizing the Nitrogen Fraction Required to Achieve the Design Downhole Density at Estimated Downhole Conditions of Pressure and Temperature in the Well

The atmospheric foamed cement slurry density (ρ_{FA}) with the required nitrogen fraction to achieve the design downhole density, at estimated downhole conditions of pressure and temperature in the well (φ_{N2A}) can now be calculated according to Equation (4):

$$\rho_{FA} = \frac{100 - \varphi_{N2A}}{100} \times \rho_{BWS} \tag{4}$$

where

ρ_{FA} is the atmospheric foamed cement slurry density calculated with the required nitrogen fraction to achieve the design downhole density, at estimated downhole conditions of pressure and temperature in the well, expressed in grams per cubic centimeter;

φ_{N2A} is the nitrogen fraction required to achieve the design downhole density at estimated downhole conditions of pressure and temperature in the well at atmospheric conditions expressed as a percentage;

ρ_{BWS} is the density of the unfoamed base cement slurry with surfactant(s), expressed in grams per cubic centimeter.

5.3.4 Mass of Unfoamed Base Cement Slurry with Surfactant(s) Required for Testing

The mass of cement slurry in grams, including surfactant(s), m_{BWS}, to be placed into the blending container to prepare the foamed cement slurry can be calculated according to Equation (5):

$$m_{BWS} = V_{bc} \times \rho_{FA} \tag{5}$$

where

m_{BWS} is the mass of unfoamed base cement slurry with surfactant(s) to be placed in the blending container, expressed in grams;

V_{bc} is the blending container volume, expressed in cubic centimeters; and

ρ_{FA} is the atmospheric foamed cement slurry density, expressed in grams per cubic centimeter and calculated with the required nitrogen fraction to achieve the design downhole density, at estimated downhole conditions of pressure and temperature in the well.

5.3.5 Surfactant(s) and Base Cement Slurry Mass Required for Testing

The masses of surfactant(s), m_S, and mass of unfoamed base cement slurry with no surfactant(s), m_{BWOS}, required for testing are found according to Equations (6) and (7).

The mass of surfactant(s) to be placed into the blending container with the unfoamed base cement slurry, m_{BWS}, can be calculated according to Equation (6):

$$m_s = m_{BWS} \times \frac{w_s}{100} \tag{6}$$

where

m_S is the mass of surfactant(s), expressed as a percentage;

m_{BWS} is the mass of unfoamed base cement slurry with surfactant(s) to be placed in the blending container, expressed in grams; and

w_S is the mass fraction of surfactant(s), expressed in grams.

The mass of unfoamed base cement slurry with no surfactants, m_{BWOS}, can be calculated according to Equation (7):

$$m_{BWOS} = m_{BWS} - m_s \tag{7}$$

where

m_{BWOS} is the mass of unfoamed base cement slurry with no surfactant(s), expressed in grams;

m_{BWS} is the mass of unfoamed base cement slurry with surfactant(s), expressed in grams; and

m_S is the mass of surfactant(s), expressed in grams.

NOTE The percentage contribution of each material by mass was determined as specified in 5.2.

5.3.6 Volume and Mass of Unfoamed Base Cement Slurry Required for Testing

The volume of unfoamed base slurry with surfactant(s), V_{BWS}, may also be calculated utilizing the laboratory atmospheric density calculated according to Equation (4); see 5.3.3. This density is calculated utilizing the nitrogen fraction required to achieve the designed downhole density at the estimated conditions of pressure and temperature in the well according to Equation (3); see 5.3.2.

The volume of unfoamed base cement slurry, V_{BWS}, can be calculated according to Equation (8):

$$V_{BWS} = V_{bc} - \frac{V_{bc} \times \varphi_{N2A}}{100} \tag{8}$$

where

V_{BWS} is the unfoamed base cement slurry volume, expressed in cubic centimeters;

V_{bc} is the blending container volume, expressed in cubic centimeters; and

φ_{N2A} is the nitrogen fraction required to achieve the design downhole density at estimated downhole conditions of pressure and temperature in the well at atmospheric conditions expressed as a percentage.

The mass of unfoamed base cement slurry, m_{BWS}, can be calculated according to Equation (9):

$$m_{BWS} = V_{BWS} \times \rho_{BWS} \tag{9}$$

where

m_{BWS} is the mass of unfoamed base cement slurry with surfactant(s), expressed in grams;

V_{BWS} is the slurry volume of the unfoamed base cement slurry with surfactant(s), expressed in cubic centimeters; and

ρ_{BWS} is the density of the unfoamed base cement slurry with surfactant(s), expressed in grams per cubic centimeter.

5.3.7 Density of a Laboratory Atmospherically Foamed Cement

Following the generation of the foamed cement slurry, the density (ρ_{FA}) may be calculated according to Equation (10):

$$\rho_{FA} = \frac{100 - \varphi_{N2L}}{100} \times \rho_{BWS} \tag{10}$$

where

ρ_{FA} is the atmospheric foamed cement slurry density calculated with the required nitrogen fraction to achieve the design downhole density, at estimated downhole conditions of pressure and temperature in the well, expressed in grams per cubic centimeter;

φ_{N2L} is the nitrogen fraction in the lab, expressed as a percentage; and

ρ_{BWS} is the density of the unfoamed base cement slurry with surfactant(s), expressed in grams per cubic centimeter.

NOTE An example of the use of these equations for calculations can be found in Annex D.

6 Base Cement Slurry Preparation and Testing

6.1 General

For the following tests performed on the unfoamed base cement slurry, the unfoamed base cement slurry without the surfactants(s) shall be prepared in accordance with API 10B-2. After the slurry is prepared, stop the blending container, add the surfactant(s), and stir gently with a spatula to distribute it uniformly in the slurry. It is recommended that the slurry should be poured gently from the blending container to a beaker and back three times to ensure a uniform distribution of the surfactant(s).

When testing unfoamed base slurry with surfactants, air entrainment can potentially create errors in some test results. A small amount of defoamer can be used to prevent air entrainment in the laboratory. This is not recommended when testing foam stability in the laboratory and is not recommended during field applications in oil and gas wells.

NOTE Preparation of sufficient volume of the base cement slurry may require multiple mixes using the standard mixing procedure, or use of a large laboratory blender; see preparation of large slurry volumes in API 10B-2.

6.2 Conditioning Procedures

For conditioning procedures for testing of the unfoamed base cement slurry, refer to API 10B-2 or API 10B-3. Report any conditioning procedure used in the preparation of the unfoamed base slurry.

6.3 Density Measurement

The density of the unfoamed base cement slurry with surfactants can be determined by methods found in API 10B-2. Failure to measure the atmospheric density of the base slurry, inclusive of the foaming surfactant(s), will lead to incorrect volumes in the blender and subsequent incorrect air fraction of the foamed slurry.

6.4 Stability of Unfoamed Base Cement Slurry

The unfoamed base cement slurry with surfactant(s) shall be evaluated in accordance with API 10B-2. The unfoamed base slurry with surfactant(s) shall be stable. If the unfoamed base cement slurry shows signs of instability, redesign the slurry.

Some signs of instability can include:

a) excessive free fluid;

b) streaking or light to dark color change from top to bottom; and/or

c) large variations in density from sample top to bottom in the sedimentation test.

6.5 Determination of Rheological Properties

Rheological properties test on the unfoamed base cement slurry with surfactant(s) shall be performed in accordance with API 10B-2 or API 10B-3.

NOTE Use of the rotational viscometer with a foamed cement slurry may result in separation of the gas from the slurry, causing erroneous results.

6.6 Determination of Static Fluid Loss

Fluid-loss tests performed on the foamed cement slurry prepared at atmospheric pressure may not yield reliable results and should not be performed. Specialized test methods have determined that fluid-loss values obtained from a foamed cement slurry are lower than those from a base unfoamed cement slurry. The fluid loss of the unfoamed base cement slurry with surfactant(s) is normally used as an indication of the fluid loss of the foamed cement slurry.

The static fluid loss test on the unfoamed base cement slurry containing the surfactant(s) shall be performed in accordance with API 10B-2.

6.7 Determination of Thickening Time

As surfactant(s) can affect the thickening time, the thickening-time test is normally performed using a standard high-pressure high-temperature (HPHT) consistometer on the unfoamed base cement slurry containing the surfactant(s).

Thickening-time test on the unfoamed base cement slurry shall be performed in accordance with API 10B-2.

6.8 Determination of Compressive Strength

While the compressive strength values of the unfoamed base cement will not match the compressive strength of the foamed slurry, the time required to develop initial compressive strength in the unfoamed base cement slurry may be used to approximate the time required to develop initial compressive strength in the foamed slurry. To estimate the approximate time required to develop initial compressive strength, perform a nondestructive sonic strength test on the unfoamed base cement slurry containing the surfactant(s); this test shall be performed in accordance with API 10B-2 or API 10B-3 for deepwater applications.

6.9 Compatibility

Compatibility testing on the unfoamed base slurry shall be performed in accordance with API 10B-2.

7 Preparation of Foamed Cement Slurry at Atmospheric Pressure

7.1 Unfoamed Base Cement Slurry Preparation

7.1.1 General

Unfoamed base slurries containing all additives except foaming surfactant(s) shall be prepared in accordance with API 10B-2. The time from the initial preparation of the unfoamed base cement slurry to the time the foamed cement is generated should be as quick as possible and not exceed 10 minutes.

All testing apparatuses used shall be calibrated in accordance with API 10B-2.

7.1.2 Temperature Considerations

The temperatures of the cement sample, additives, and mix water should be within ±1 °C (±2 °F) of the ambient temperature in the laboratory. The temperature of the cement sample, additives, and water shall be measured and reported.

7.1.3 Conditioning Procedures

Current methods do not provide fully representative HPHT conditioning of foamed slurries.

Conditioning the unfoamed base cement slurry used for the preparation of foamed cement at atmospheric pressure may have an effect on foamed cement slurry stability. Slurry conditioning for atmospheric foamed cement testing is limited to simulation of batch mixing. If conditioning of the unfoamed base cement slurry is performed, then a comparison of conditioned and unconditioned unfoamed base cement slurry that is subsequently foamed should be performed and reported to provide information regarding the foamed slurry stability.

The conditioning schedule shall be reported with any resulting test data of foamed cement slurries.

If the foamed cement used in the field is generated utilizing a recirculating mixing system and pumped downhole (“mixed on-the-fly”), then the time from mixing the base slurry to the point of the initial foam generation on surface will not be accurately represented by slurries conditioned at bottom-hole conditions. Therefore, if testing is conducted to determine the stability of the foam at conditions of surface foam generation, then conditioning schedules, if any, should reflect surface pressure, temperature, and slurry residence time as closely as possible.

7.2 Blending Apparatus

7.2.1 Blending Container

The blending container is similar to that used for standard slurry preparation, except it has a threaded cap with an O-ring seal and a removable plug. A conventional blending container that does not have a seal cannot be used for these tests. The base and the cap shall have a matching demarcation line to show closure level. This will ensure that the volumes used are identical each time the cap is closed, regardless of user.

7.2.2 Mixing Blade Assembly

Multi-blade (stacked-blade) assembly is constructed of a series of blade assemblies (see Figure 1), and each individual blade assembly shall be in accordance with API 10B-2.

Figure 1—Blending Container and Multi-blade Assembly

The assembly consists of five standard blades attached to a central shaft and spaced equally along the shaft.

The blender motor should be capable of providing 12,000 revolutions per minute (r/min) to an unfoamed base slurry with the stacked blade assembly.

If 12,000 r/min is not achieved, report achieved at end of mixing and record the final revolutions per minute of the mixer before mixing is terminated.

