Addendum 1
October 1999

Recommended Practice for Testing Well Cements

API RECOMMENDED PRACTICE 10B
TWENTY-SECOND EDITION, DECEMBER 1997

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Addendum 1 to API RP 10B, Testing Well Cements (Contains errata items to Twenty-Second Edition and a revised Section 15, Slurry Stabillity Tests)

Page 13, Section 7.6.2

The reference to Section 11 should be Section 9.

Page 16, Table 2, Schedule 10Sg, Elapsed Time 120 min, column 7, for temperature gradient of 2.7°C/100 m

Replace "(1520" with "(152)".

Page 18, Section 9.2, metric value for Specific Heat

Replace "[2.1 – 2.4kJ/9kg x K)]" with "[2.1 – 2.4 kJ/(kg x K)]".

Page 19, Section 9.2, 4th paragraph, first sentence

Replace "rotated as a speed" with "rotated at a speed".

Page 22, Equation (8b)

The constant should be 9.776.

Page 87, Section 10.6.2.10

The reference to 10.6 should be "10.8".

Page 87, Section 10.7.1.11

The reference to 10.6 should be "10.8".

Page 89, Section 11.2.1.1, first sentence

The inside dimensions given for the bottom, 1.102 in., 27.99 mm, and top, 1.154 in., 29.31 mm are reversed. The inside dimension for the bottom should be 1.154 in. (29.31 mm) and the inside dimension for the top should be 1.102 in. (27.99 mm) as shown in Figure 9.

Page 95, Equation (17b)

Replace "4" with "2".

Page 96, Section 12.4.2 (begins on page 95)

Remove the words "which is also transmitted to the" and add the word "or" following "cylinder".

Page 96, Equation (19b)

Replace "32.55" with "16.28".

Page 98, Section 12.8.1.1

First paragraph:

The reference to Curve A should be Curve D.

Second paragraph:

The reference to Curve B should be Curve A.

Page 98, Section 12.8.1.2

First paragraph:

The reference to Figure 11, Curve C, should be Figure 11, Curves B and C.

Second paragraph, second sentence:

The reference to Figure 11, Curve C should be Figures 11 and 12, Curve B.

Second paragraph, fourth sentence:

The reference to Figure 11, Curve D should be Figures 11 and 12, Curve C.

Second paragraph, sixth sentence:

The reference to Figure 11, Curve B should be Figures 11 and 12, Curve A.

Page 101, Figure 12

The scale for the Shear-rate axis (x-axis) should begin with 1, not 0.

Page 104, Section 13.2, first sentence

Replace "m" with "μ" and "r" with "ρ".

Page 105, Section 13.3, first sentence

Replace "r" with "ρ".

Page 105, Equations (62), (63), and (64)

The term K_{RePL} should be in the denominator rather than the numerator.

Page 106, Section 13.4, third paragraph

Replace "m_p" with "μ_p" and "r" with "ρ."

Page 106, Equation (72)

The title should read "Annular Flow: Pipe".

Page 106, Equation (73)

The title should read "Annular Flow: Slot".

Page 106, Equation (75)

The title should read "Annular Flow: Pipe".

Page 106, Equation (76)

The title should read "Annular Flow: Slot".

Page 106, Section 13.4, right-hand column, first paragraph

The introductory sentence and table should read as follows:

Depending on the value of the Reynolds number the flow regime is classified as follows:

Flow Regime	Pipe Flow	Annular Flow
Laminar	$Re_{BP} \leq Re_{BP1}$	$Re_{BP} \leq Re_{BP1}$
Transitional	$Re_{BP} < Re_{BP1} < Re_{BP2}$	$Re_{BP} < Re_{BP1} < Re_{BP2}$
Turbulent	$Re_{BP} \geq Re_{BP2}$	$Re_{BP} \geq Re_{BP2}$

Page 106, Equation (78)

The title should read "Annular Flow: Pipe".

Page 106, Equation (79)

The title should read "Annular Flow: Slot".

Page 107, Equation (88)

The title should read "Annular Flow: Pipe".

Page 107, Equation (89)

The title should read "Annular Flow: Slot".

Page 107, Equations (90), (91), (92), and (93)

The term in the denominator of each of these equations, $6Re_{BP2}$, should read "$6Re^2_{BP}$".

Page 107, Equation (91)

The title should read "Annular Flow: Pipe".

Page 107, Equation (92)

The title should read "Annular Flow: Slot".

Page 107, Section 13.4 (begins on page 106), right-hand column, first sentence

The expression $(\tau_o/\tau_w)^4$ should read $(\tau_o/\tau_w)^3$.

Page 108, Section 13.5.1, example calculation of Reynolds number, R_e

The correct answer is 192,000.

Page 108, Section 13.5.1, example calculation of friction factor, f

Replace 19,200 with 192,000.

Page 108, Section 13.5.1, third example problem

Replace "8 $^5/_7$ inch" with "8.5 x 7 inch".

Page 109, Section 13.5.2, third example problem

Replace "8 $^5/_7$ inch" with "8.5 x 7 inch".

Page 109, Section 13.5.3.1, equation for τ_o

The equation should be $\tau_o = [1.193 \times 8 - 1.611] = 7.933$

Page 110, Section 13.5.3.2, second paragraph

1.5×10^5 should be 1.575×10^5.

Page 110, Section 13.5.3.3, Annular Flow: Slot equation for Re_{BP2}

The denominator should read 12×0.5102.

Page 111, Section 13.5.3.4, third paragraph

1.5×10^5 should be 1.575×10^5.

Page 111, Table 10

The U.S. Oil Field Unit for K_{RePL} should be $0.2325/12^n$.

Page 112, Table 11

Change m to μ, m_p to μ_p, r to ρ, and t_y to τ_o.

Replace Section 15, Well Simulation Slurry Stability Tests, (including Table 13) with the following:

15 Slurry Stability Tests

15.1 INTRODUCTION

The purpose of this test is to determine the stability of a static (quiescent) cement slurry. The cement slurry is conditioned to simulate dynamic placement in a wellbore. The slurry is then left static to determine if free fluid separates from the slurry and if particle sedimentation occurs. Both the free fluid result and the sedimentation result are required to understand the static stability of the slurry under downhole conditions. Free fluid can be formed with minimal sedimentation and sedimentation can take place without free fluid being formed. Therefore, both results must be evaluated to determine slurry stability. Excessive free fluid and sedimentation are normally considered detrimental to cement sheath quality. The acceptable amount of free fluid or sedimentation will vary with the application. Table 13 can be used to record the results of these tests.

15.2 SLURRY MIXING

The cement slurry should be prepared according to Section 5. If performing the sedimentation test described in 15.7, measure the density of the slurry using a pressurized fluid density balance (see Section 6) immediately after mixing the slurry.

15.3 SLURRY CONDITIONING

15.3.1 The cement slurry should be poured immediately into the slurry cup of an atmospheric or a pressurized consistometer for conditioning. The slurry cup should be initially at ambient temperature to avoid the possibility of thermally shocking temperature sensitive slurries. The slurry may then be heated or cooled to the desired test temperature up to 176°F (80°C) in the atmospheric or pressurized consistometer, or to the desired elevated temperature [if greater than 176°F (80°C)] and pressure in a pressurized consistometer. The thickening time schedule which most closely simulates actual field conditions should be followed with either consistometer.

15.3.2 After completing the heat-up schedule, the slurry may be conditioned at the specified temperature and pressure for 30 ± ½ minutes, or other desired conditioning period, before proceeding.

15.3.3 If the conditioning temperature is greater than 194°F (90°C), safe operating practices require cooling the slurry to a minimum of 194°F (90°C) before releasing the pressure from the consistometer.

Note: The 194°F (90°C) safety temperature assumes a boiling point for water of 212°F (100°C). If the boiling point of water in your area is less than 212°F (100°C), adjust test temperatures accordingly.

Release the pressure slowly [about 200 psi/sec (1380 kPa/sec)]. Remove the slurry cup from the consistometer, keeping the container upright so oil does not mix with the slurry. Remove the top locking ring, drive bar and collar from the shaft and the diaphragm cover. Syringe and blot oil from the top of the diaphragm. Remove the diaphragm and the support ring. Syringe and blot any remaining oil from the top of the slurry. If contamination is severe, discard the slurry and begin the test again. Remove the paddle and stir the slurry briskly with a spatula for five seconds to re-disperse any solids which may have settled to the bottom of the cup.

15.3.4 After conditioning by either method, proceed with either 15.4 or 15.5 for a free fluid test. For a sedimentation test, proceed to 15.7.

15.4 FREE FLUID TEST WITH HEATED STATIC PERIOD

Pour the slurry into a clear graduated tube. The ratio of the slurry-filled length to the inside tube diameter should be greater than 6:1 and less than 8:1. The clear tube must be inert to well cements and must not deform during the test. The clear tube must be graduated such that the slurry volume placed in the tube can be visually determined with a precision of ± 2 mL. The free fluid test slurry volume must be between 100 mL and 250 mL, inclusive. Document the slurry volume placed in the tube when the tube is vertical. Document the tube dimensions as well.

A test chamber for curing the slurry during the static period should be preheated or precooled to the test temperature or 176°F (80°C), whichever is cooler. 176°F (80°C) was chosen to minimize the effects of condensation on the test results and assumes a boiling point for water of 212°F (100°C). If the boiling point of water in your area is less than 212°F (100°C), adjust the 176°F (80°C) test temperature accordingly. This chamber may be an atmospheric pressure heating or cooling bath/oven/jacket/chamber, or a suitable pressurized heating/cooling chamber that uses hydrocarbon oil to transmit heating/cooling to the slurry.

Note: Bath/oven/jacket/chamber or pressurized chamber will be designated as a chamber for the rest of this section. When hydrocarbon oil is used, the oil should have a flash point that satisfactorily meets the safety requirements of the organization performing the test.

15.4.1 Free Fluid Tests at Temperatures Less Than 176°F (80°C)

Cover the opening of the graduated tube to prevent evaporation and immediately place the graduated tube in a heating or cooling chamber that is preheated or pre-cooled to test temperature. The chamber must be able to heat or cool the entire slurry. The tube can be tilted to simulate wellbore deviation, if desired. Appropriate precautions should be taken to ensure the static curing is performed at essentially vibration free conditions.

The temperature is maintained at test temperature for the remainder of the test. The test duration is two hours from the time the slurry is poured into the clear tube. After the two-hour test period, measure the free fluid (clear or colored fluid on top of the cement slurry inside the clear tube). The volume measurement should be made with a precision of ± 0.2 mL.

Calculate the free fluid according to 15.6.

15.4.2 Free Fluid Test at Temperatures Greater Than or Equal to 176°F (80°C)

Place the graduated tube in a preheated [176°F (80°C)] oil filled heating chamber. If desired, tilt the tube to simulate wellbore deviation. Further heat the slurry to test temperature in the time required to take the slurry from a depth with 176°F (80°C) circulating temperature to test temperature. Some heating chambers may not be able to heat fast enough and in that case heat as fast as possible but minimize overshooting the test temperature. Maintain the slurry at test temperature until it is time to cool the chamber to 176°F (80°C). The time required to cool various pieces of equipment from elevated temperatures to 176°F (80°C) will vary. The pressure on the curing chamber should be maintained high enough throughout the test so the slurry cannot boil (see Table 8). The pressure applied can simulate bottom hole conditions, if desired. So as to prevent vibration, constant pump cycling should be avoided. The schedules found in Section 9 can be used to aid in selecting pressurization and heating rates. Appropriate precautions should be taken to ensure the static curing is performed at essentially vibration free conditions.

The two hour test period is initiated when the conditioned slurry is poured into the graduated tube. Slurries should be cooled to 176°F (80°C) before the free fluid is measured. This cooling time is part of the two-hour test period. After the two-hour test period, measure the free fluid (clear or colored fluid on top of the cement slurry inside the cylinder). Free fluid for slurries immersed in hydrocarbon oil will collect above the cement but below the oil. The volume measurement of the free fluid should be made with a precision of ± 0.2 mL.

Calculate the free fluid according to 15.6.

15.5 FREE FLUID TEST WITH AMBIENT TEMPERATURE STATIC PERIOD

Pour 250 mL of the slurry from Section 15.3 into a 250 mL graduated glass cylinder. The zero to 250 mL graduated portion of the cylinder shall be no less that 232 mm nor more than 250 mm in length, graduated in 2 mL increments or less. The slurry should be stirred with a spatula during pouring to assure a uniform sample of the slurry. The two-hour test period is initiated when the conditioned slurry is poured into the cylinder. The cylinder should be sealed with plastic film wrap or equivalent material to prevent evaporation. The cylinder may be inclined at an angle to simulate wellbore deviation. Appropriate precautions should be taken to ensure that static curing is performed at essentially vibration free conditions.

After the 2-hour test period, measure the free fluid (clear or colored fluid on top of the cement slurry inside the cylinder). The volume measurement of the free fluid should be made with a precision of ± 0.2 mL.

Calculate the free fluid according to 15.6.

15.6 PERCENT FREE FLUID CALCULATION

The percent free fluid is calculated by the following:

$$\% \text{ Free Fluid} = \frac{(\text{mL of Free Fluid})(100)}{\text{mL of Slurry}}$$

15.7 SEDIMENTATION TEST

15.7.1 Pour the slurry from 15.3 into a sedimentation tube until it is approximately ¾ inch (20 mm) from the top. The sedimentation tube should have an inner diameter of 25 ± 5 mm and a minimum length of 100 mm (the most common length is approximately 200 mm). The tube may be split to aid in removal of the set cement. See Figure 17. The inside of the tube, and all joints, should be lightly greased to ensure that it is leak-tight and so that the set cement can be removed without damage. The tube must be inert to well cements and not deform during the course of the test. The slurry in the filled tube should be puddled to dislodge any air bubbles. The tube should then be filled completely. A top closure can be used to prevent spillage of the slurry. The top closure should allow pressure communication. The filled tube should be placed in a water-filled preheated/precooled heating/cooling chamber in a vertical position. The chamber should be preheated or precooled to the desired test temperature or 194°F (90°C), whichever is cooler (see safety note in 15.3).

15.7.2 The slurry temperature should be adjusted further to simulate temperature changes in the wellbore. Sufficient pressure must be maintained to prevent boiling of the slurry (see Table 8). The pressure applied can simulate bottom hole conditions, if desired. Constant pump cycling should be avoided to minimize vibration. The schedules in Sections 7 and 9 can be used to aid in selecting the temperature and pressure.

15.7.3 Allow the slurry to cure for 24 hours, or until set, before removing it from the heating/cooling chamber.

15.7.4 Cool the chamber to 194°F (90°C), if required (see safety note in Section 15.3). Release pressure from the chamber, if required. Remove the tube from the heating/cooling chamber and bring the tube to 80° ±10°F (27° ±6°C) by plac-

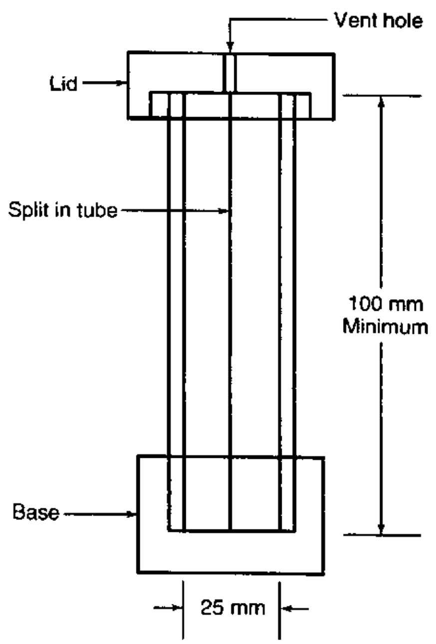

Figure 17—Typical Sedimentation Tube

ing it in a water bath. Once the tube has cooled remove the cement from the tube. Keep the cement sample immersed in water to prevent it from drying out. The length of the set cement specimen should be measured. Mark the specimen approximately ¾ inch (20 mm) from the bottom and from the top of the sample. The middle section, between the marks, should then be divided by further marks into roughly equal pieces with a minimum of 2 segments. The sample should be broken or cut at these marks. The sections must be kept in order. Keep the sections immersed in water until each is weighed.

15.7.5 The preferred way to determine the density of each section is to place a beaker containing water on the balance (a balance with a precision of 0.01 gram is necessary; 0.001 gram is preferred) and tare the balance to zero. Remove a section to be measured from the water bath and gently dry it with a paper towel. Place this section on the balance beside the beaker. Record the weight and remove the section from the balance. Tare the balance to zero. Place a noose of thin line around the section. Pick up the section by the line and suspend the section in the water in the beaker such that the sample is totally immersed in water and does not touch the bottom or sides of the beaker. Air bubbles should not be clinging to the section. Obtain the weight of the sample suspended in water. Remove the sample from the water. Repeat the procedure for each set cement section.

15.7.6 By applying the Principle of Archimedes, calculate the specific gravity of each cement section.

$$\text{S.G.} = \frac{\text{Weight of section in air, g}}{\text{Weight of section in water, g}}$$

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

Note: It is normal for cement slurries to experience a small density increase upon setting.

The liquid slurry density was measured prior to curing to permit the calculation of the % density difference between the liquid sample and the set sample.

$$\text{\% Density Difference} = \frac{\text{Density of Cement Segment} - \text{Density of Cement Slurry (100)}}{\text{(Density of Cement Slurry)}}$$

The density difference for well cements can vary greatly and depends on many factors. The amount of density difference that is acceptable will vary with the application.

Replace Table 13 with the following:

Table 13—Free Fluid and Sedimentation Results Reporting Form

Slurry Mixing
- Cement Temperature: ________
- Mix Water Temperature: ________
- Slurry Initial Temperature: ________
- Slurry Final Temperature: ________
- Time to Final Temperature: ________
- Optional Additional Conditioning Period: ________
- Pressure Profile:
  - Initial Pressure: ________
  - Final Pressure: ________
  - Time to Final Pressure: ________

Conditioning (applies to free fluid and sedimentation test)
- Final Temperature: ________
- Time to Final Temperature: ________minutes
- Initial Pressure: ________
- Final Pressure: ________
- Time to Final Pressure: ________
- Conditioning Time at T & P: ________
- Time to Cool the Slurry to 194°F (90°C): ________
- Section 9 Schedules Employed: ❑ Yes ❑ No
- If Yes, Schedule Number: ________

Free Fluid Test (Two-hour Test Period)
- Length of Graduated Tube Section: ________
- Graduated Tube ID: ________
- Slurry Volume: ________
- Test Angle: ________
- Preheated or Precooled Chamber Temperature: ________
- Test Temperature: ________
- Time to Test Temperature: ________
- Initial Test Pressure: ________
- Pressure at Test Temperature: ________
- Time to Pressure at Test Temperature: ________
- Time at Test Temperature: ________ hours
- Time to Cool the Chamber to 194°F (90°C): ________

Free Fluid Results
- Measured Free Fluid Volume: ________ mL
- % Free Fluid: ________

Sedimentation Test (Period after Conditioning)
- Preheated or Precooled Chamber Temperature: ________
- Test Temperature: ________
- Time to Test Temperature: ________
- Initial Test Pressure: ________
- Pressure at Test Temperature: ________
- Time to Pressure at Test Temperature: ________
- Time at Test Temperature: ________ hours
- Time to Cool the Chamber to 194°F (90°C): ________
- Length of Sedimentation Tube: ________
- Length of Set Specimen: ________
- Section 7 Schedules Employed: ❑ Yes ❑ No
- If Yes, Schedule Number: ________
- Conditioning time at T & P: ________

Sedimentation Results
- Measured Slurry Density: ________

Density Profile:

S_1 (top) Density:	_____;	% Density Diff: _____
S_2 Density:	_____;	% Density Diff: _____
S_3 Density:	_____;	% Density Diff: _____
S_4 Density:	_____;	% Density Diff: _____
S_5 Density:	_____;	% Density Diff: _____
S_x (bottom) Density:	_____;	% Density Diff: _____

Note: The heating/cooling, pressurizing, and cooling information that is requested in the results reporting form will allow other laboratories to reproduce the test. The information requested is sufficient only if the heating/cooling rate, pressurizing rate, and cool down rate are linear. If the rates are not linear, specify the exact heating/cooling, pressurizing, and cool down schedules.