7.2.3 Determination of Blending Container Volume

This method assumes the base cement slurry as described in 5.2 is prepared in a separate blending container and this prepared slurry weighed into the blending container with a sealed lid. Accurate determination of the volume of the blending container is critical to this procedure. The calculations for slurry volume, density, and foamed cement slurry-to-gas ratio are based on determination of this sealed lid container volume. The volume shall be determined as follows:

a) weigh the clean dry blending container (including mixing assembly, screw-on lid, and screw-in plug for the lid), record the weight, then tare the balance to zero in preparation to determine the mass of water to fill the blender;

b) remove the screw-on lid from the blending container and remove the screw-in plug from the lid;

c) fill the blending container with distilled water or measure the density of the water using a hydrometer and water temperature (refer to API 13J);

d) screw the lid on tightly so that the base and cap matching demarcation lines indicate the correct closure level;

e) pour additional water into the hole in the lid until the container is completely full and screw the plug into the lid;

f) wipe the excess water that exits from the plug's vent hole; and

g) re-weigh the container and record the mass of the water inside the container (m_{wfb}).

To determine the volume of the blending container, the mass of the water inside the container is divided by the density of the water to determine an accurate volume for the blending container according to Equation (11):

$$V_{\text{bc}} = \frac{m_{\text{wfb}}}{\rho_{\text{water}}} \qquad (11)$$

where

V_{bc} is blending container volume expressed in cubic centimeter; and

m_{wfb} is mass of water to fill blender expressed in grams; and

ρ_{water} is density of water expressed in grams per cubic centimeter.

The volume of the blending container shall be checked any time the blades are replaced, or after any damage to the container that may affect the volume. The volume shall be verified at least every six months.

7.3 Generation of a Foamed Cement Slurry

7.3.1 Mass of Cement Slurry

Using the mass calculated as specified in 5.3, weigh half of the appropriate amount of the prepared unfoamed base cement slurry with no surfactant(s) into the blending container. Add the calculated amount of surfactant(s). Add the remaining half of the prepared unfoamed base cement slurry. The final mass of the base cement slurry and added surfactant(s) should be checked against the final desired base cement slurry mass calculated as specified in 5.3.4.

The weigh up should use the nitrogen fraction for the atmospheric conditions (see 5.3.1).

NOTE More than one mixing of base slurry may be needed.

7.3.2 Cement Slurry Mixing

Place the lid (containing the plug) on the mixing container and make sure the blending container is sealed. Using the blade assembly as specified in 7.2.2, mix the slurry at the 12,000 r/min setting for 15 seconds. If the slurry does not fill the blending container at the end of 15 seconds, the slurry shall be redesigned.

NOTE During the mixing, there will be a noticeable change in the sound (pitch) from the blending container indicating that the blender is full of foamed cement.

7.3.3 Mixing Completed

After mixing, remove the plug at the top of the blending container and check that the slurry completely fills the container.

Because of the slurry volume and viscosity increase when foamed, the maximum revolutions per minute of the blending container blade(s) may be less than 12,000 r/min. The maximum attainable revolutions per minute depend on the power of the blending container motor, slurry density and slurry air (nitrogen) fraction. Record the revolutions per minute at the end of mixing.

When preparing the foamed cement slurry in the sealed blending container, it is common for the final density of the foamed cement slurry to be less than designed. It is likely due to expansion caused by the temperature increase generated from the mixing energy. The foamed cement slurry may expand upon removal from the blending container.

Some testing performed has indicated that the foam expansion that occurs in the sealed blending container after foaming may not be strictly caused by heat generation. By sealing the top of the plug in the blending container, it may be possible to obtain acceptable foam densities from the initial mixing design without using the low density slurry offset procedure as specified in 7.3.5.

One method to obtain a foamed cement slurry having a density closer to the design density is described below; see 7.3.4 and 7.3.5.

7.3.4 Checking Slurry Design

Check the slurry design for use in laboratory tests in accordance with the following procedure:

a) design the cement slurry density to be foamed [e.g. 1.893 g/cm^3 base cement slurry foamed to 1.318 g/cm^3 (15.8 lbm/gal foamed to 11.0 lbm/gal)];

b) prepare the 1.318 g/cm^3 (11.0 lbm/gal) foamed cement slurry in the laboratory according to the design; and

c) measure the density of the foamed cement slurry according to 8.2.

If the volume of the blending container is not completely filled with foamed cement slurry or if the measured foam density is above the design, it may be difficult to obtain the proper foamed cement density in the field, and the slurry should be redesigned.

If the measured density is less than designed, see 7.3.5.

7.3.5 Low Slurry Density

If the measured density is less than the design [e.g. 1.246 g/cm^3 (10.4 lbm/gal)], the following procedure can be used to check design calculations:

a) if the calculations are correct, subtract the measured density from the design density to obtain an "offset correction" [e.g. 1.318 g/cm^3 – 1.246 g/cm^3 = 0.072 g/cm^3 (11.0 lbm/gal – 10.4 lbm/gal = 0.6 lbm/gal) offset correction];

b) recalculate the slurry density using the offset correction [e.g. 1.318 g/cm^3 + 0.072 g/cm^3 = 1.390 g/cm^3 (11.0 lbm/gal + 0.6 lbm/gal = 11.6 lbm/gal)];

c) prepare a new foamed cement slurry according to the corrected density [e.g. 1.890 g/cm^3 foamed to 1.390 g/cm^3 (15.8 lbm/gal foamed to 11.6 lbm/gal)]; and

d) measure the density of the foamed cement slurry; the density of this foamed cement slurry should be close to the desired density of 1.318 g/cm^3 (11.0 lbm/gal).

If this density is still not acceptable, obtain a new offset correction and prepare a new base cement slurry.

The user and provider of the foamed cement should agree on an acceptable density decrease limit to indicate when this correction factor should be applied.

8 Atmospheric Testing of Foamed Cement Slurries

8.1 General

Because of the high volume of gas in a foamed cement slurry, it is necessary to modify some of the standard testing procedures to prevent erroneous test results.

8.2 Determination of Foamed Cement Slurry Density

The density of the foamed cement slurry shall be determined by pouring the foamed cement slurry into a large open top container (no pouring lip and flat across the top) that has a known volume no less than 150 ml when completely filled. A rheometer cup will work fine after being calibrated.

Calibrate the container with water by determining the mass of the water in the container after filling with water (see 7.2.3).

Measure and report the temperature of the foamed cement slurry that is being tested.

Weigh the container then gently pour the foamed cement slurry, with minimal agitation to avoid additional air entrainment, into the container and level the top with a straight blade. Wipe the outside of the container clean and again weigh the container with the slurry. The density of the foamed cement slurry in the container is determined by dividing the slurry mass by the container volume and converting to the appropriate density units.

A balance is required for foamed cement density measurement. This balance shall have accuracies in accordance with API 10B-2. A pressurized fluid density balance should never be used to determine the density of a foamed cement slurry prepared at atmospheric pressure. This can compress the gas bubbles and the slurry density indication will be too high. A nonpressurized slurry density balance is not recommended because the small hole in the center of the lid can cause a restriction resulting in partial pressurization of the slurry. This can cause errors in the density determination.

8.3 Determination of Foamed Cement Slurry Stability

8.3.1 General

To utilize the test method within this recommended practice, it is necessary to determine the maximum predicted nitrogen fraction of the foamed cement slurry in the annulus following cement placement (in situ). This value is typically determined with the use of computer-aided cement job design tools. The maximum nitrogen fraction should be determined and agreed to by the user and the provider of the foamed cement before testing begins. This maximum nitrogen fraction shall be utilized during testing to evaluate the stability of the foamed cement slurry for any job design (see 5.3.1).

NOTE This method does not address the maximum nitrogen fraction that may occur at or near the surface inside the casing; the foaming methods, and equipment, applied in this document are often not capable of producing stable foamed cements at the maximum nitrogen fraction often predicted in this part of the well.

8.3.2 Stability of Unset Foamed Cement Slurry

The stability of the unset foamed cement slurry shall be evaluated. Evaluate the foam stability by pouring a sample of the foamed cement slurry into a standard 250-ml graduated cylinder. The dimensions of the graduated cylinder shall be in accordance with API 10B-2 Free Fluid Test (length = 232 mm to 250 mm with 2 ml or less graduations). Seal the top of the cylinder to prevent dehydration.

Allowing temperature fluctuation during the test will impact the gas fraction in the sample and potentially impact stability. Temperature should be maintained in accordance with 7.1.2. Placing the sample in a water bath should help to provide a more constant temperature environment. Let stand for a 2-hour period ±1 minute. Vibrations to the container should be minimized to the extent reasonably possible. Any decrease in the final height of the foamed cement column should be recorded as a percentage of total height. Any other evidence of potential instability shall be reported. A digital photograph of the slurry in the graduated cylinder at the start of the test and following the 2-hour period ±1 minute shall be reported. The cylinder contents cannot be cured at temperatures above ambient temperature in the laboratory because an increase in temperature will increase the bubble size and slurry volume and may affect the slurry stability.

8.3.3 Stability of Set Foamed Cement Slurry

8.3.3.1 General

The stability of the set foamed cement shall be evaluated. The set foamed stability is evaluated by determining the set sample's density and through visual inspections made for bubble consistency, overall volume reductions, or other indications of foam instability as specified in 8.3.5.

Samples may be cured in covered cylinders of at least 25.4-mm diameter × 101.6-mm height (1-in. diameter × 4-in. height); the most common tube length is 200 mm (7.9 in.). Grease or other mold-release agents should not be used as these materials can affect the stability of the foamed cement slurry. The tube (or other sample container) should be placed vertically to evaluate set foamed cement stability.

Allow the sample to set, remove the cement from the tube, and photograph the sample. Samples for density determination shall be prepared in accordance with 8.3.3.2.

NOTE These tests are intended for evaluation of foam cement slurries at room temperature; it is possible that foam cement slurries designed for higher temperatures may not set at room temperature.

8.3.3.2 Density Determination

8.3.3.2.1 The mass of each section in air and in water can be determined as follows.

a) Measure and record the length of the cement sample.

b) Mark the sample approximately 20 mm (0.75 in.) from the bottom and from the top.

    1) Divide the section between the marks by further marks into segments of roughly equal length with a minimum of four segments.

    2) Mark the segments to keep track of their order.

c) Break or cut the cement sample at these mark.

    NOTE If using a saw to segment the cement sample, do not use a saw that uses water as the segments will absorb water during preparation.

d) Photograph each segment alongside a ruler for scale; note and record any change in appearance between the segments.

e) To determine the density of the segments, place a beaker containing water on the balance and tare the balance to zero.

NOTE A balance with a precision of 0.01 g is necessary.

f) Place a segment on the balance beside the beaker.

g) Record the weight of the foamed cement segment, m_{airf}, and remove the segment from the balance.

h) Tare the balance if necessary.

i) Place a noose of thin string around the segment (dental floss works well).

j) Suspend the segment in the beaker such that the segment is totally surrounded by water, but such that the segment should not touch the bottom or the sides of the beaker.

k) Obtain and record the weight of the foamed cement sample, m_{waterf}, with the segment suspended in water, and the length of time the segment was suspended in water.

NOTE Obtain the weight of the sample as quickly as possible (preferably in less than 10 seconds) to prevent excessive water absorption.

l) Remove the segment from the water and tare the balance.

m) Repeat the procedure for each segment.

n) By applying Archimedes Principle, calculate the relative density of each cement segment using Equation (12).

Use of wet measurement techniques may be prone to greater error in cases of high foam quality or significant open bubble structure on the surface of the sample; it is important to take wet measurements as quickly as possible to limit errors.

$$d_{rel} = \frac{m_{airf}}{m_{waterf}} \tag{12}$$

where

d_{rel} is the relative density of the set foamed cement segment;

m_{airf} is the foamed cement segment weight in air, expressed in grams; and

m_{waterf} is the foamed cement segment weight in water, expressed in grams.