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API RECOMMENDED PRACTICE 10B
TWENTY-SECOND EDITION, DECEMBER 1997

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Exploration and Production Department

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FOREWORD

This recommended practice is under the jurisdiction of the API Subcommittee on Standardization of Well Cements.

The purpose of this recommended practice is to provide guidance for the testing of cement slurries and related materials under simulated well conditions.

Conversions of U.S. customary units[a] to International System (SI) metric units are provided throughout the text of this document in parentheses, e.g., 6,000 ft (1,830 m). SI equivalents have also been included in all tables. U.S. customary units, where stated, are preferential and shall be the standard in this recommended practice. U.S. customary units are based on the foot, the pound, the gallon and the degree Fahrenheit commonly used in the United States of America and defined by the National Institute of Standards and Technology. The factors used for conversion of U.S. customary units to SI units are listed below:

1 cubic foot (ft^3) = 0.02831685 cubic meter (m^3)
1 cubic foot per minute = 0.4719474 liter per second (L/s)
1 inch = 25.4 millimeters (mm) exactly
1 foot (ft) = 0.3048 meter (m) exactly
1 pound mass (lb) = 0.4535924 kilogram (kg)
1 pound per foot (lb/ft) = 1.488164 kilograms per meter (kg/m)
1 pound force (lbf) = 4.448222 Newton (N)
1 pound force per square inch (psi) = 0.006894757 megapascals (MPa)
degrees Fahrenheit (°F) = [(°Celsius)(1.8)]+32
1 U.S. gallon = 3.785412 liter (L)

API *Recommended Practice for Testing Well Cements* (API RP10B) is published as an aid to the laboratory testing of well cements. By the use of this recommended practice, well cement test data produced by different laboratories can be compared. Well cement specification testing is covered in API Specification 10A (Spec 10A), *Specification for Well Cements*.

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[a]Some of these units have the same name as similar units in the United Kingdom (British, English, or U.K. Units) but are not necessarily equal to them

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Tables

Recommended Practice for Testing Well Cements

1 Scope

1.1 WELL CEMENTS

Well cement slurries can be based on (but are not limited to) one of the API classes and grades of cement identified in this section and shown in Table 1. API well cements are produced by grinding Portland cement clinker, generally consisting of hydraulic calcium silicates and aluminates and usually containing one or more of the forms of calcium sulfate as an interground addition.

API cements are graded according to sulfate resistance. Three grades are defined: ordinary (O), moderate sulfate-resistant (MSR), and high sulfate-resistant (HSR).

Table 1—Grades of API Classes of Well Cements*

Class	Ordinary (O) (C_3A Not Specified)	Moderate Sulfate Resistant (MSR) (3-8% C_3A)	High Sulfate Resistant (HSR) (<3% C_3A)
A	X		
B		X	X
C	X	X	X
D		X	X
E		X	X
F		X	X
G		X	X
H		X	X

*From API Specification 10A.

1.2 API CEMENT CLASSES

The following is a brief discussion of the differences and similarities among API classes of cement.

1.2.1 Class A

This product is intended for use when special properties are not required. It is available only in ordinary (O) grade. Class A cement is similar to ASTM C 150, Type I with regard to both chemistry and fineness. Processing additions may be used in the manufacture of Class A cement provided such materials in the amounts used have been shown to meet the requirements of ASTM C 465. Specification testing of Class A cement slurries requires 46 percent water (100 parts dry cement by weight to 46 parts mixing water by weight) according to API Specification 10A.

1.2.2 Class B

This product is intended for use when conditions require moderate or high sulfate-resistance. Class B cement is similar to Class A cement except that it is available in both moderate (MSR) and high sulfate-resistant (HSR) grades. The MSR grade is similar to ASTM C 150, Type II with regard to both chemistry and fineness. The HSR grade is similar to ASTM C 150 Type V with regard to both chemistry and fineness. Specification testing of Class B cement slurries requires 46 percent water (100 parts dry cement by weight to 46 parts mixing water by weight) according to API Specification 10A.

1.2.3 Class C

This product is intended for use when conditions require high early strength; it is typically the most finely ground of all API classes of well cement. It is available in ordinary (O), moderate sulfate-resistant (MSR), and high sulfate-resistant (HSR) grades. Class C (O) cement is similar to ASTM C 150, Type III. Processing additions may be used in the manufacture of Class C cement provided such materials in the amounts used have been shown to meet the requirements of ASTM C 465. Specification testing of Class C cement slurries requires 56 percent water (100 parts dry cement by weight to 56 parts mixing water by weight) according to API Specification 10A.

1.2.4 Class D

This product is intended for use under conditions of moderately high temperatures. Specifications for Class D cement cover moderate sulfate-resistant (MSR) and high sulfate-resistant (HSR) grades. Processing additions may be used in the manufacture of the cement provided such materials in the amount used have been shown to meet the requirements of ASTM C 465. Suitable set-modifying agents are typically interground or blended during manufacture. Specification testing of Class D cement slurries requires 38 percent water (100 parts dry cement by weight to 38 parts mixing water by weight) according to API Specification 10A.

1.2.5 Class E

This product is similar to Class D cement. It is intended for use under conditions of high temperature. Specification testing of Class E cement slurries requires 38 percent water (100 parts dry cement by weight to 38 parts mixing water by weight) according to API Specification 10A.

1.2.6 Class F

This product is similar to Class D cement. It is intended for use under conditions of extremely high temperatures. Specification testing of Class F cement slurries requires 38 percent water (100 parts dry cement by weight to 38 parts mixing water by weight) according to API Specification 10A.

1.2.7 Class G

This product is intended for use as a basic well cement. No additions other than calcium sulfate or water, or both, shall be interground or blended with clinker during manufacture. It is available in moderate sulfate-resistant (MSR) and high sulfate-resistant (HSR) grades. Specification testing of Class G cement slurries requires 44 percent water (100 parts dry cement by weight to 44 parts mixing water by weight) according to API Specification 10A.

1.2.8 Class H

This product is intended for use as a basic well cement. Class H cement is similar to Class G cement. Class H cement is typically more coarsely ground than Class G cement. Specification testing of Class H cement slurries requires 38 percent water (100 parts dry cement by weight to 38 parts mixing water by weight) according to API Specification 10A.

2 Referenced Publications

Unless otherwise specified, the most recent editions or revisions of the following standards, codes, and specifications shall, to the extent specified herein, form a part of this standard:

API

Spec 10A	*Specification for Well Cements*
Spec 10D	*Specification for Bow-Spring Casing Centralizers*
RP 10E	*Recommended Practice for Application of Cement Lining to Steel Tubular Goods, Handling, Installation and Joining*
Spec 13A	*Specification for Drilling-Fluid Materials*
RP 13B-1	*Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids*
Bul 13D	*Bulletin on the Rheology of Oil-Well Drilling Fluids*
RP13J	*Recommended Practice for Testing Heavy Brines*
Bul D17	*Running and Cementing Liners in the Delaware Basin, Texas*
GOT	*Glossary of Oilfield Production Terminology*

ASTM[1]

C 109	*Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)*
C 150	*Standard Specification for Portland Cement*
C 183	*Standard Practice for Sampling and the Amount of Testing of Hydraulic Cement*
C 188	*Standard Test Method for Density of Hydraulic Cement*
C 465	*Standard Specification for Processing Additions for Use in the Manufacture of Hydraulic Cements*

3 Definitions

The following is a listing of terms found in the API Recommended Practice 10B. The bold numbers in parenthesis following the definitions are the location in the document from which the term was taken. These definitions are only valid within the context of the Recommended Practice 10B. The terms, mathematical abbreviations and expressions found in Sections 12 and 13 of Recommended Practice 10B are defined in each respective section and are not part of this listing.

3.1 absolute volume: The volume per unit mass. The reciprocal of absolute density expressed as volume per unit mass. **(17.3)**

3.2 additives: Materials added to a cement slurry to modify or enhance some desired property. Common properties that are modified include: modification of the setting time by use of retarders or accelerators, fluid loss control, viscosity modification, etc. **(4.1)**

3.3 annulus: Space surrounding the pipe in the wellbore. The outer wall of the annular space may be either formation or casing.

3.4 API: Abbreviation for the American Petroleum Institute, headquartered in Washington, D.C. This is the trade association for the petroleum industry.

3.5 API specification: A document which describes the approved specification for a product. The conditions of a specification test are applicable only to the product for which the specification is intended and the test procedure shall not be modified in any manner.

3.6 API recommended practice: A document which describes the approved recommended inspection or test procedure for a product. The testing procedure may be readily modified to simulate specific well conditions.

[1]American Society for Testing and Materials, 100 Bar Harbor Drive, West Conshohocken, Pennsylvania 19428.

3.7 AST (assumed surface temperature): The assumed temperature at surface used for calculating a Pseudo-Temperature Gradient. **(C.9)**

3.8 batch mixing: The process of mixing and holding a volume of cement slurry prior to placement in the wellbore. **(9.5.3.1)**

3.9 B_c (Bearden units of consistency): The consistency of a cement slurry when determined on a pressurized consistometer. **(9.3.1.1)**

3.10 BHCT: Bottom hole circulating temperature. **(7.6.1)**

3.11 BHP (bottom hole pressure): The hydrostatic pressure at the bottom of the well calculated from the true vertical depth and the fluid densities in the wellbore. **(9.5.3.5)**

3.12 BHST (bottom hole static temperature): The static temperature at the bottom of the wellbore. **(Table 2)**

3.13 blow out: The point in time at which nitrogen flows through the sample in a fluid loss test. **(10.9.4)**

3.14 bottom hole circulating temperature (BHCT): The circulating temperature at the bottom of the wellbore. **(7.6.1)** The temperature at the bottom of a well with a fluid circulating in the well. The BHCT can vary with time, fluid being circulated, pump rate, pipe size, etc.