8.3.3.2.2 The results are used to construct a density profile for the entire sample.

Reporting of results shall also include at a minimum:

a) original length of sample in an unset state (this may be the length of the sample tube);

b) length of the sample after set;

c) relative densities of the samples;

d) comments on visual inspection to include:

1) consistency of bubble distribution—noting any variance in size of bubbles from top to the bottom of the sample or between samples; and

2) presence of any streaking or other color anomalies.

Photos of the samples shall be included in the final report. Every effort should be made to test samples from the very top and bottom of the prepared sample.

Relative density difference calculations between slurry and set foamed cement shall be performed in accordance with API 10B-2.

The density differences between slurry and set foamed cements, and the density difference from top to bottom in the set foamed cement, can vary greatly and depend on many factors. The amount of density difference that is acceptable varies with the application and should be defined prior to testing and the results should be considered prior to job execution.

8.3.4 Evaluating Foamed Cement Slurry Stability at Temperature <90 °C (194 °F)

The following procedure shall be followed for evaluating foamed cement slurry stability at temperatures <90 °C (194 °F).

a) Prepare an appropriate mold for curing the foamed cement slurry sample.

For example, a PVC or HPVC (high-temperature PVC) curing mold can be prepared by applying primer/cleaner and glue to the PVC parts and assembling them in the manner shown in Figure 2.

Allow sufficient time for the glue to harden. Apply a nonadhesive sealing tape to the threads of the brass fittings.

NOTE 1 PVC or other plastic material is preferred because the foamed cement slurry will not bond to the mold material; other materials are acceptable provided a mold-release compound is not used on the surface of the mold.

NOTE 2 The use of a 50 mm × 50 mm (2 in. × 2 in.) mold for this section is not appropriate as there is insufficient length to properly determine density variations within the sample.

b) Pour the foamed cement slurry into the mold and screw the large brass reducer (or other corrosion-resistant material) into the top until tight.

1) Slurry shall exit the center hole of the large brass reducer.

2) Screw the small brass plug into the large brass fitting and tighten both.

If liquid cement slurry in the fitting threads prevents tightening large brass reducer sufficiently, the curing mold can be filled to below the threads of the large brass reducer. Place and tighten the reducer, then fill the remainder of the curing mold through the hole of the reducer and tighten the small brass plug.

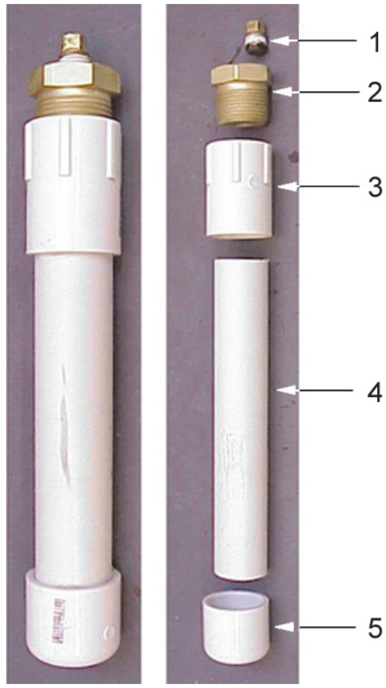
c) Allow the slurry to cure for 24 hours or until set at the desired temperature.

NOTE The sample may be cured in a vertical position or at a specific angle.

d) After curing, cool to room temperature at a rate that will not cause thermal shock induced stress fracturing of the sample.

1) Remove the brass reducer and plug from the top and examine the sample.

2) Note any obvious signs of instability in the top of the sample (see 8.3.5).



Key

1 6.35-mm (1/4-in.) brass plug

2 25.4 mm × 6.35 mm (1 in. × 1/4 in.) brass reducer

3 25.4-mm (1-in.) female adapter for PVC schedule 40 pipe

4 25.4-mm (1-in.) PVC schedule 40 tubing [OD 33.4 mm (1.315 in.), ID 26.6 mm (1.049 in.)], length 152 mm to 203 mm (6 in. to 8 in.)

5 25.4-mm (1-in.) PVC cap

Figure 2—Example of Curing Mold for Evaluation of Foamed Cement Slurry Stability

e) Segment samples for density determination shall be prepared in accordance with 8.3.3.2.

   1) The sample should not be cut with a saw that uses water, since water can be absorbed by the sample and change its density.

   2) If the sample is cut dry, remove any dust resulting from cutting with a brush.

   3) Carefully cut the PVC longitudinally along each segment until the PVC can be removed.

   4) Care should be taken when removing the set cement to assure all of the cement is recovered from the sample container.

f) Examine the set foamed sections for signs of instability (see 8.3.5).

g) The segments shall then be tested for density using the Archimedes Principle according to 8.3.3.2.

h) Results shall be presented in accordance with 8.3.3.2.2.

Figure 3 can be used for the results of the evaluation.

8.3.5 Signs of Unstable Foamed Cement

The acceptance criteria are dependent upon well conditions and should be defined prior to testing.

Some signs of instability in set or unset foamed cement may include:

a) bubble breakout noted by large bubbles on the top of the sample;

b) excessive gap at the top of the specimen (minor meniscus effects are normal);

c) discontinuous column or discontinuity in the column;

d) large variations in density from sample top to bottom or large variation in density from design; and/or

e) visual signs of density segregation as indicated by streaking or light-to-dark color change from top to bottom.

Unfoamed base cement slurry stability shall be confirmed before proceeding to foamed cement stability testing.

Any cement slurry design that shows signs of instability shall be redesigned.

Bubble size variations may be seen better when an entire sample is cut in half from top to bottom. For this observation, one sample can be prepared and cut wet or dry. After cutting, clean the cut surface under running water to expose the bubble cavities for visual inspection and a digital photo.

Figure 3 is merely an example for illustration purposes only and is not to be considered exclusive or exhaustive in nature. Each company should develop its own approach. API makes no warranties, express or implied reliance on, or any omissions from the information contained in the figure/form below.

8.4 Determination of Compressive Strength

Pour the foamed cement slurry into a curing mold that can be sealed. The sealing lid prevents the foamed cement slurry from expanding as it is heated. The expansion can result in an undesired density decrease.

A suitable curing mold is a standard 50-mm (2-in.) cube mold (described in ASTM C109) with a cover (without grooves) and gasket clamped on. Plastic cylinder, 50-mm diameter × 101.6-mm height (2-in. diameter × 4-in. height) with a sealable top and 50-mm (2-in.) plastic cube molds with a sealable lid have also been used.

Place the sealed mold containing the foamed cement slurry into an atmospheric-pressure water bath, cure the sample, and determine the compressive strength. The surface ends of the sample that contact the loading platens shall be parallel, smooth, and planar. This testing shall be conducted in accordance with API 10B-2.

Caution should be used with any plastic molds as the cement sample may expand when heated resulting in an undesired density decrease, or the container may result in surface ends of the sample that are not parallel, smooth, and planar.

NOTE 1 Sample geometry affects the values determined for compressive strength, i.e. strength determined with one sample geometry may not correspond to that of a different geometry.

NOTE 2 Ultrasonic, nondestructive, sonic strength data of the unfoamed base cement slurry can be used to estimate the time for initial strength development.

Preheated or precooled chamber temperature:___________

Total time of test:_______

Time to test temperature :_______

Time at maximum test temperature :________hours

Inside length of sedimentation tube that can contain a fluid volume: __________

Length of sample in an unset state __________

Length of set sample: ___________

Dimensions of each tested sample (length and diameter)

Top sample length: ___________; diameter:_____________

Next sample length: ___________; diameter:_____________

Next sample length: ___________; diameter:_____________

Next sample length: ___________; diameter:_____________

Next sample length: ___________; diameter:_____________

Bottom sample length: ___________; diameter:_____________

Slurry measured density:________________

Density profile:

Top segment density: ___________; % density diff from measured density:____________

Next segment density: ___________; % density diff from measured density:____________

Next segment density: ___________; % density diff from measured density:____________

Next segment density: ___________; % density diff from measured density:____________

Next segment density: ___________; % density diff from measured density:____________

Bottom segment density: ___________; % density diff from measured density:____________

% density diff top to bottom segment:____________

{[1 − (top density ÷ bottom density)] × 100}

Comments on visual inspection to include:

Consistency of bubble distribution—noting any variance in size of bubbles from top to the bottom of the sample or between samples or bubble grouping within a sample or between samples:

Presence of any streaking or other color anomalies:

Other:

Figure 3—Evaluation Report Form: Foamed Cement Slurry Stability at Temperature <90 °C (194 °F)

Annex A
(informative)

Nitrogen Density, ρ_{N2}

Table A.1—Nitrogen Density (kg/m^3) from Temperature and Absolute Pressure in SI Units

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
101.325	1.228	1.206	1.165	1.126	1.090	1.057	1.025	0.995	0.967	0.940	0.915	0.891	0.868	0.847	0.826	0.807
500	6.068	5.959	5.753	5.561	5.382	5.213	5.055	4.907	4.767	4.635	4.510	4.392	4.279	4.173	4.071	3.975
1000	12.16	11.94	11.52	11.13	10.77	10.43	10.11	9.81	9.53	9.26	9.01	8.77	8.55	8.33	8.13	7.94
1500	18.27	17.93	17.29	16.70	16.15	15.64	15.16	14.70	14.28	13.88	13.50	13.14	12.80	12.48	12.18	11.88
2000	24.39	23.94	23.08	22.28	21.54	20.84	20.20	19.59	19.02	18.48	17.98	17.50	17.04	16.61	16.21	15.82
2500	30.53	29.95	28.87	27.86	26.92	26.05	25.23	24.47	23.75	23.08	22.44	21.84	21.27	20.73	20.22	19.74
3000	36.69	35.98	34.66	33.43	32.30	31.24	30.26	29.34	28.47	27.66	26.89	26.17	25.49	24.84	24.23	23.64
3500	42.85	42.01	40.45	39.01	37.67	36.43	35.27	34.19	33.18	32.23	31.33	30.49	29.69	28.93	28.21	27.53
4000	49.01	48.05	46.24	44.58	43.04	41.61	40.28	39.04	37.87	36.78	35.75	34.79	33.87	33.00	32.18	31.40
4500	55.18	54.09	52.03	50.14	48.40	46.78	45.27	43.87	42.55	41.32	40.16	39.07	38.04	37.06	36.14	35.26
5000	61.36	60.12	57.82	55.70	53.74	51.93	50.25	48.68	47.22	45.84	44.55	43.34	42.19	41.11	40.08	39.10
5500	67.52	66.15	63.59	61.24	59.08	57.07	55.22	53.48	51.87	50.35	48.93	47.59	46.32	45.13	44.00	42.93
6000	73.69	72.18	69.36	66.77	64.40	62.20	60.16	58.27	56.50	54.84	53.28	51.82	50.44	49.14	47.90	46.73
6500	79.84	78.19	75.11	72.29	69.70	67.31	65.09	63.03	61.11	59.31	57.62	56.04	54.54	53.13	51.79	50.52
7000	85.99	84.19	80.85	77.79	74.99	72.40	70.01	67.78	65.70	63.76	61.94	60.23	58.62	57.10	55.66	54.29
7500	92.12	90.18	86.57	83.28	80.26	77.47	74.90	72.51	70.28	68.19	66.24	64.41	62.68	61.05	59.51	58.05
8000	98.23	96.14	92.27	88.74	85.50	82.53	79.77	77.21	74.83	72.61	70.52	68.56	66.72	64.98	63.34	61.78
8500	104.32	102.09	97.95	94.18	90.73	87.55	84.62	81.90	79.36	77.00	74.78	72.70	70.74	68.90	67.15	65.50
9000	110.39	108.01	103.61	99.60	95.93	92.56	89.45	86.56	83.87	81.37	79.02	76.82	74.74	72.79	70.94	69.20
9500	116.43	113.91	109.24	104.99	101.11	97.54	94.25	91.20	88.36	85.71	83.23	80.91	78.72	76.66	74.72	72.88
10,000	122.44	119.78	114.84	110.36	106.26	102.50	99.03	95.81	92.82	90.04	87.43	84.98	82.68	80.52	78.47	76.53
11,000	134.37	131.42	125.96	121.00	116.48	112.33	108.50	104.96	101.68	98.61	95.75	93.06	90.54	88.16	85.92	83.79
12,000	146.15	142.92	136.94	131.51	126.57	122.04	117.87	114.01	110.43	107.09	103.97	101.05	98.30	95.72	93.28	90.97
13,000	157.76	154.25	147.77	141.89	136.54	131.63	127.11	122.94	119.07	115.46	112.09	108.94	105.98	103.19	100.56	98.07
14,000	169.19	165.42	158.44	152.12	146.36	141.09	136.24	131.76	127.60	123.73	120.12	116.73	113.56	110.57	107.75	105.08
15,000	180.42	176.39	168.93	162.18	156.04	150.41	145.23	140.45	136.02	131.89	128.04	124.43	121.04	117.86	114.85	112.02
16,000	191.44	187.16	179.25	172.08	165.56	159.59	154.09	149.02	144.31	139.94	135.85	132.02	128.43	125.06	121.87	118.86
17,000	202.23	197.72	189.37	181.81	174.92	168.62	162.82	157.46	152.49	147.87	143.56	139.52	135.73	132.16	128.80	125.62

Table A.1—Nitrogen Density (kg/m^3) from Temperature and Absolute Pressure in SI Units (Continued)

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
18,000	212.79	208.06	199.30	191.36	184.12	177.50	171.40	165.77	160.55	155.69	151.15	146.91	142.92	139.17	135.64	132.30
19,000	223.12	218.18	209.02	200.72	193.16	186.22	179.84	173.94	168.48	163.39	158.64	154.19	150.01	146.09	142.38	138.89
20,000	233.20	228.07	218.54	209.90	202.02	194.79	188.14	181.98	176.28	170.97	166.01	161.37	157.01	152.91	149.04	145.39
21,000	243.04	237.72	227.86	218.89	210.71	203.20	196.28	189.89	183.95	178.43	173.27	168.44	163.90	159.63	155.61	151.80
22,000	252.64	247.15	236.96	227.69	219.22	211.45	204.29	197.66	191.50	185.77	180.42	175.40	170.70	166.26	162.08	158.13
23,000	261.98	256.34	245.86	236.30	227.57	219.54	212.14	205.29	198.92	193.00	187.45	182.26	177.39	172.80	168.47	164.38
24,000	271.09	265.31	254.54	244.73	235.74	227.47	219.85	212.78	206.22	200.10	194.38	189.02	183.98	179.24	174.76	170.53
25,000	279.95	274.04	263.02	252.96	243.74	235.25	227.41	220.14	213.38	207.08	201.19	195.67	190.47	185.58	180.97	176.60
26,000	288.58	282.55	271.30	261.01	251.57	242.87	234.82	227.36	220.42	213.95	207.89	202.21	196.87	191.84	187.08	182.59
28,000	305.15	298.92	287.25	276.56	266.72	257.64	249.22	241.41	234.13	227.33	220.96	214.99	209.36	204.06	199.05	194.31
30,000	320.84	314.44	302.44	291.40	281.22	271.80	263.06	254.93	247.35	240.25	233.60	227.35	221.47	215.92	210.67	205.70
32,000	335.69	329.16	316.89	305.56	295.09	285.38	276.36	267.94	260.09	252.73	245.82	239.32	233.20	227.42	221.95	216.76
34,000	349.76	343.13	330.64	319.08	308.36	298.40	289.13	280.47	272.36	264.77	257.63	250.90	244.56	238.57	232.89	227.51
36,000	363.11	356.40	343.73	331.98	321.06	310.89	301.39	292.52	284.20	276.39	269.04	262.11	255.57	249.38	243.52	237.95
38,000	375.77	369.01	356.21	344.31	333.22	322.86	313.18	304.12	295.61	287.60	280.07	272.95	266.23	259.87	253.83	248.10
40,000	387.81	381.01	368.11	356.09	344.86	334.35	324.52	315.28	306.61	298.43	290.73	283.45	276.56	270.03	263.84	257.95
42,000	399.26	392.44	379.48	367.36	356.02	345.39	335.41	326.04	317.21	308.89	301.04	293.61	286.57	279.89	273.55	267.52
44,000	410.17	403.34	390.33	378.15	366.72	355.99	345.90	336.40	327.45	319.00	311.01	303.45	296.27	289.46	282.99	276.83
46,000	420.58	413.75	400.72	388.49	376.99	366.18	356.00	346.40	337.34	328.77	320.66	312.97	305.68	298.75	292.15	285.87
48,000	430.52	423.70	410.67	398.41	386.86	375.99	365.73	356.04	346.88	338.21	330.00	322.21	314.80	307.76	301.06	294.66
50,000	440.04	433.23	420.21	407.93	396.36	385.43	375.11	365.35	356.11	347.35	339.05	331.16	323.66	316.51	309.71	303.21
52,000	449.15	442.37	429.37	417.09	405.49	394.53	384.16	374.34	365.03	356.20	347.81	339.84	332.25	325.02	318.12	311.53
54,000	457.90	451.14	438.17	425.90	414.29	403.30	392.89	383.03	373.66	364.77	356.31	348.26	340.59	333.28	326.30	319.63
56,000	466.30	459.56	446.63	434.38	422.78	411.77	401.34	391.43	382.02	373.07	364.55	356.44	348.70	341.31	334.26	327.51
58,000	474.37	467.67	454.79	442.56	430.97	419.96	409.50	399.56	390.11	381.12	372.55	364.38	356.58	349.13	342.01	335.19
60,000	482.15	475.48	462.65	450.46	438.88	427.87	417.40	407.44	397.96	388.93	380.31	372.09	364.24	356.73	349.55	342.67
62,000	489.64	483.01	470.23	458.08	446.52	435.52	425.05	415.08	405.57	396.51	387.85	379.59	371.69	364.13	356.90	349.96
64,000	496.88	490.28	477.56	465.45	453.92	442.93	432.46	422.48	412.96	403.87	395.18	386.88	378.94	371.34	364.06	357.07

Table A.1—Nitrogen Density (kg/m^3) from Temperature and Absolute Pressure in SI Units (Continued)

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
66,000	503.86	497.31	484.65	472.59	461.08	450.12	439.65	429.67	420.13	411.02	402.31	393.98	386.00	378.36	371.03	364.00
68,000	510.62	504.10	491.51	479.49	468.03	457.08	446.63	436.65	427.10	417.98	409.25	400.89	392.88	385.21	377.84	370.77
70,000	517.16	510.68	498.15	486.19	474.76	463.84	453.40	443.43	433.88	424.75	416.00	407.62	399.59	391.88	384.48	377.37
72,000	523.49	517.05	504.60	492.68	481.30	470.41	459.99	450.02	440.48	431.34	422.58	414.18	406.13	398.39	390.96	383.82
74,000	529.64	523.23	510.85	498.99	487.64	476.78	466.39	456.43	446.90	437.75	428.99	420.58	412.50	404.75	397.29	390.12
76,000	535.60	529.24	516.91	505.11	493.81	482.99	472.62	462.68	453.15	444.01	435.23	426.81	418.72	410.95	403.47	396.28
78,000	541.39	535.06	522.81	511.07	499.81	489.02	478.68	468.76	459.24	450.10	441.33	432.90	424.80	417.01	409.51	402.29
80,000	547.01	540.73	528.55	516.86	505.65	494.90	484.58	474.68	465.18	456.05	447.27	438.84	430.73	422.93	415.42	408.18
82,000	552.49	546.24	534.13	522.50	511.34	500.63	490.34	480.46	470.97	461.85	453.08	444.65	436.53	428.72	421.19	413.94
84,000	557.82	551.61	539.56	527.99	516.88	506.21	495.95	486.10	476.62	467.51	458.75	450.32	442.20	434.38	426.84	419.57
86,000	563.00	556.83	544.86	533.35	522.28	511.65	501.43	491.60	482.14	473.05	464.29	455.86	447.74	439.91	432.37	425.09
88,000	568.06	561.93	550.02	538.57	527.55	516.96	506.77	496.97	487.54	478.45	469.71	461.28	453.16	445.33	437.78	430.49
90,000	572.99	566.90	555.06	543.66	532.70	522.15	511.99	502.22	492.81	483.74	475.01	466.59	458.47	450.64	443.08	435.78
95,000	584.82	578.81	567.13	555.88	545.04	534.60	524.53	514.83	505.48	496.46	487.76	479.36	471.26	463.43	455.86	448.55
100,000	595.98	590.06	578.54	567.43	556.71	546.38	536.40	526.78	517.49	508.52	499.86	491.50	483.41	475.59	468.03	460.72
105,000	606.54	600.71	589.34	578.37	567.78	557.55	547.67	538.12	528.90	519.99	511.38	503.05	494.99	487.19	479.64	472.33
110,000	616.58	610.82	599.61	588.77	578.29	568.17	558.38	548.92	539.77	530.92	522.35	514.06	506.04	498.26	490.73	483.43
115,000	626.13	620.45	609.38	598.67	588.31	578.30	568.60	559.22	550.14	541.35	532.84	524.59	516.60	508.85	501.34	494.06
120,000	635.25	629.65	618.71	608.13	597.88	587.97	578.36	569.06	560.06	551.33	542.87	534.67	526.72	519.00	511.52	504.26
125,000	643.97	638.44	627.63	617.17	607.04	597.22	587.71	578.49	569.55	560.89	552.48	544.33	536.42	528.74	521.29	514.05
130,000	652.33	646.86	636.19	625.84	615.81	606.09	596.67	587.53	578.67	570.06	561.72	553.62	545.75	538.11	530.68	523.47
135,000	660.36	654.96	644.40	634.16	624.24	614.61	605.28	596.22	587.42	578.89	570.60	562.54	554.72	547.12	539.73	532.54
140,000	668.08	662.74	652.30	642.17	632.35	622.81	613.56	604.58	595.85	587.38	579.15	571.15	563.37	555.80	548.45	541.29

NOTE E.W. Lemmon, M.O. McLinden, and D.G. Friend, “Thermophysical Properties of Fluid Systems” in *NIST Chemistry WebBook*, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Table A.2—Nitrogen Density (lbm/gal) from Temperature and Absolute Pressure in USC Units