3.15 bottom hole static temperature (BHST): The undisturbed temperature at the bottom of the well. **(Table 2)**

3.16 bulk density: The weight per unit volume of a dry material containing entrained air. **(17.2.2)**

3.17 casing cementing: The complete or partial annular cementing of a full casing string. **(9.5.1)**

3.18 cement (Portland): Ground clinker generally consisting of hydraulic calcium silicates and aluminates and usually containing one or more of the forms of calcium sulfate as an interground addition. **(1.1)**

3.19 cement class: The designation by API to denote the various classification of API cement according to its intended use. **(1.2)**

3.20 cement grade: The designation by API to denote the sulfate resistance of a particular cement. **(1.2)**

3.21 cement type: The designation used by ASTM to denote the various classifications of ASTM cement according to its intended use.

3.22 cement blend: A mixture of dry cement and other dry materials.

3.23 clinker: The fused materials from the kiln in cement manufacturing that are interground with calcium sulfate to make cement. **(1.1)**

3.24 compatibility: Capacity of forming a fluid mixture that does not undergo undesirable chemical and/or physical reactions. **(16.2)**

3.25 compressive strength: The force per unit area required to crush a set cement sample. **(7.1)**

3.26 consistometer: A device used to measure the thickening time of a cement slurry under temperature and pressure. **(9.2)**

3.27 continuous pumping squeeze cementing operations: A squeeze cementing operation that does not involve cessation of pumping. **(9.5.4.1)**

3.28 density: Mass per unit volume. **(6.1)**

3.29 equivalent sack: The weight in pounds of the blend of Portland cement and fly ash or pozzolan that has the same absolute volume as 94 lbs of Portland cement. **(17.3)**

3.30 filtrate: The liquid that is forced out of a cement slurry during a fluid loss test. **(10.9.2)**

3.31 fly ash: The powdered residue from the combustion of coal having pozzolanic properties. **(17.1.3)**

3.32 free fluid: The colored or colorless liquid which has separated from a cement slurry. **(15.4.1)**

3.33 freeze thaw cycle: Test involving a cement sample that is alternately exposed to temperatures from 20°F (–7°C) to 170°F (77°C). **(14.6)**

3.34 hesitation pumping squeeze cementing operations: A squeeze cementing operation that incorporates discontinuous pumping of the cement slurry. The slurry is placed into the well, the pumps are stopped for some period of time, then a volume of slurry is again pumped. The process is repeated until a predetermined pressure is reached or the volume of cement slurry has been completely pumped. **(9.5.4.2)**

3.35 H_{ur} [heat up rate in °F/min (°C/min)]: The rate of temperature change from the SST to the PBHCT. **(9.5.3.4)**

3.36 liner cementing: Annular cementing operations for which the top of the casing being cemented is not at the top of the wellbore. **(9.5.2)**

3.37 MaxRBHST: The maximum recorded bottom hole static temperature at the bottom of the wellbore after a static period. **(C.9)**

3.38 MinRBHCT: The minimum recorded bottom hole circulating temperature after sufficient circulation in the well to obtain a stabilized or steady-state temperature. **(C.9)**

3.39 mud: The fluid that is circulated through the wellbore during drilling or workover operations. **(16.3.2)**

3.40 mud balance: A beam type balance used to measure fluid density at atmospheric pressure. **(6.1)**

3.41 neat cement slurry: A cement slurry consisting of only cement and water.

3.42 PBHCT: Predicted bottom hole circulating temperature. (9.5.3.3) (See also C.9.)

3.43 P_{dr} (pressure down rate): The rate at which pressure is reduced from BHP to TOCP during a thickening time test. **(9.5.3.12)**

3.44 permeability: The measure of the capacity of a porous medium to allow flow of fluids or gasses. The unit of measure is normally millidarcy, mD. **(Section 11)**

3.45 plug cementing: The process of placing a volume of cement in a well to form a plug across the wellbore. **(9.5.6)**

3.46 pozzolan: A siliceous or siliceous and aluminous material which in finely divided form will react with calcium hydroxide to form a cementitious material. **(17.1.1)**

3.47 preflush: A fluid containing no insoluble weighting agents used to separate drilling fluids and cementing slurries. **(16.2)**

3.48 pressure vessel: The vessel in a consistometer used for thickening time testing into which the slurry container is placed for testing. **(9.4.3)**

3.49 pressurized curing vessel: A vessel used for curing a sample of cement under temperature and pressure for compressive strength testing. **(7.4.3.2, 7.5.4)**

3.50 *PSqT* (predicted squeeze temperature in degrees F): A squeeze temperature based on a mathematical correlation. **(9.5.5.1)**.

3.51 *PsTG*: Pseudo temperature gradient in °F/100 feet calculated from the difference between the MaxPBHST and the AST. **(9.5.3.3)** (See also **C.2.**)

3.52 *PsUT* (pseudo undisturbed temperature): The calculated value for formation temperature based on field data and associated correlation techniques. **(C.9)**

3.53 P_{ur} (pressure up rate): The rate at which pressure is increased from the starting pressure to the bottom hole pressure during a thickening time test. **(9.5.3.7)**

3.54 *RSqT*: Recorded Squeeze Temperature. **(C.5)**

3.55 sedimentation: The separation and settling of solids in a cement slurry. **(10.10.4 Note 1 and 15.1)**

3.56 slurry container/cup: The container in a pressurized consistometer used to hold the slurry for conditioning the sample or for thickening time testing. **(7.6.2)**

3.57 sonic strength: The extent of strength development of a cement sample calculated by measuring the sonic velocity. The calculation is based on specific mathematical correlations and not direct measurements of strength. **(Section 8)**

3.58 SP: Starting pressure in a thickening time test. The initial pressure applied to the test sample at the beginning of the thickening time test. Also used to determine the pressure up rate. **(9.5.3.7)**

3.59 spacer: A fluid with insoluble weighting materials that is used to separate drilling fluids and cementing slurries. **(16.2)**

3.60 specific gravity: The ratio of the mass of a substance to the weight of an equal volume of a standard substance (water) at a reference temperature (4°C). **(5.3)**

3.61 squeeze cementing: The remedial process of forcing cementing material under pressure into a specific portion of the well such as fractures or openings. **(9.5.4)**

3.62 SST (slurry surface temperature): The temperature of the cement slurry at surface prior to placement in the wellbore. **(9.5.3.4)**

3.63 static fluid loss: Fluid lost from a cement slurry when tested against a 325 mesh screen and 1,000 psi differential pressure according to Section 10. **(10.1)**

3.64 static stability: A test for determination of the degree of sedimentation and free fluid development in a cement slurry. **(Section 15)**

3.65 stirred fluid loss cell: A specially designed cell that allows for conditioning of the cement slurry within the same cell used to perform a static fluid loss test. **(10.1)**

3.66 strength retrogression: The reduction in compressive strength and the increase in permeability of a cement brought on by exposure to temperatures exceeding 230°F (110°C). **(7.7)**

3.67 t_a: Time to displace the leading edge of the cement slurry from bottom of the casing to the top of the annular cement column. **(9.5.3.9)**

3.68 TCCT (top of cement circulating temperature): The circulating temperature at the top of the cement column. **(7.6.2.1)**

3.69 TCST (top of cement static temperature): The static temperature at the top of the cement column. **(7.6.1)**

3.70 TCTVD (top of cement true vertical depth): The true vertical depth at the top of the cement column. **(9.5.3.11)**

3.71 t_{disp}: Time to displace leading edge of cement slurry to the bottom of the wellbore or other predetermined location in the well. **(9.5.3.2)**

3.72 thickening time: The time for a cement slurry to develop a selected B_c. **(9.1)** The results of a thickening time test provide an indication of the length of time a cement slurry will remain pumpable under the test conditions. (See also 9.4.5.)

3.73 TOCP: Top of cement pressure. (9.5.3.8 and 9.5.3.11)

3.74 TOCT (top of cement column temperature): The circulating temperature at the top of the cement column. (9.5.3.8 and 9.5.3.10)

3.75 UFT: Undisturbed formation temperature. (C.2)

3.76 weigh batch mixer: Device or system for the weighing and blending of cement with dry additives. Also called a scale tank. (4.3)

3.77 well simulation test: A test whose parameters are designed and modified as required to simulate the conditions found in a wellbore. (7.1)

4 Sampling

4.1 GENERAL

Past API documents have dealt only with sampling unblended cement according to the procedure outlined in ASTM C 183. For cement blends, the purpose for which samples are taken must be considered. In many cases, samples of the cement, cement blend, solid and liquid additives, and mixing water may be required to test a slurry according to API Recommended Practice 10B. The best available sampling technology should be employed to ensure accurate samples are taken. Some commonly-used sampling techniques are contained in this section.

4.2 SAMPLING CEMENT AT FIELD LOCATION

When sampling from bulk tanks, transports or sacks, the cement should be dry and uniform. Multiple samples should be extracted using a suitable device (see Figure 1). A composite of the samples should be prepared, packaged and labeled (see 4.7). Average sample size should be 2 to 5 gallons. Sampling procedures are also outlined in ASTM C 183.

4.3 SAMPLING CEMENT BLENDS AT FIELD LOCATION

Cement blends may be sampled from the weigh batch mixer (scale tank), bulk transport or extracted from the flow lines during transfer. The cement and dry additives should be thoroughly blended prior to sampling. This can be done by transferring the cement (air blowing) from the weigh batch mixer to some other container three (3) to six (6) times. Samples from the bulk container may be extracted according to 4.2. Samples extracted from a flow line during a transfer may be taken from a properly installed sample valve, diverted flow sampler or automatic in-line sampling device (see Figure 1). The samples should be prepared, packaged, and labeled (see 4.7). Sample size should be sufficient to perform the desired testing.