Absolute Pressure (psia)	Temperature (°F)													
	40	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**220**	**240**	**260**	**280**	**300**
14.7	0.010	0.010	0.010	0.009	0.009	0.009	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007
100	0.070	0.067	0.065	0.062	0.060	0.058	0.056	0.054	0.053	0.051	0.050	0.048	0.047	0.046
200	0.140	0.135	0.130	0.125	0.120	0.116	0.112	0.109	0.106	0.102	0.099	0.097	0.094	0.091
300	0.211	0.202	0.195	0.187	0.181	0.174	0.169	0.163	0.158	0.153	0.149	0.145	0.141	0.137
400	0.282	0.270	0.260	0.250	0.241	0.232	0.224	0.217	0.210	0.204	0.198	0.192	0.187	0.182
500	0.353	0.338	0.324	0.312	0.301	0.290	0.280	0.271	0.262	0.254	0.247	0.240	0.233	0.227
600	0.424	0.406	0.389	0.374	0.360	0.348	0.336	0.325	0.314	0.305	0.296	0.287	0.279	0.272
700	0.495	0.474	0.454	0.436	0.420	0.405	0.391	0.378	0.366	0.355	0.344	0.334	0.325	0.316
800	0.566	0.542	0.519	0.498	0.479	0.462	0.446	0.431	0.417	0.404	0.392	0.381	0.370	0.360
900	0.638	0.609	0.583	0.560	0.539	0.519	0.501	0.484	0.468	0.454	0.440	0.427	0.415	0.404
1000	0.708	0.677	0.648	0.621	0.598	0.576	0.555	0.537	0.519	0.503	0.488	0.474	0.460	0.448
1100	0.779	0.744	0.712	0.683	0.656	0.632	0.610	0.589	0.570	0.552	0.535	0.520	0.505	0.491
1200	0.850	0.811	0.775	0.743	0.714	0.688	0.663	0.641	0.620	0.600	0.582	0.565	0.549	0.534
1300	0.920	0.877	0.839	0.804	0.772	0.743	0.717	0.692	0.670	0.649	0.629	0.610	0.593	0.577
1400	0.989	0.943	0.902	0.864	0.830	0.799	0.770	0.744	0.719	0.696	0.675	0.655	0.637	0.619
1500	1.059	1.009	0.964	0.924	0.887	0.854	0.823	0.795	0.768	0.744	0.721	0.700	0.680	0.661
1600	1.127	1.074	1.026	0.983	0.944	0.908	0.875	0.845	0.817	0.791	0.767	0.744	0.723	0.703
1700	1.195	1.138	1.087	1.042	1.000	0.962	0.927	0.895	0.865	0.838	0.812	0.788	0.766	0.745
1800	1.263	1.202	1.148	1.100	1.056	1.015	0.979	0.945	0.913	0.884	0.857	0.832	0.808	0.786
1900	1.330	1.266	1.209	1.157	1.111	1.068	1.030	0.994	0.961	0.930	0.902	0.875	0.850	0.827
2000	1.396	1.328	1.268	1.214	1.166	1.121	1.080	1.043	1.008	0.976	0.946	0.918	0.892	0.867
2100	1.461	1.390	1.327	1.271	1.220	1.173	1.130	1.091	1.055	1.021	0.990	0.960	0.933	0.907
2200	1.525	1.452	1.386	1.327	1.273	1.225	1.180	1.139	1.101	1.066	1.033	1.003	0.974	0.947
2300	1.589	1.512	1.444	1.382	1.326	1.276	1.229	1.186	1.147	1.110	1.076	1.044	1.015	0.987
2400	1.651	1.572	1.501	1.437	1.379	1.326	1.278	1.233	1.192	1.154	1.119	1.086	1.055	1.026
2500	1.713	1.631	1.557	1.491	1.431	1.376	1.326	1.280	1.237	1.198	1.161	1.127	1.095	1.065

Table A.2—Nitrogen Density (lbm/gal) from Temperature and Absolute Pressure in USC Units (Continued)

Absolute Pressure (psia)	Temperature (°F)													
	40	60	80	100	120	140	160	180	200	220	240	260	280	300
2600	1.774	1.689	1.612	1.544	1.482	1.425	1.373	1.326	1.282	1.241	1.203	1.167	1.134	1.103
2700	1.834	1.746	1.667	1.596	1.532	1.474	1.420	1.371	1.326	1.284	1.244	1.208	1.173	1.141
2800	1.893	1.802	1.721	1.648	1.582	1.522	1.467	1.416	1.369	1.326	1.285	1.247	1.212	1.179
2900	1.951	1.858	1.775	1.700	1.632	1.570	1.513	1.461	1.412	1.368	1.326	1.287	1.251	1.216
3000	2.008	1.912	1.827	1.750	1.680	1.617	1.558	1.505	1.455	1.409	1.366	1.326	1.289	1.253
3200	2.119	2.019	1.930	1.849	1.776	1.709	1.648	1.591	1.539	1.490	1.445	1.403	1.364	1.327
3400	2.226	2.122	2.029	1.945	1.869	1.799	1.735	1.676	1.621	1.570	1.523	1.479	1.437	1.398
3600	2.329	2.222	2.126	2.039	1.959	1.887	1.820	1.758	1.701	1.648	1.599	1.553	1.509	1.469
3800	2.428	2.319	2.219	2.129	2.047	1.972	1.903	1.839	1.779	1.724	1.673	1.625	1.580	1.538
4000	2.524	2.412	2.310	2.217	2.133	2.055	1.983	1.917	1.856	1.799	1.746	1.696	1.649	1.605
4200	2.616	2.502	2.397	2.302	2.216	2.136	2.062	1.994	1.931	1.872	1.817	1.766	1.717	1.672
4400	2.705	2.588	2.482	2.385	2.296	2.214	2.139	2.069	2.004	1.943	1.887	1.834	1.784	1.737
4600	2.790	2.672	2.564	2.465	2.375	2.291	2.213	2.142	2.075	2.013	1.955	1.900	1.849	1.801
4800	2.873	2.753	2.643	2.543	2.451	2.365	2.286	2.213	2.145	2.081	2.021	1.965	1.913	1.863
5000	2.952	2.831	2.720	2.618	2.524	2.438	2.357	2.282	2.212	2.147	2.086	2.029	1.975	1.924
5200	3.029	2.907	2.795	2.691	2.596	2.508	2.426	2.350	2.279	2.212	2.150	2.092	2.036	1.985
5400	3.102	2.980	2.867	2.762	2.666	2.576	2.493	2.416	2.343	2.276	2.212	2.153	2.096	2.043
5600	3.174	3.050	2.936	2.831	2.733	2.643	2.559	2.480	2.407	2.338	2.273	2.212	2.155	2.101
5800	3.242	3.118	3.004	2.898	2.799	2.708	2.622	2.543	2.468	2.398	2.333	2.271	2.213	2.158
6000	3.309	3.185	3.069	2.963	2.863	2.771	2.685	2.604	2.528	2.458	2.391	2.328	2.269	2.213
6200	3.373	3.248	3.133	3.025	2.925	2.832	2.745	2.664	2.587	2.516	2.448	2.384	2.324	2.267
6400	3.435	3.310	3.195	3.087	2.986	2.892	2.804	2.722	2.645	2.572	2.504	2.439	2.378	2.321
6600	3.495	3.371	3.254	3.146	3.045	2.950	2.862	2.779	2.701	2.628	2.558	2.493	2.431	2.373
6800	3.553	3.429	3.312	3.204	3.102	3.007	2.918	2.834	2.756	2.682	2.612	2.546	2.483	2.424
7000	3.610	3.485	3.369	3.260	3.158	3.063	2.973	2.889	2.809	2.735	2.664	2.597	2.534	2.474
7500	3.744	3.620	3.503	3.394	3.292	3.195	3.104	3.019	2.938	2.862	2.790	2.722	2.657	2.596

Table A.2—Nitrogen Density (lbm/gal) from Temperature and Absolute Pressure in USC Units (Continued)

Absolute Pressure (psia)	Temperature (°F)													
	40	60	80	100	120	140	160	180	200	220	240	260	280	300
8000	3.869	3.745	3.629	3.520	3.417	3.320	3.228	3.142	3.061	2.983	2.910	2.841	2.775	2.712
8500	3.985	3.862	3.747	3.638	3.535	3.438	3.346	3.259	3.176	3.098	3.024	2.953	2.886	2.823
9000	4.094	3.973	3.858	3.749	3.646	3.549	3.457	3.369	3.286	3.207	3.132	3.061	2.993	2.928
9500	4.197	4.076	3.962	3.854	3.752	3.654	3.562	3.474	3.391	3.312	3.236	3.164	3.095	3.030
10,000	4.294	4.174	4.061	3.954	3.851	3.754	3.662	3.574	3.491	3.411	3.335	3.262	3.193	3.127
10,500	4.385	4.267	4.155	4.048	3.946	3.849	3.757	3.669	3.586	3.506	3.429	3.357	3.287	3.220
11,000	4.472	4.355	4.244	4.138	4.037	3.940	3.848	3.760	3.677	3.597	3.520	3.447	3.377	3.310
11,500	4.554	4.439	4.329	4.223	4.123	4.027	3.935	3.847	3.764	3.684	3.607	3.534	3.463	3.396
12,000	4.633	4.519	4.409	4.305	4.205	4.109	4.018	3.931	3.847	3.767	3.690	3.617	3.546	3.479
12,500	4.708	4.595	4.487	4.383	4.284	4.189	4.098	4.011	3.927	3.847	3.771	3.697	3.626	3.558
13,000	4.780	4.668	4.561	4.458	4.359	4.265	4.174	4.088	4.004	3.925	3.848	3.774	3.703	3.635
13,500	4.849	4.738	4.632	4.530	4.432	4.338	4.248	4.162	4.079	3.999	3.922	3.849	3.778	3.710
14,000	4.915	4.805	4.700	4.599	4.502	4.408	4.319	4.233	4.150	4.071	3.994	3.920	3.850	3.782
14,500	4.979	4.870	4.765	4.665	4.569	4.476	4.387	4.301	4.219	4.140	4.063	3.990	3.919	3.851
15,000	5.040	4.932	4.829	4.729	4.633	4.541	4.453	4.368	4.286	4.207	4.130	4.057	3.987	3.918
15,500	5.099	4.992	4.890	4.791	4.696	4.604	4.516	4.432	4.350	4.271	4.195	4.122	4.052	3.984
16,000	5.156	5.050	4.949	4.851	4.756	4.665	4.578	4.494	4.412	4.334	4.258	4.185	4.115	4.047
16,500	5.211	5.107	5.006	4.908	4.815	4.724	4.637	4.554	4.473	4.395	4.319	4.246	4.176	4.108
17,000	5.265	5.161	5.061	4.964	4.871	4.782	4.695	4.612	4.531	4.453	4.378	4.306	4.236	4.168
17,500	5.316	5.214	5.114	5.019	4.926	4.837	4.751	4.668	4.588	4.511	4.436	4.363	4.293	4.226
18,000	5.367	5.265	5.166	5.071	4.979	4.891	4.805	4.723	4.643	4.566	4.491	4.419	4.350	4.282
18,500	5.415	5.314	5.216	5.122	5.031	4.943	4.858	4.776	4.697	4.620	4.546	4.474	4.404	4.337
19,000	5.463	5.362	5.265	5.172	5.081	4.994	4.910	4.828	4.749	4.673	4.599	4.527	4.458	4.391
19,500	5.509	5.409	5.313	5.220	5.130	5.043	4.960	4.878	4.800	4.724	4.650	4.579	4.510	4.443
20,000	5.554	5.455	5.359	5.267	5.178	5.092	5.008	4.927	4.849	4.773	4.700	4.629	4.560	4.493

NOTE E.W. Lemmon, M.O. McLinden and D.G. Friend, "Thermophysical Properties of Fluid Systems" in *NIST Chemistry WebBook*, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Annex B
(informative)

Nitrogen—A Real Gas

Nitrogen is a real gas. The volume of nitrogen changes with pressure and temperature. As a result, there is a change in the nitrogen density. An ideal gas follows the Boyle-Mariotte law (Boyle's law) and its volume changes directly in relation with pressure and temperature. Nitrogen does not follow the ideal gas law; a deviance is expressed by a compressibility factor, Z, in the real gas equation (in case of ideal gas Z is equal to 1) according to Equation (B.1).

$$PV = nZRT \tag{B.1}$$

where

P is the absolute pressure expressed in Pascals (kPa);

V is the gaseous volume expressed in cubic meters;

n is the number of gas moles;

Z is the thermodynamic gas compressibility factor;

R is the universal gas constant expressed in joules per mole.Kelvin (K) (where R = 8.3145 J/mol.K, unit equivalent to m^3 Pa /mol.K); and

T is the thermodynamic temperature expressed in Kelvin.

Thermodynamic temperature, T, is calculated from temperature θ that is expressed in degree Celsius, according to Equation (B.2):

$$T = \theta + 273.15 \tag{B.2}$$

Nitrogen compressibility factor is also a function of temperature and pressure. The real gas equation permits the calculation of the density of nitrogen, which changes with pressure and temperature.

The mass of a gaseous phase can be calculated knowing the number of moles and the molecular mass of the gas according to Equation (B.3).

$$\text{Mass of gas} = \text{number of moles} \times \text{gas molecular mass} \tag{B.3}$$

Applied to nitrogen gas (N_2), the gaseous density of nitrogen expressed in kilograms per cubic meter or grams per cubic decimeter according to Equation (B.4).

$$\rho_{\mathrm{N2}} = \frac{n \times M_{\mathrm{N2}}}{V} \tag{B.4}$$

where

ρ_{N2} is the density of nitrogen gas expressed in kilograms per cubic meter;

n is a number of moles of nitrogen gas;

M_{N2} is the molecular mass of nitrogen gas (M_{N2} = 28.0134 g); and

V is the volume of n moles of nitrogen.

The volume of moles of nitrogen, V, can be calculated using real gas Equation (B.1). Then Equation (B.4) becomes Equation (B.5):

$$\rho_{N2} = \frac{P \times M_{N2}}{Z_{N2} \times R \times T} \tag{B.5}$$

Equation (B.5) is valid for any gas to calculate density of the gas function of its conditions of temperature and pressure. Molecular mass of the gas and its compressibility factor according the conditions should be used for the calculation.

Knowing the universal gas constant R and nitrogen gas molecular mass M_{N2}, Equation (B.5) can be expressed in SI units by Equation (B.6):

$$\rho_{N2} = \frac{3.3692 \times P}{Z_{N2} \times (\theta + 273.15)} \tag{B.6}$$

where

ρ_{N2} is the density of nitrogen gas expressed in kilograms per cubic meter;

Z_{N2} is the compressibility factor for nitrogen gas;

P is the absolute pressure expressed in kilopascals; and

θ is the temperature expressed in degree Celsius.

In USC units, density of nitrogen gas expressed in pounds per gallon can be determined by Equation (B.7):

$$\rho_{N2} = \frac{0.34895 \times P}{Z_{N2} \times (\theta + 459.67)} \tag{B.7}$$

where

ρ_{N2} is the density of nitrogen gas expressed in pounds per gallon;

Z_{N2} is the compressibility factor for nitrogen gas;

P is the absolute pressure expressed in pounds per square inch; and

θ is the temperature expressed in degree Fahrenheit.

Nitrogen compressibility factors are provided versus temperature and absolute pressure in SI units in Table A.1 and USC units in Table A.2.

Annex C
(informative)

Nitrogen Compressibility Factor, Z (Dimensionless)

Table C.1—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in SI Units

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
101.33	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	0.998	0.998	0.999	0.999	1.000	1.000	1.000	1.000	1.001	1.001	1.001	1.001	1.001	1.001	1.002	1.002
1000	0.996	0.997	0.998	0.999	0.999	1.000	1.001	1.001	1.001	1.002	1.002	1.002	1.003	1.003	1.003	1.003
1500	0.995	0.995	0.997	0.998	0.999	1.000	1.001	1.002	1.002	1.003	1.003	1.004	1.004	1.004	1.005	1.005
2000	0.993	0.994	0.996	0.998	0.999	1.000	1.001	1.002	1.003	1.004	1.005	1.005	1.006	1.006	1.006	1.007
2500	0.992	0.993	0.995	0.997	0.999	1.001	1.002	1.003	1.004	1.005	1.006	1.007	1.007	1.008	1.008	1.009
3000	0.991	0.992	0.995	0.997	0.999	1.001	1.003	1.004	1.005	1.006	1.007	1.008	1.009	1.009	1.010	1.010
3500	0.989	0.991	0.994	0.997	1.000	1.002	1.003	1.005	1.006	1.008	1.009	1.010	1.010	1.011	1.012	1.012
4000	0.989	0.991	0.994	0.997	1.000	1.002	1.004	1.006	1.008	1.009	1.010	1.011	1.012	1.013	1.014	1.014
4500	0.988	0.990	0.994	0.997	1.000	1.003	1.005	1.007	1.009	1.010	1.012	1.013	1.014	1.015	1.015	1.016
5000	0.987	0.990	0.994	0.998	1.001	1.004	1.006	1.008	1.010	1.012	1.013	1.015	1.016	1.017	1.017	1.018
5500	0.987	0.989	0.994	0.998	1.002	1.005	1.007	1.010	1.012	1.013	1.015	1.016	1.017	1.019	1.019	1.020
6000	0.986	0.989	0.994	0.999	1.002	1.006	1.009	1.011	1.013	1.015	1.017	1.018	1.019	1.020	1.021	1.022
6500	0.986	0.989	0.995	0.999	1.003	1.007	1.010	1.013	1.015	1.017	1.019	1.020	1.021	1.023	1.023	1.024
7000	0.986	0.989	0.995	1.000	1.004	1.008	1.011	1.014	1.016	1.019	1.020	1.022	1.023	1.025	1.026	1.027
7500	0.986	0.990	0.996	1.001	1.005	1.009	1.013	1.016	1.018	1.020	1.022	1.024	1.025	1.027	1.028	1.029
8000	0.987	0.990	0.996	1.002	1.007	1.011	1.014	1.017	1.020	1.022	1.024	1.026	1.028	1.029	1.030	1.031
8500	0.987	0.991	0.997	1.003	1.008	1.012	1.016	1.019	1.022	1.024	1.026	1.028	1.030	1.031	1.032	1.033
9000	0.988	0.991	0.998	1.004	1.009	1.014	1.018	1.021	1.024	1.026	1.028	1.030	1.032	1.033	1.035	1.036
9500	0.988	0.992	0.999	1.006	1.011	1.015	1.019	1.023	1.026	1.028	1.031	1.032	1.034	1.036	1.037	1.038
10,000	0.989	0.993	1.001	1.007	1.013	1.017	1.021	1.025	1.028	1.030	1.033	1.035	1.036	1.038	1.039	1.040
11,000	0.992	0.996	1.004	1.010	1.016	1.021	1.025	1.029	1.032	1.035	1.037	1.039	1.041	1.043	1.044	1.045
12,000	0.995	0.999	1.007	1.014	1.020	1.025	1.030	1.033	1.037	1.040	1.042	1.044	1.046	1.048	1.049	1.050
13,000	0.998	1.003	1.011	1.018	1.024	1.030	1.034	1.038	1.042	1.045	1.047	1.049	1.051	1.053	1.054	1.055
14,000	1.002	1.007	1.016	1.023	1.029	1.035	1.039	1.043	1.047	1.050	1.052	1.055	1.057	1.058	1.060	1.061
15,000	1.007	1.012	1.021	1.028	1.034	1.040	1.045	1.049	1.052	1.055	1.058	1.060	1.062	1.064	1.065	1.066
16,000	1.012	1.017	1.026	1.033	1.040	1.045	1.050	1.054	1.058	1.061	1.063	1.066	1.068	1.069	1.071	1.072
17,000	1.018	1.023	1.032	1.039	1.046	1.051	1.056	1.060	1.064	1.067	1.069	1.071	1.073	1.075	1.076	1.078

Table C.1—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in SI Units (Continued)

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
18,000	1.025	1.029	1.038	1.045	1.052	1.057	1.062	1.066	1.070	1.073	1.075	1.077	1.079	1.081	1.082	1.083
19,000	1.031	1.036	1.045	1.052	1.058	1.064	1.068	1.072	1.076	1.079	1.081	1.084	1.085	1.087	1.088	1.089
20,000	1.039	1.043	1.052	1.059	1.065	1.070	1.075	1.079	1.082	1.085	1.088	1.090	1.092	1.093	1.094	1.095
21,000	1.047	1.051	1.059	1.066	1.072	1.078	1.082	1.086	1.089	1.092	1.094	1.096	1.098	1.099	1.101	1.101
22,000	1.055	1.059	1.067	1.074	1.080	1.085	1.089	1.093	1.096	1.099	1.101	1.103	1.104	1.106	1.107	1.108
23,000	1.063	1.068	1.075	1.082	1.087	1.092	1.096	1.100	1.103	1.106	1.108	1.110	1.111	1.112	1.113	1.114
24,000	1.072	1.076	1.084	1.090	1.095	1.100	1.104	1.107	1.110	1.113	1.115	1.117	1.118	1.119	1.120	1.121
25,000	1.082	1.086	1.092	1.098	1.104	1.108	1.112	1.115	1.118	1.120	1.122	1.124	1.125	1.126	1.127	1.127
26,000	1.091	1.095	1.101	1.107	1.112	1.116	1.120	1.123	1.125	1.127	1.129	1.131	1.132	1.133	1.133	1.134
28,000	1.111	1.115	1.120	1.125	1.129	1.133	1.136	1.139	1.141	1.143	1.144	1.145	1.146	1.147	1.147	1.147
30,000	1.133	1.135	1.140	1.144	1.148	1.151	1.153	1.155	1.157	1.159	1.160	1.160	1.161	1.161	1.161	1.161
32,000	1.155	1.157	1.161	1.164	1.167	1.169	1.171	1.173	1.174	1.175	1.175	1.176	1.176	1.176	1.176	1.175
34,000	1.177	1.179	1.182	1.184	1.186	1.188	1.189	1.190	1.191	1.191	1.192	1.192	1.191	1.191	1.191	1.190
36,000	1.201	1.202	1.204	1.205	1.206	1.207	1.208	1.208	1.208	1.208	1.208	1.208	1.207	1.206	1.206	1.205
38,000	1.225	1.225	1.226	1.227	1.227	1.227	1.227	1.227	1.226	1.226	1.225	1.224	1.223	1.222	1.221	1.220
40,000	1.249	1.249	1.249	1.248	1.248	1.247	1.247	1.246	1.245	1.244	1.242	1.241	1.239	1.238	1.236	1.235
42,000	1.274	1.273	1.272	1.271	1.269	1.268	1.266	1.265	1.263	1.261	1.260	1.258	1.256	1.254	1.252	1.250
44,000	1.299	1.298	1.296	1.293	1.291	1.289	1.286	1.284	1.282	1.280	1.277	1.275	1.273	1.270	1.268	1.266
46,000	1.325	1.323	1.319	1.316	1.313	1.310	1.307	1.304	1.301	1.298	1.295	1.292	1.290	1.287	1.284	1.281
48,000	1.351	1.348	1.343	1.339	1.335	1.331	1.327	1.324	1.320	1.317	1.313	1.310	1.307	1.303	1.300	1.297
50,000	1.376	1.373	1.368	1.362	1.357	1.353	1.348	1.344	1.340	1.335	1.332	1.328	1.324	1.320	1.317	1.313
52,000	1.402	1.399	1.392	1.386	1.380	1.374	1.369	1.364	1.359	1.354	1.350	1.346	1.341	1.337	1.333	1.329
54,000	1.428	1.424	1.416	1.409	1.402	1.396	1.390	1.384	1.379	1.373	1.368	1.363	1.359	1.354	1.350	1.345
56,000	1.455	1.450	1.441	1.433	1.425	1.418	1.411	1.405	1.399	1.393	1.387	1.382	1.376	1.371	1.366	1.361
58,000	1.481	1.476	1.466	1.457	1.448	1.440	1.432	1.425	1.418	1.412	1.406	1.400	1.394	1.388	1.383	1.378
60,000	1.507	1.502	1.491	1.480	1.471	1.462	1.454	1.446	1.438	1.431	1.424	1.418	1.412	1.406	1.400	1.394
62,000	1.534	1.527	1.515	1.504	1.494	1.484	1.475	1.467	1.458	1.451	1.443	1.436	1.429	1.423	1.417	1.411
64,000	1.560	1.553	1.540	1.528	1.517	1.506	1.497	1.487	1.479	1.470	1.462	1.455	1.447	1.440	1.434	1.427

Table C.1—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in SI Units (Continued)