4.4 SAMPLING DRY CEMENT ADDITIVES AT FIELD LOCATION

Dry cement additive samples may be extracted from a bulk container or sack. The additive should be dry and uniform prior to sampling. Multiple samples should be extracted from the center of the source using a suitable sampling device (see Figure 1). A composite of the samples from the same lot should be prepared, packaged and labeled (see 4.7). The sample size of each dry cement additive should be sufficient to perform the desired testing.

4.5 SAMPLING LIQUID CEMENT ADDITIVES AT FIELD LOCATION

Most liquid additives are solutions or suspensions of dry materials. Prolonged storage may cause separation of the active ingredients. Thus, the active ingredients may float to the top of the container, be suspended as a phase layer, or settle to the bottom. For these reasons, liquid additives should be thoroughly mixed prior to sampling. The sample should then be extracted from the center of the container using a clean, dry sampling device. A composite of the samples from the same lot should be prepared, packaged and labeled (see 4.7). The sample size of each liquid additive should be sufficient to perform the desired testing.

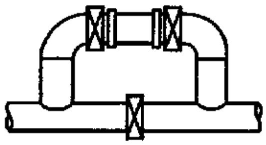
4.6 SAMPLING MIXING WATER

The mixing water should be sampled from the source. The sample should be extracted in such a way as to avoid contamination. The sample should be packaged and labeled (see 4.7). The sample size should be sufficient to perform the desired testing.

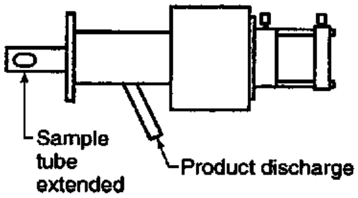
4.7 SHIPPING AND STORAGE

Test samples must be packaged promptly in clean, airtight, moisture-proof containers suitable for shipping and long-term storage. The containers should be lined metal, plastic, or some other heavy-walled flexible or rigid material to assure maximum protection. Re-sealable plastic bags may be used provided the bag is placed in a protective container prior to shipping to prevent puncturing, and to contain all material that may leak out during shipping. Ordinary cloth sacks, cans or jars should not be used. Shipping in glass containers is not recommended.

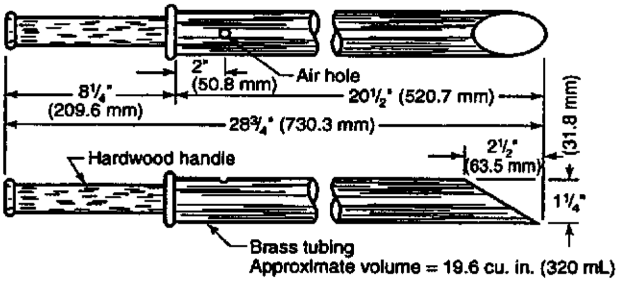
Each sample container should be clearly labeled and identified with the type of material, lot number, source, and date of sampling. Shipping containers should also be labeled. Do not mark the lids of containers, since the lids may be readily interchanged and lead to confusion. Any required regulatory identification or documentation should be enclosed or



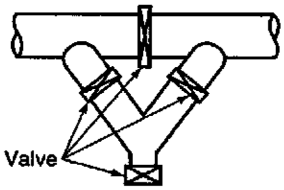
Top view—diverted flow sampler



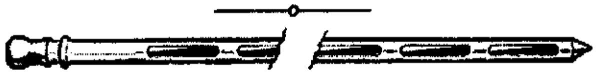
Automatic probe sampler



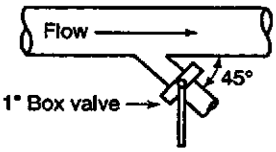
Tube sampler for sacked cement



Modified diverted flow sampler



Tube sampler for bulk cement



Top view—lateral sampler

Figure 1—Commonly Used Sampling Devices

securely attached to the container. All hazardous material samples should be packaged and labeled according to all regulatory requirements.

4.8 SAMPLE PREPARATION PRIOR TO TESTING

Upon arrival at the testing location the samples should be closely examined to ensure they have remained sealed during shipment and are not contaminated. Each sample should be thoroughly blended just prior to slurry preparation (see Section 5).

For storage, each sample should be transferred into a suitable, leak-proof container (if one has not been used in shipping), properly labeled and dated, and stored in a dry place where room temperatures remain fairly constant. At time of testing, each sample should be examined for quality, and thoroughly blended just prior to slurry preparation.

Optimum shelf life(s) for all samples should be determined by the supplier or manufacturer. If unknown, use of any cement additive that has been stored for longer than one year is not recommended.

4.9 SAMPLE DISPOSAL

Sample disposal should comply with all regulatory requirements.

5 Preparation of Slurry

5.1 GENERAL

The preparation of cement slurries varies from that of classical solid/liquid mixtures due to the reactive nature of cement. Shear rate and time at shear are important factors in the mixing of cement slurries. Varying these parameters has been shown to affect slurry performance properties.

The procedure described in this section is recommended for the laboratory preparation of slurries that require no special mixing conditions. If large slurry volumes are needed, an alternate method for slurry preparation is found in Appendix A.

5.2 APPARATUS

5.2.1 Electronic Balances

The indicated load on balances should be accurate within ±0.1 percent of the indicated load. Balances should be calibrated frequently enough to ensure accuracy, and at least annually.

5.2.2 Mechanical Balances

Free or sliding-beam weights used on mechanical balances should be accurate within ±0.1 percent of the weight indicated.

5.2.3 Mixing Device

The mixing device for preparation of slurries should be a one quart size, bottom drive, blade type mixer. Examples of mixing devices in common use are shown in Figure 2. The mixing container and the mixing blade should be constructed of corrosion-resistant material (see Figure 3). The mixing assembly should be constructed so that the blade can be separated from the drive mechanism. The mixing blade should be separated from the mixing assembly and weighed prior to use and replaced with a new blade when 10 percent weight loss has occurred. The blade should also be visually inspected for damage prior to each use and replaced as necessary. Should the mixing device leak at any time during the mixing procedure, the contents should be discarded, the leak repaired and the procedure restarted.

5.3 PROCEDURE

5.3.1 Determination of Specific Gravity of Components

The specific gravity of different batches of cement may vary due to natural changes in the composition of the raw materials used in the manufacturing process. Studies have shown that cement specific gravity may vary from 3.10 to 3.25. This variability could result in deviation of slurry densities by as much as 0.4 lb/gal for slurries with constant water-to-solids ratio. The specific gravity of mix water may also vary, depending on the source, resulting in slurry density inconsistencies. Determination of the specific gravity of all components of the slurry is necessary to properly calculate the required amounts for slurry preparation.

5.3.1.1 Specific Gravity of Cement and Dry Additives

The specific gravity of the cement and any dry additives may be determined by the use of a Le Chatelier flask as outlined in ASTM C 188. Alternately, a pycnometer may be used for determining the specific gravity of these materials.

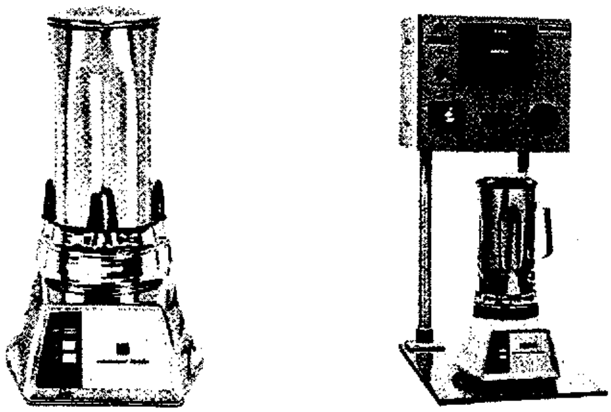
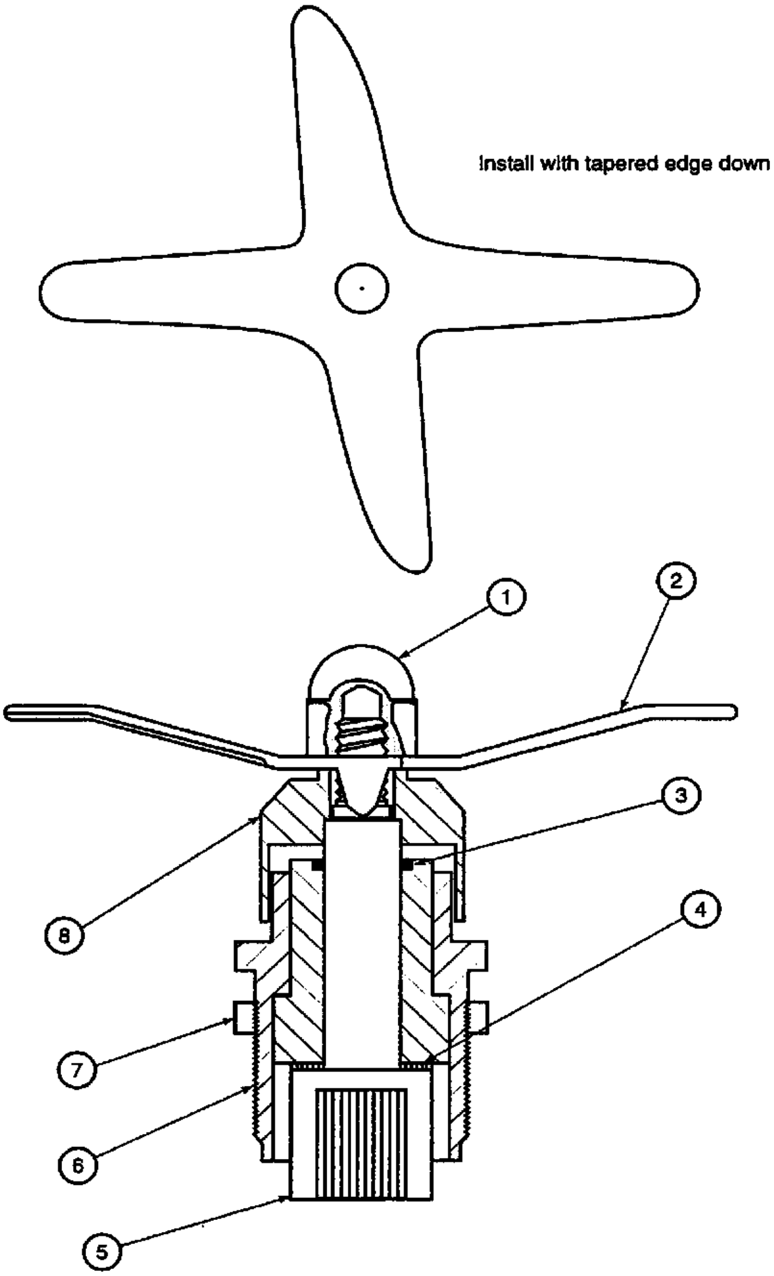