Absolute Pressure (kPa)	Temperature (°C)															
	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
66,000	1.587	1.579	1.565	1.552	1.540	1.529	1.518	1.508	1.499	1.490	1.481	1.473	1.465	1.458	1.451	1.444
68,000	1.613	1.605	1.590	1.576	1.563	1.551	1.540	1.529	1.519	1.509	1.500	1.492	1.483	1.475	1.468	1.460
70,000	1.640	1.631	1.615	1.600	1.586	1.573	1.561	1.550	1.539	1.529	1.519	1.510	1.501	1.493	1.485	1.477
72,000	1.666	1.657	1.640	1.624	1.610	1.596	1.583	1.571	1.559	1.549	1.538	1.529	1.519	1.510	1.502	1.494
74,000	1.692	1.683	1.665	1.648	1.633	1.618	1.605	1.592	1.580	1.568	1.557	1.547	1.537	1.528	1.519	1.510
76,000	1.719	1.709	1.690	1.672	1.656	1.641	1.626	1.613	1.600	1.588	1.577	1.566	1.555	1.546	1.536	1.527
78,000	1.745	1.735	1.715	1.696	1.679	1.663	1.648	1.634	1.620	1.608	1.596	1.584	1.574	1.563	1.553	1.544
80,000	1.772	1.760	1.740	1.720	1.702	1.685	1.670	1.655	1.641	1.627	1.615	1.603	1.592	1.581	1.570	1.561
82,000	1.798	1.786	1.764	1.744	1.725	1.708	1.691	1.676	1.661	1.647	1.634	1.622	1.610	1.598	1.588	1.577
84,000	1.824	1.812	1.789	1.768	1.748	1.730	1.713	1.697	1.681	1.667	1.653	1.640	1.628	1.616	1.605	1.594
86,000	1.850	1.838	1.814	1.792	1.772	1.752	1.735	1.718	1.702	1.687	1.672	1.659	1.646	1.634	1.622	1.611
88,000	1.876	1.863	1.839	1.816	1.795	1.775	1.756	1.739	1.722	1.706	1.692	1.678	1.664	1.651	1.639	1.628
90,000	1.903	1.889	1.864	1.840	1.818	1.797	1.778	1.760	1.742	1.726	1.711	1.696	1.682	1.669	1.656	1.644
95,000	1.968	1.953	1.925	1.899	1.875	1.853	1.832	1.812	1.793	1.775	1.759	1.743	1.728	1.713	1.699	1.686
100,000	2.032	2.017	1.987	1.959	1.933	1.908	1.885	1.864	1.844	1.824	1.806	1.789	1.773	1.757	1.742	1.728
105,000	2.097	2.080	2.048	2.018	1.990	1.963	1.939	1.916	1.894	1.873	1.854	1.835	1.818	1.801	1.785	1.770
110,000	2.161	2.143	2.108	2.076	2.047	2.019	1.992	1.968	1.944	1.922	1.901	1.882	1.863	1.845	1.828	1.812
115,000	2.225	2.205	2.169	2.135	2.103	2.073	2.045	2.019	1.994	1.971	1.949	1.928	1.908	1.889	1.871	1.853
120,000	2.288	2.268	2.229	2.193	2.159	2.128	2.098	2.070	2.044	2.019	1.996	1.974	1.952	1.932	1.913	1.895
125,000	2.351	2.330	2.289	2.251	2.215	2.182	2.151	2.122	2.094	2.068	2.043	2.019	1.997	1.976	1.955	1.936
130,000	2.414	2.391	2.349	2.309	2.271	2.236	2.203	2.172	2.143	2.116	2.090	2.065	2.041	2.019	1.998	1.977
135,000	2.476	2.453	2.408	2.366	2.327	2.290	2.256	2.223	2.193	2.164	2.136	2.110	2.086	2.062	2.040	2.018
140,000	2.538	2.514	2.467	2.423	2.382	2.344	2.308	2.274	2.242	2.211	2.183	2.155	2.130	2.105	2.082	2.059

NOTE E.W. Lemmon, M.O. McLinden, and D.G. Friend, "Thermophysical Properties of Fluid Systems" in *NIST Chemistry WebBook*, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Table C.2—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in USC Units

Absolute Pressure (psia)	Temperature (°F)													
	40	60	80	100	120	140	160	180	200	220	240	260	280	300
14.70	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	0.997	0.998	0.999	0.999	1.000	1.000	1.001	1.001	1.001	1.002	1.002	1.002	1.002	1.002
200	0.995	0.997	0.998	0.999	1.000	1.001	1.002	1.002	1.003	1.003	1.004	1.004	1.004	1.005
300	0.993	0.995	0.997	0.999	1.000	1.002	1.003	1.004	1.004	1.005	1.006	1.006	1.007	1.007
400	0.991	0.994	0.997	0.999	1.001	1.002	1.004	1.005	1.006	1.007	1.008	1.008	1.009	1.009
500	0.989	0.993	0.996	0.999	1.001	1.003	1.005	1.007	1.008	1.009	1.010	1.011	1.011	1.012
600	0.988	0.993	0.996	1.000	1.002	1.005	1.007	1.008	1.010	1.011	1.012	1.013	1.014	1.015
700	0.987	0.992	0.996	1.000	1.003	1.006	1.008	1.010	1.012	1.013	1.015	1.016	1.017	1.017
800	0.986	0.992	0.997	1.001	1.004	1.007	1.010	1.012	1.014	1.016	1.017	1.018	1.019	1.020
900	0.986	0.992	0.997	1.002	1.006	1.009	1.012	1.014	1.016	1.018	1.020	1.021	1.022	1.023
1000	0.986	0.993	0.998	1.003	1.007	1.011	1.014	1.017	1.019	1.021	1.022	1.024	1.025	1.026
1100	0.986	0.993	0.999	1.005	1.009	1.013	1.016	1.019	1.021	1.023	1.025	1.027	1.028	1.029
1200	0.986	0.994	1.001	1.006	1.011	1.015	1.019	1.022	1.024	1.026	1.028	1.030	1.031	1.032
1300	0.987	0.995	1.002	1.008	1.013	1.017	1.021	1.024	1.027	1.029	1.031	1.033	1.034	1.035
1400	0.988	0.997	1.004	1.010	1.016	1.020	1.024	1.027	1.030	1.032	1.034	1.036	1.037	1.039
1500	0.990	0.999	1.006	1.013	1.018	1.023	1.027	1.030	1.033	1.035	1.037	1.039	1.041	1.042
1600	0.991	1.001	1.008	1.015	1.021	1.025	1.030	1.033	1.036	1.038	1.041	1.042	1.044	1.045
1700	0.993	1.003	1.011	1.018	1.023	1.028	1.033	1.036	1.039	1.042	1.044	1.046	1.047	1.049
1800	0.995	1.005	1.014	1.020	1.026	1.031	1.036	1.039	1.043	1.045	1.047	1.049	1.051	1.052
1900	0.998	1.008	1.016	1.024	1.030	1.035	1.039	1.043	1.046	1.049	1.051	1.053	1.054	1.056
2000	1.001	1.011	1.020	1.027	1.033	1.038	1.043	1.046	1.050	1.052	1.055	1.056	1.058	1.060
2100	1.004	1.014	1.023	1.030	1.036	1.042	1.046	1.050	1.053	1.056	1.058	1.060	1.062	1.063
2200	1.007	1.018	1.026	1.034	1.040	1.045	1.050	1.054	1.057	1.060	1.062	1.064	1.066	1.067
2300	1.011	1.021	1.030	1.038	1.044	1.049	1.054	1.058	1.061	1.064	1.066	1.068	1.070	1.071
2400	1.015	1.025	1.034	1.042	1.048	1.053	1.058	1.062	1.065	1.068	1.070	1.072	1.073	1.075
2500	1.019	1.030	1.038	1.046	1.052	1.057	1.062	1.066	1.069	1.072	1.074	1.076	1.077	1.079
2600	1.024	1.034	1.043	1.050	1.056	1.062	1.066	1.070	1.073	1.076	1.078	1.080	1.082	1.083
2700	1.028	1.038	1.047	1.054	1.061	1.066	1.070	1.074	1.077	1.080	1.082	1.084	1.086	1.087

Table C.2—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in USC Units (Continued)

Absolute Pressure (psia)	Temperature (°F)													
	40	60	80	100	120	140	160	180	200	220	240	260	280	300
2800	1.033	1.043	1.052	1.059	1.065	1.070	1.075	1.079	1.082	1.084	1.087	1.088	1.090	1.091
2900	1.038	1.048	1.057	1.064	1.070	1.075	1.079	1.083	1.086	1.089	1.091	1.093	1.094	1.095
3000	1.044	1.053	1.062	1.069	1.075	1.080	1.084	1.088	1.091	1.093	1.095	1.097	1.098	1.099
3200	1.055	1.064	1.072	1.079	1.085	1.090	1.094	1.097	1.100	1.102	1.104	1.106	1.107	1.108
3400	1.067	1.076	1.083	1.090	1.095	1.100	1.104	1.107	1.110	1.112	1.114	1.115	1.116	1.117
3600	1.080	1.088	1.095	1.101	1.106	1.110	1.114	1.117	1.119	1.121	1.123	1.124	1.125	1.126
3800	1.093	1.101	1.107	1.113	1.117	1.121	1.125	1.127	1.130	1.131	1.133	1.134	1.135	1.135
4000	1.107	1.114	1.120	1.125	1.129	1.133	1.136	1.138	1.140	1.142	1.143	1.144	1.144	1.144
4200	1.121	1.127	1.133	1.137	1.141	1.144	1.147	1.149	1.151	1.152	1.153	1.153	1.154	1.154
4400	1.136	1.141	1.146	1.150	1.154	1.156	1.159	1.160	1.162	1.163	1.163	1.164	1.164	1.164
4600	1.151	1.156	1.160	1.163	1.166	1.168	1.170	1.172	1.173	1.173	1.174	1.174	1.174	1.173
4800	1.167	1.171	1.174	1.177	1.179	1.181	1.182	1.183	1.184	1.184	1.184	1.184	1.184	1.183
5000	1.183	1.186	1.188	1.191	1.192	1.194	1.195	1.195	1.195	1.195	1.195	1.195	1.194	1.193
5200	1.199	1.201	1.203	1.205	1.206	1.207	1.207	1.207	1.207	1.207	1.206	1.206	1.205	1.204
5400	1.216	1.217	1.218	1.219	1.219	1.220	1.220	1.219	1.219	1.218	1.217	1.216	1.215	1.214
5600	1.232	1.233	1.233	1.233	1.233	1.233	1.233	1.232	1.231	1.230	1.229	1.227	1.226	1.224
5800	1.249	1.249	1.249	1.248	1.247	1.246	1.245	1.244	1.243	1.242	1.240	1.238	1.237	1.235
6000	1.266	1.265	1.264	1.263	1.261	1.260	1.259	1.257	1.255	1.253	1.252	1.250	1.248	1.245
6200	1.284	1.282	1.280	1.278	1.276	1.274	1.272	1.270	1.268	1.265	1.263	1.261	1.258	1.256
6400	1.301	1.298	1.295	1.293	1.290	1.288	1.285	1.283	1.280	1.277	1.275	1.272	1.270	1.267
6600	1.319	1.315	1.311	1.308	1.305	1.302	1.299	1.296	1.293	1.290	1.287	1.284	1.281	1.278
6800	1.336	1.332	1.327	1.323	1.320	1.316	1.312	1.309	1.305	1.302	1.298	1.295	1.292	1.289
7000	1.354	1.349	1.344	1.339	1.334	1.330	1.326	1.322	1.318	1.314	1.310	1.307	1.303	1.299
7500	1.399	1.391	1.384	1.378	1.372	1.366	1.360	1.355	1.350	1.345	1.341	1.336	1.332	1.327
8000	1.444	1.434	1.425	1.417	1.409	1.402	1.395	1.389	1.383	1.377	1.371	1.366	1.360	1.355
8500	1.490	1.478	1.467	1.457	1.448	1.439	1.431	1.423	1.416	1.409	1.402	1.395	1.389	1.383
9000	1.535	1.521	1.509	1.497	1.486	1.476	1.466	1.457	1.449	1.441	1.433	1.426	1.419	1.412
9500	1.581	1.565	1.550	1.537	1.524	1.513	1.502	1.492	1.482	1.473	1.464	1.456	1.448	1.440

Table C.2—Nitrogen Compressibility Factor from Temperature and Absolute Pressure in USC Units (Continued)

Absolute Pressure (psia)	Temperature (°F)													
	40	60	80	100	120	140	160	180	200	220	240	260	280	300
10,000	1.627	1.609	1.592	1.577	1.563	1.550	1.538	1.526	1.515	1.505	1.496	1.486	1.477	1.469
10,500	1.672	1.652	1.634	1.617	1.602	1.587	1.574	1.561	1.549	1.538	1.527	1.517	1.507	1.498
11,000	1.718	1.696	1.676	1.658	1.640	1.625	1.610	1.596	1.583	1.570	1.559	1.547	1.537	1.527
11,500	1.763	1.740	1.718	1.698	1.679	1.662	1.646	1.631	1.616	1.603	1.590	1.578	1.567	1.556
12,000	1.809	1.783	1.760	1.738	1.718	1.699	1.682	1.665	1.650	1.635	1.622	1.609	1.596	1.585
12,500	1.854	1.827	1.801	1.778	1.757	1.737	1.718	1.700	1.684	1.668	1.653	1.639	1.626	1.614
13,000	1.899	1.870	1.843	1.818	1.795	1.774	1.754	1.735	1.717	1.701	1.685	1.670	1.656	1.643
13,500	1.944	1.913	1.885	1.858	1.834	1.811	1.790	1.770	1.751	1.733	1.717	1.701	1.686	1.672
14,000	1.989	1.956	1.926	1.898	1.872	1.848	1.826	1.804	1.785	1.766	1.748	1.731	1.716	1.701
14,500	2.034	1.999	1.967	1.938	1.911	1.885	1.861	1.839	1.818	1.798	1.780	1.762	1.745	1.730
15,000	2.078	2.042	2.009	1.978	1.949	1.922	1.897	1.874	1.852	1.831	1.811	1.793	1.775	1.758
15,500	2.123	2.085	2.050	2.017	1.987	1.959	1.933	1.908	1.885	1.863	1.843	1.823	1.805	1.787
16,000	2.167	2.127	2.091	2.057	2.025	1.996	1.968	1.942	1.918	1.895	1.874	1.854	1.834	1.816
16,500	2.211	2.170	2.131	2.096	2.063	2.032	2.004	1.977	1.951	1.928	1.905	1.884	1.864	1.845
17,000	2.255	2.212	2.172	2.135	2.101	2.069	2.039	2.011	1.985	1.960	1.936	1.914	1.893	1.874
17,500	2.299	2.254	2.213	2.174	2.139	2.105	2.074	2.045	2.018	1.992	1.968	1.945	1.923	1.902
18,000	2.342	2.296	2.253	2.213	2.176	2.142	2.109	2.079	2.051	2.024	1.999	1.975	1.952	1.931
18,500	2.386	2.338	2.293	2.252	2.214	2.178	2.144	2.113	2.084	2.056	2.030	2.005	1.982	1.959
19,000	2.429	2.379	2.333	2.291	2.251	2.214	2.179	2.147	2.116	2.088	2.061	2.035	2.011	1.988
19,500	2.472	2.421	2.373	2.329	2.288	2.250	2.214	2.181	2.149	2.119	2.091	2.065	2.040	2.016
20,000	2.515	2.462	2.413	2.368	2.325	2.286	2.249	2.214	2.182	2.151	2.122	2.095	2.069	2.045

NOTE E.W. Lemmon, M.O. McLinden, and D.G. Friend, "Thermophysical Properties of Fluid Systems" in *NIST Chemistry WebBook*, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Annex D
(informative)

Example Calculations for the Preparation of Foamed Cement Slurry at Atmospheric Pressure

D.1 General

The example calculations in this annex demonstrate the use of the equations in 5.2 and 5.3 to determine the proper quantities of a base cement slurry and surfactant(s) to use in the laboratory, accounting for changing pressure.

The following criteria can be used for the calculations in this annex:

a) downhole conditions: 6000 psi and 60 °F;

b) downhole N_2 density (from Annex A) = 3.185 lbm/gal;

c) planned downhole foamed cement slurry density = 13.5 lbm/gal;

d) base cement slurry design: cement + surfactant(s) 0.20 gallons per sack + water;

e) base cement slurry density 16.4 lbm/gal;

f) density of dry cement (Class H in this example) = 26.41 lbm/gal;

g) density of base slurry = 16.37 lbm/gal;

h) surfactant density = 10 lbm/gal;

i) density of water = 8.345 lbm/gal; and

j) blending container volume = 1170 cm^3.

The following example calculations are merely examples for illustration purposes only and are not to be considered exclusive or exhaustive in nature. Each company should develop its own approach. API makes no warranties, express or implied reliance on, or any omissions from the information contained in the example calculations below.

D.2 Example Calculation of Nitrogen Fraction and Laboratory Density (Atmospheric)

Goal: Foaming a base slurry density to the nitrogen fraction required to achieve a downhole foam density of 13.5 lbm/gal for use in the lab at atmospheric conditions.

Using Equation (3) as specified in 5.3.2, calculate the nitrogen fraction required to achieve a 13.5 lbm/gal downhole foam density at the estimated conditions of pressure and temperature in the well—6000 psi and 60 °F.

$$\varphi_{\text{N2A}} = 100 \times [(16.4\ \text{lbm/gal} - 13.5\ \text{lbm/gal}) / (16.4\ \text{lbm/gal} - 3.185\ \text{lbm/gal})] = 21.94\ \%$$

Using Equation (4) as specified in 5.3.3, calculate the atmospheric foamed cement slurry density with the required nitrogen fraction to achieve the design downhole density, at estimated downhole conditions of pressure and temperature in the well, expressed in grams per cubic centimeter:

$$\rho_{\text{FA}} = [(100 - 21.94)/100] \times 16.4\ \text{lbm/gal} = 12.80\ \text{lbm/gal}\text{, and}$$

$$\rho_{\text{FA}} = 12.80\ \text{lbm/gal} / 8.345 = 1.534\ \text{g/cm}^3\text{.}$$

D.3 Example Calculation of Mass Percentages

Slurry design: Cement + surfactant(s) at 0.20 gallons per sack.

Downhole foamed slurry density = 13.50 lbm/gal

Base cement slurry density = 16.40 lbm/gal

Surfactant density = 10.0 lbm/gal

For 16.40 lbm/gal:

	Mass	Volume
Cement	94.00 lbm	3.56 gal
Surfactant	2.00 lbm	0.20 gal
Water	35.57 lbm	4.26 gal
Total	131.57 lbm	8.02 gal

Calculate the mass fraction of surfactant(s) from Equation (1) as specified in 5.2.

Goal: Determine the relative mass fraction (percentage) contribution for the surfactant(s) from Equation (1) as specified in 5.2. Then determine the mass fraction (percentage) contributions for cement and water for a base slurry with the given target density of 16.40 lbm/gal.

Cement (94.00 lbm/131.57 lbm) × 100 = 71.44 %

Surfactant(s) (2.0 lbm/131.57 lbm) × 100 = 1.52 %

Water (35.57 lbm/131.57 lbm) × 100 = 27.04 %

D.4 Example Calculation of Slurry Density Without Surfactant(s) for Use in On-the-fly Mixing Operations

To calculate the defined target mixing density for the base unfoamed cement slurry during job execution using a downstream foaming surfactant injection system [foaming surfactant(s) injected following slurry mixing], the slurry shall be mixed at the slurry density excluding the surfactant(s).

Goal: Determine the density of the base cement slurry without surfactant(s) (ρ_{BWOS}) with the given composition. For example, using Equation (2) as specified in 5.2:

$m_{\text{BWOS}} = m_{\text{c}} + m_{\text{w}} + m_{\text{a}}$ = 94 lbm + 35.57 lbm + 0 = 129.57 lbm

$V_{\text{BWOS}} = V_{\text{c.abs}} + V_{\text{w}} + V_{\text{ad.abs}}$ = 3.56 gal + 4.26 gal + 0 = 7.82 gal

$\rho_{\text{BWOS}} = m_{\text{BWOS}}/V_{\text{BWOS}}$ = 129.57 lbm/7.82 gal = 16.57 lbm/gal

where

m_{BWOS} is the mass of unfoamed base cement slurry with no surfactant; and

V_{BWOS} is the slurry volume without surfactant(s).

This calculated target mixing density will be reported for all jobs utilizing a downstream foaming surfactant injection system.

D.5 Example Calculation of Required Grams of Unfoamed Base Cement Slurry and Surfactant for Use in the Lab at Atmospheric Conditions

Goal: Prepare a foamed cement slurry sample from the example slurry in a 1170 cm^3 blending container.

For laboratory calculations, unfoamed base slurry density with surfactant and atmospheric foamed slurry density need to be expressed in grams per cubic centimeter.

Unfoamed base slurry density with surfactant(s) expressed in grams per cubic centimeter:

$$\rho_{BWOS} = 16.40 \text{ lbm/gal} / 8.345 = 1.965 \text{ g/cm}^3$$

Atmospheric foamed slurry density with the required foam quality of 21.94 % expressed in grams per cubic centimeter (see 5.3.7):

$$\rho_{FA} = 12.8 \text{ lbm/gal} / 8.345 = 1.534 \text{ g/cm}^3$$

a) Calculate the mass of the unfoamed base cement slurry with surfactant(s) using Equation (5) as specified in 5.3.4. This is the total mass that will be in the blending container after the foam is created.

$$m_{BWS} = 1170 \text{ cm}^3 \times 1.534 \text{ g/cm}^3 = 1794.78 \text{ g base slurry with surfactant(s)}$$

b) Calculate the mass of surfactant(s) that will be added to the slurry in the blending container to create the foam using Equation (6) as specified in 5.3.5.

$$m_S = 1794.78 \text{ g} \times (1.52/100) = 27.28 \text{ g of surfactant(s)}$$

c) Calculate the mass of unfoamed cement slurry without surfactant(s) to add to the blending container before adding surfactant(s) using Equation (7) as specified in 5.3.5.

$$m_{BWOS} = 1794.78 \text{ g} - 27.28 \text{ g} = 1767.50 \text{ g of base slurry without surfactant(s)}$$

D.6 Example Calculation of Volume and Mass of Unfoamed Base Cement Slurry with Surfactant(s) Required for Testing

The volume of unfoamed base slurry with surfactant(s) may also be calculated utilizing the laboratory atmospheric density calculated from Equation (4) as specified in 5.3.3. This density is calculated utilizing the nitrogen fraction required to achieve the design downhole density at the estimated conditions of pressure and temperature in the well from Equation (3) as specified in 5.3.2.

a) Calculate the volume of unfoamed base cement slurry with surfactant(s), expressed in cubic centimeters using Equation (8) as specified in 5.3.6.

$$V_{BWS} = 1170 \text{ cm}^3 - (1170 \text{ cm}^3 \times 21.94\,\%/100) = 913.30 \text{ cm}^3 \text{ of base slurry with surfactant(s)}$$

b) Calculate the mass of the unfoamed base cement slurry with surfactant(s), expressed in cubic centimeters using Equation (9) as specified in 5.3.6.

$$m_{BWS} = 913.30 \text{ cm}^3 \times 1.965 \text{ g/ cm}^3 = 1794.64 \text{ g of base slurry with surfactant(s)}$$

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[2] API Recommended Practice 10B-6, *Recommended Practice on Determining the Static Gel Strength of Cement Formulations*

[3] API Recommended Practice 13J, *Testing of Heavy Brines*

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[5] API Standard 65–Part 2, *Isolating Potential Flow Zones During Well Construction*

[6] ASTM C109 [1], *Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens)*

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

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