Figure 2—Examples of Mixing Devices



8	1		Bearing cup
7	1		Hex nut
6	1		Bearing holder
5	1		Socket head shaft
4	1		Thrust washer
3	1		O-ring
2	1		Hardened blade
1	1		Cap nut
Item no.	Qty. Reqd.	Part number	Description
			Parts list

Figure 3—Blade Assembly

5.3.1.2 Specific Gravity of Mix Water and Liquid Additives

The specific gravity of the mix water and any liquid additives should be determined by the use of a hydrometer as outlined in API Recommended Practice 13J. Alternately, a pycnometer may be used for determining the specific gravity of these materials.

5.3.2 Laboratory Density and Volume Calculations

A slurry volume of approximately 600 mL should be sufficient to perform most laboratory test procedures while not overfilling the mixing container. Laboratory blend requirements may be calculated by use of the following formulas. Alternate, suitable equations may also be used to calculate laboratory blend requirements.

For the purpose of these calculations, assume that specific gravity is equal to density in g/mL.

$$V_s = V_c + V_w + V_a$$

$$M_s = M_c + M_w + M_a$$

$$D_s = \frac{M_s}{V_s}$$

Where:

V_s = slurry volume (mL).
V_c = cement volume (mL).
V_w = water volume (mL).
V_a = additive volume (mL).
D_s = density of slurry (g/mL).
M_s = slurry mass (g).
M_c = cement mass (g).
M_w = water mass (g).
M_a = additive mass (g).
$V_c = M_c/D_c$
$V_w = M_w/D_w$
$V_a = M_a/D_a$

5.3.3 Temperature of Water and Cement

The temperature of the mix water, dry cement or cement blend, mixing and blending devices should be representative of field mixing conditions. If field conditions are unknown, the temperature of the mix water and dry cement should be 73, ±2°F (22.8, ±1.1°C) immediately prior to mixing. In all cases, the temperatures of the mix water and dry cement should be measured and documented.

5.3.4 Mix Water

Water composition may affect slurry performance. Water from the field source should be used. If field mix water is unavailable, a water of similar composition should be used. If field mix water composition is unknown, deionized, distilled, or tap water may be used. The mix water and any liquid additives should be weighed into a clean, dry, mixing container. No excess water should be added to compensate for evaporation or wetting.

5.3.5 Mixing Cement and Water

Dry materials should be weighed and then thoroughly and uniformly blended prior to being added to the mixing fluid. The mixing container with the required weight of mix water and any liquid additives should be placed on the mixer base. The motor should be turned on and maintained at 4,000, ±200 rpm (66.7, ±3.3 rev/sec). If additives are present in the mix water, stir at the above rotational speed to thoroughly disperse them prior to the addition of cement. In certain cases, the order of addition of the additives to the mixing water may be critical. Special mixing procedures and mixing time should be documented. The cement or cement/dry additive blend should be added at a uniform rate, in not more than 15 seconds if possible. Some slurry designs may take longer to completely wet the cement blend however, the time used to add the blend should be kept at a minimum. When all the dry materials have been added to the mix water, the cover should be placed on the mixing container and mixing should be continued at 12,000, ±500 rpm (200, ±8.3 rev/sec) for 35, ±1 seconds. Rotational speed under load should be measured and documented.

6 Determination of Slurry Density

6.1 PREFERRED APPARATUS

The preferred method for measuring the density of a cement slurry is by using the pressurized fluid density balance. The pressurized fluid density balance is similar in operation to the conventional mud balance, the difference being that the slurry can be placed in a fixed volume sample cup under pressure.

The purpose of placing the sample under pressure is to minimize the effect of entrained air upon slurry density measurements. A major problem found in the density measurement of cement slurries is that oftentimes these fluids have a considerable amount of air entrained when initially mixed. By pressurizing the sample cup, any entrained air will be decreased to a negligible volume, thus providing a slurry density measurement more closely in agreement with that which will be realized under downhole conditions.

6.2 CALIBRATION

The apparatus should be checked for calibration by placing water or heavier fluids of known density in the sample cup or by using manufacturer-specified weights for equivalent densities placed in the sample cup.

6.3 PROCEDURE

6.3.1 The sample cup should be filled to a level slightly below the upper edge of the cup [approximately 1/4 inch (6 mm)].

6.3.2 Place the lid on the cup with the check valve in the down (open) position. Push the lid downward into the mouth of the cup until surface contact is made between the outer skirt of the lid and the upper edge of the cup. Excess slurry must be expelled through the check valve. (Note: slurry may be expelled forcibly.) When the lid has been placed on the cup, pull the check valve up in the closed position, rinse off the cup and threads with water, and screw the threaded cap on the cup.

6.3.3 The pressurizing pump is similar in operation to a syringe. The pump is filled by submersing the nose of the pump assembly in the slurry with the piston rod in the completely inward position. The piston rod is then drawn upward, thereby filling the pump cylinder with slurry.

6.3.4 The nose of the pump is pushed onto the mating O-ring surface of the check valve. The sample cup is pressurized by maintaining a downward force on the pump cylinder housing in order to hold the check valve down (open) and at the same time forcing the piston rod inward. Approximately 50 pounds (255 N) force or greater should be maintained on the piston rod (see Figure 4).

6.3.5 The check valve in the lid is pressure actuated, which means the pressure in the cup keeps the valve closed. The valve is initially closed by gradually lifting the cylinder housing of the pressurizing pump while pressure is being applied to the piston rod. When the check valve closes, release pressure on piston rod before disconnecting the pump.

6.3.6 The exterior of the cup should be rinsed off and wiped dry. The instrument should then be placed on the knife edge as illustrated (see Figure 4). The sliding weight should be moved right or left until the beam is balanced. The beam is balanced when the attached bubble is centered between the two scribed marks. The density is obtained by reading one of the four calibrated scales on the arrow side of the sliding weight.

6.3.7 The pressure is released by pushing the valve downward. This is done by reconnecting the pump assembly and pushing downward on the pump cylinder housing.

The cup and pump assembly should then be emptied of its contents and all components should be thoroughly cleaned.

For best operation the valve, lid and cylinder should be lightly greased.

6.4 ALTERNATE APPARATUS AND CALIBRATION

Cement slurry density may be determined by use of the mud balance described in API Recommended Practice 13B-1, *Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids.*

6.5 ALTERNATE PROCEDURE

The recommended procedure for using a mud balance should be in accordance with the latest edition of API 13B-1 except that the slurry, after being poured into the mud balance cup, should be puddled 25 times to eliminate entrapped air.

7 Well-Simulation Compressive Strength Tests

7.1 GENERAL

This section presents procedures for well-simulation compressive strength testing. Well-simulation compressive strength tests are not required for compliance with Specification 10A.

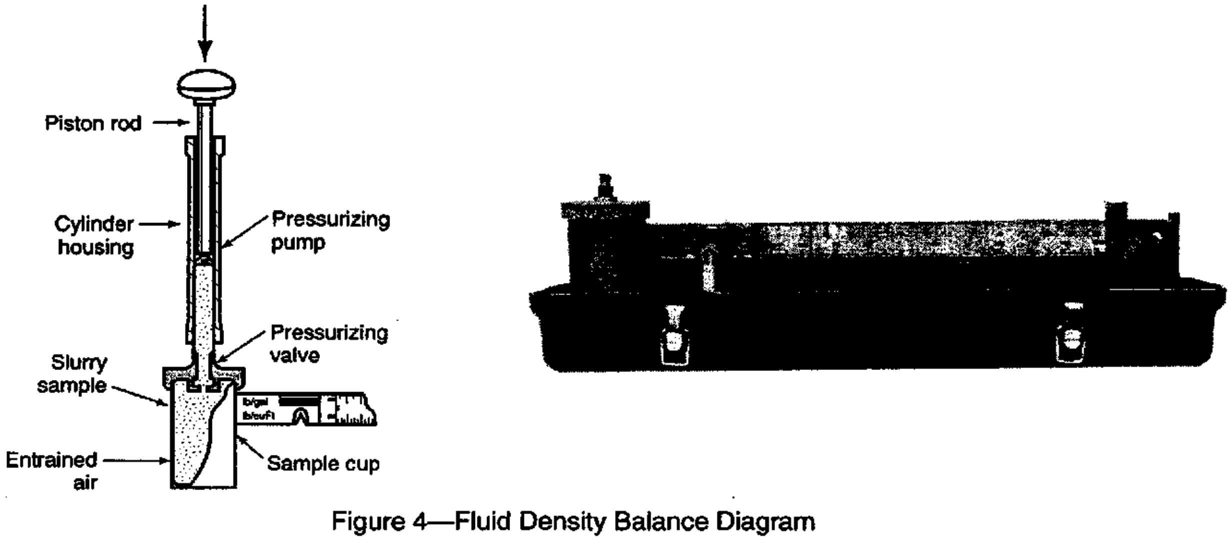


Figure 4—Fluid Density Balance Diagram

7.2 SAMPLING

Samples of the cement, additives, and mix water should be obtained according to Section 4 of API Recommended Practice 10B.

7.3 PREPARATION OF SLURRY

The slurry should be prepared according to Section 5 of API Recommended Practice 10B.

7.4 APPARATUS

7.4.1 Two-Inch Cube Molds and Compressive Strength-Testing Device

Molds and the testing device for compressive strength tests should conform to the requirements of ASTM C 109, except that the molds may be separable into more than two parts. Calibrate the testing device to be accurate to ±1 percent throughout the expected load range. The molds and testing device should be calibrated at least every two years.

7.4.2 Base and Cover Plates

Use corrosion-resistant plates having a minimum thickness of 1/4 inch (6 mm) for the cover plate. Grooves may be incorporated into the surface of the cover plate contacting the surface of the cement. Use only corrosion-resistant metal plates for the base plates. Glass plates are not recommended for tests above 230°F (110°C) because of silica replacement.

7.4.3 Water Curing Bath

Utilize a curing bath or tank having dimensions suitable for the complete immersion of compressive strength molds in water and operable within ±3°F (±1.7°C) of the test temperature. The two types of water curing baths are:

7.4.3.1 Atmospheric Pressure

An atmospheric pressure vessel for curing samples should have an agitator or circulating system. Atmospheric curing baths may be used for curing compressive strength samples at or below 150°F (65.6°C) when pressure is not required.

7.4.3.2 Pressurized

A pressure vessel suitable for curing samples at the appropriate final test temperature and capable of maintaining a pressure of at least 3,000 psig (20,700 kPa) is recommended. The vessel should be capable of being heated at the desired heating rate.

7.4.4 Cooling Bath

The cooling bath should be designed so that the sample to be cooled from the curing temperature can be completely submerged in water maintained at 80, ±5°F (27, ±3°C).

7.4.5 Temperature Measuring System

7.4.5.1 Thermocouple, range 0°F to 220°F (–18°C to 104°C), calibrated to an accuracy of ±3°F (1.7°C) is preferred in a non-pressure vessel.

7.4.5.2 Thermometer, range 0°F to 220°F (–18°C to 104°C), with minimum scale divisions not to exceed 2°F (1°C) may be used in a non-pressure vessel.

7.4.5.3 Thermocouple, range 0°F to at least 400°F (–18°C to at least 204°C), calibrated to an accuracy of ±3°F (1.7°C), should be used in pressure vessels.

7.4.6 Puddling Rod

A corrosion-resistant rod with a width of approximately 1/4 inch (6mm) is recommended.

7.4.7 Mold Sealing Grease

Any grease that possesses the following properties when subjected to anticipated test temperatures and pressures is suitable for use: 1) a consistency to permit ease of application, 2) good sealing properties to prevent leakage, 3) water resistance, and 4) inert to the cement. The grease will be non-corrosive in the temperature range of 0°F to at least 400°F (–18°C to at least 204°C).

7.4.8 Mold Release Agent

A thin layer of mold release agent may be applied to the interior surfaces of the mold to prevent the sample from being damaged when removed from the mold.

7.5 PROCEDURE

7.5.1 Preparation of Molds

The interior faces of the molds and the contact surfaces of the plates may be coated with mold release agent. The assembled molds should be water tight. Care should be taken to ensure there is no bead of sealant on the interior of the mold (see Figure 5).

7.5.2 Preparation and Placement of Cement Slurry

7.5.2.1 Preparation

Prepare the slurry in accordance with Section 5, API Recommended Practice 10B.

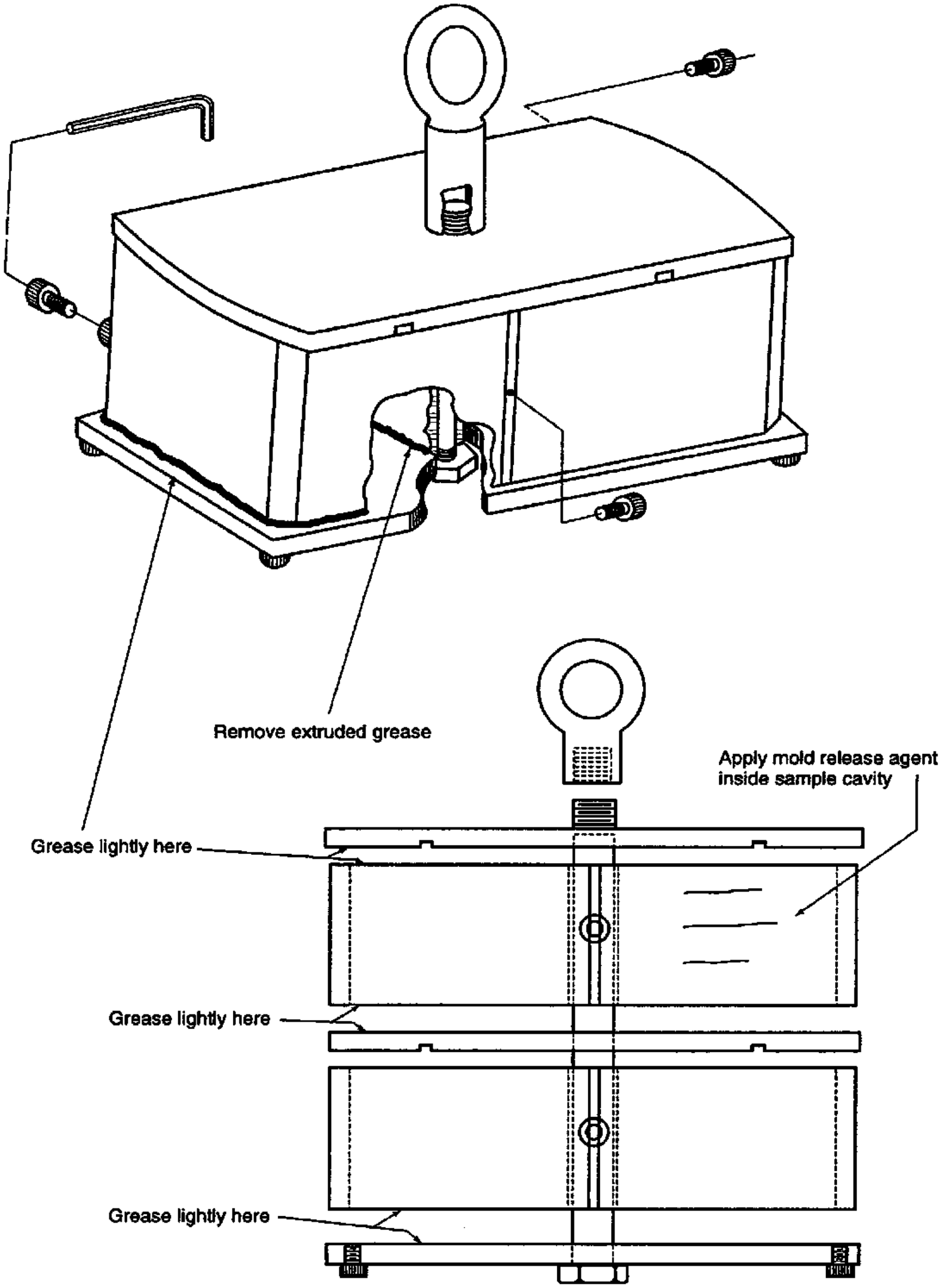


Figure 5—Diagram of Mold Preparation

7.5.2.2 Placement

Pour the cement slurry into the prepared molds to $^1/_2$ (one half) of the mold depth. Puddle each sample approximately 30 times with a puddling rod after all chambers have received slurry. Stir the remaining slurry by hand to re-suspend the components. Completely fill each sample mold with slurry and puddle as before. After the chambers are completely filled, place the cover plate on top of the molds. Samples that leak should be discarded.

7.5.3 Curing at Atmospheric Pressure

After the molds have been filled and covered with the top plate, immediately place them in a water curing bath maintained at the desired curing temperature. Elevate the molds off the bottom of the bath using a perforated baffle plate or suitable spacers to allow water to completely circulate around the samples during the curing period. At approximately 45 minutes prior to the age at which the samples are to be tested, remove the molds from the water bath and remove the cured samples from the molds. Immediately immerse the samples in a water bath at 80, ±5°F (27, ±3°C) until the samples are tested.

7.5.4 Curing at Pressures Above Atmospheric

After the molds have been filled and covered with the top plate, immediately place them in a pressurized curing vessel at the desired test initiation temperature [normally 80, ±5°F (27, ±3°C)]. Apply heat and pressure according to the test schedule. Cement samples may be cured according to pressure/temperature schedules provided in Section 7 or a schedule designed to simulate a specific well's conditions.

For samples cured at or below 194°F (90°C), maintain test temperature and pressure until 45 minutes prior to testing. For test temperatures above 194°F (90°C), discontinue heating and allow samples to cool at such a rate that the sample temperature is 194°F (90°C) or less 45 minutes prior to testing. Maintain test pressure on the curing vessel during the cooling process. At 45 minutes prior to testing the samples, release the pressure gradually and remove the molds from the curing vessel. Immediately remove the samples from the molds and place them in a water bath at 80, ±5°F (27, ±3°C) until the samples are tested.

7.5.5 Test Period

The test period is the elapsed time from subjecting the sample to temperature in the curing vessel to testing the sample for strength.

7.5.6 Sample Testing

Test samples immediately after removal from the cooling bath. The test procedure will be in accordance with ASTM C 109, *Compressive Strength of Hydraulic Cement Mortars*, except:

7.5.6.1 A compressive strength testing device shall be used and the rate of loading for samples with strength greater than 500 psi (3.5 MPa) will be 4,000, ±400 psi (16,000, ±1,600 lbf) (71.7, ±7.2 kN) per minute. For a nominal four square inch sample surface, this rate can be achieved by adjusting the load rate to obtain a gauge indicator travel between 2,000 and 6,000 lbf (gauge reading) in 15 seconds. For samples with strength of 500 psi (3.5 MPa) or less, a 1,000, ±100 psi (4,000, ±400 lbf) (17.9, ±1.8kN) per minute shall be used. For a nominal four square inch sample surface, this rate can be achieved by adjusting the load rate to obtain a gauge indicator travel between 2,000 and 6,000 lbf (gauge reading) in one minute. Make no adjustment in the controls of the testing machine while a sample is yielding before failure.

7.5.6.2 Report compressive strength as the force required to break the sample divided by the smallest measured cross-sectional area in contact with the load-bearing plates of the compression tester. Average the compressive strength of all acceptable test samples (see ASTM C 109) made from the same slurry and tested at the same time. Report compressive strength results to the nearest 10 psi (0.1 MPa) and test schedule used.

7.6 PROCEDURE OF DETERMINING CEMENT COMPRESSIVE STRENGTH AT THE TOP OF LONG CEMENT COLUMNS

7.6.1 Guidelines for Use

Use this procedure if the bottomhole circulating temperature (BHCT) is higher than the static temperature at the top of the cement column (TCST).

7.6.2 Procedure

Prepare a cement slurry in accordance with Section 5, API Recommended Practice 10B. Pour the slurry into the slurry cup of a pressurized consistometer and heat to BHCT according to pressure/temperature schedules provided in Section 11 or a schedule designed to simulate a specific well's conditions. Hold test temperature and pressure for 60 minutes to allow the cement temperature to reach equilibrium.

7.6.2.1 Upon completion of the appropriate test schedule, plus the 60 minutes to reach equilibrium, cool to the top of the cement column's circulating temperature (TCCT) or 194°F (90°C), whichever is lower at 2.0°F (1.1°C)/minute. Use the following equation to determine the cool down time (T) in minutes:

$$T = \frac{\text{BHCT} - \text{TCCT}}{2.0°\text{F}\ (1.1°\text{C})}$$

Decrease the temperature while maintaining test pressure. When the TCCT or 194°F (90°C) (whichever is lower) is reached, release the pressure slowly and remove the slurry cup.

7.6.2.2 Take care to minimize oil contamination of the slurry. Open the slurry container from the top (while leaving the paddle in place). This will eliminate the need for inverting the slurry cup and reduce contamination that could be caused by oil migrating through the slurry. Blot the top of the slurry with an absorbent cloth or paper towel to remove any visible oil. Transfer the slurry three (3) times between the slurry cup and a beaker to re-suspend any solids that may have settled.

7.6.2.3 Pour the slurry into a prepared mold as specified in 7.5.2.2. and place molds into a preheated curing vessel [preheated to TCCT or 194°F (90°C), whichever is lower]. A nondestructive sonic test device as described in Section 8 may also be used. No longer than 15 minutes after removing the slurry from the consistometer, apply 3,000, ±500 psi (20,700, ±3,400 kPa} curing pressure. Adjust to the final curing temperature.

7.6.2.4 Adjust sample temperature TCST over a period appropriate to well conditions while maintaining curing pressure. If a time to reach final conditions is not known or specified, use 6 hours.

7.6.2.5 Remove samples as prescribed in 7.5.4.

7.6.2.6 Test the samples for strength in accordance with procedure in 7.5.6 or Section 8.

7.7 WELL SIMULATION COMPRESSIVE STRENGTH TESTS (SEE TABLE 2)

The well-simulation compressive strength tests described in the section may be used to test cements or cement blends for resistance to thermally-induced strength retrogression. To do this, the cement or cement blend is exposed to temperature and pressure for varying periods of time and observed for changes in compressive strength. The procedure involves comparing the compressive strength observed after some initial period (such as 24, 48, or 72 hours) with the compressive strength observed after some extended period or periods (such as 28 days). Cements or cement blends that exhibit lower compressive strength after extended aging may be considered to exhibit strength retrogression. The commonly-cited threshold for thermally induced strength retrogression is 230°F (110°C) although deviation from this value has been reported.

Table 2—Well-Simulation Test Schedules for Curing Compressive Strength Specimens

1	2	3		4		5		6		7		8		9	
	Elapsed Time (min)	Pressure		Temperature Gradient, °F/100 ft depth (°C/100 m depth)[a] Temperature, °F (°C)											
				°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
Schedule		psi	(kPa)	0.9	(1.6)	1.1	(2)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
1Sg	15[b]	800	(5,500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1,000 ft	30[b]			81	(27)	81	(27)	81	(27)	81	(27)	81	(27)	81	(27)
(305 m)	60[b]			82	(28)	82	(28)	83	(28)	83	(28)	84	(29)	84	(29)
	90[b]			83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	86	(30)
	120[b]			84	(29)	85	(29)	86	(30)	87	(31)	88	(31)	89	(32)
	150[b]			85	(29)	87	(31)	88	(31)	89	(32)	90	(32)	91	(33)
	180[b]			87	(31)	88	(31)	90	(32)	91	(33)	93	(34)	94	(34)
	210[b]			88	(31)	90	(32)	91	(33)	93	(34)	95	(35)	96	(36)
	240			89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)
2Sg	15	1,600	(11,000)	88	(31)	88	(31)	89	(32)	89	(32)	90	(32)	90	(32)
2,000 ft	30[b]			90	(32)	90	(32)	91	(33)	91	(33)	92	(33)	93	(34)
(610 m)	60[b]			91	(33)	92	(33)	93	(34)	94	(34)	95	(35)	96	(36)
	90[b]			92	(33)	93	(34)	95	(35)	97	(36)	99	(37)	100	(38)
	120[b]			93	(34)	95	(35)	97	(36)	99	(37)	102	(39)	103	(39)
	150[b]			94	(34)	97	(36)	00	(38)	102	(39)	105	(41)	107	(42)
	180[b]			96	(36)	99	(37)	102	(39)	105	(41)	108	(42)	111	(44)
	210[b]			97	(36)	100	(38)	104	(40)	107	(42)	111	(44)	114	(46)
	240			98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)

Table 2—Well-Simulation Test Schedules for Curing Compressive Strength Specimens (Continued)

1	2	3		4		5		6		7		8		9	
	Elapsed Time (min)	Pressure		Temperature Gradient, °F/100 ft depth (°C/100 m depth)[a] Temperature, °F (°C)											
				°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
Schedule		psi	(kPa)	0.9	(1.6)	1.1	(2)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
3Sg	15	3,000	(20,700)	91	(33)	92	(33)	93	(34)	93	(34)	94	(34)	94	(34)
4,000 ft	30[b]			99	(37)	101	(38)	102	(39)	103	(39)	104	(40)	105	(41)
(1,220 m)	60[b]			102	(99)	104	(40)	106	(41)	108	(42)	110	(43)	112	(44)
	90[b]			104	(40)	107	(42)	110	(43)	113	(45)	117	(47)	120	(49)
	120[b]			107	(42)	111	(44)	115	(46)	119	(48)	123	(51)	127	(53)
	150[b]			109	(43)	114	(46)	119	(48)	124	(51)	129	(54)	134	(57)
	180[b]			111	(44)	117	(47)	123	(51)	129	(54)	135	(57)	141	(61)
	210[b]			114	(46)	121	(49)	128	(53)	135	(57)	142	(61)	149	(65)
	240			116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	156	(69)
4Sg	15	3,000	(20,700)	95	(35)	95	(35)	96	(36)	97	(36)	98	(37)	101	(38)
6,000 ft	30			109	(43)	111	(44)	113	(45)	115	(46)	116	(47)	122	(50)
(1,830 m)	45[b]			113	(45)	116	(47)	118	(48)	121	(49)	124	(51)	130	(54)
	60[b]			115	(46)	118	(48)	121	(49)	125	(52)	128	(53)	135	(57)
	90[b]			118	(48)	123	(51)	128	(53)	132	(56)	137	(58)	145	(63)
	120[b]			121	(49)	127	(53)	134	(57)	140	(60)	146	(63)	155	(68)
	150[b]			124	(51)	132	(56)	140	(60)	147	(64)	155	(68)	164	(73)
	180[b]			128	(53)	137	(58)	146	(63)	155	(68)	164	(73)	174	(79)
	210[b]			131	(55)	141	(61)	152	(67)	162	(72)	173	(78)	184	(84)
	240			134	(57)	146	(63)	158	(70)	170	(77)	182	(83)	194	(90)
5Sg	15	3,000	(20,700)	97	(36)	98	(37)	100	(38)	102	(39)	104	(40)	109	(43)
8,000 ft	30			114	(46)	116	(47)	120	(49)	124	(51)	128	(53)	139	(59)
(2,440 m)	45[b]			127	(53)	130	(54)	136	(58)	141	(61)	147	(64)	161	(72)
	60[b]			128	(53)	133	(56)	140	(60)	146	(63)	153	(67)	167	(75)
	90[b]			132	(56)	139	(59)	147	(64)	155	(68)	163	(73)	178	(81)
	120[b]			136	(58)	144	(62)	154	(68)	164	(73)	174	(79)	189	(87)
	150[b]			140	(60)	150	(66)	162	(72)	173	(78)	184	(84)	199	(93)
	180[b]			144	(62)	156	(69)	169	(76)	182	(83)	195	(91)	210	(99)
	210[b]			148	(64)	162	(72)	177	(81)	191	(88)	205	(96)	221	(105)
	240			152	(67)	168	(76)	184	(84)	200	(93)	216	(102)	232	(111)
6Sg	15	3,000	(20,700)	98	(37)	100	(38)	103	(39)	106	(41)	110	(43)	116	(47)
10,000 ft	30			116	(47)	120	(49)	127	(530	132	(56)	140	(60)	152	(67)
(3,050 m)	45			134	(57)	139	(59)	150	(66)	158	(70)	170	(77)	188	(87)
	60[b]			142	(61)	148	(64)	161	(72)	170	(77)	184	(84)	204	(96)
	90[b]			146	(63)	155	(68)	169	(76)	180	(82)	195	(91)	215	(102)
	120[b]			151	(66)	162	(72)	177	(81)	190	(88)	206	(97)	226	(108)
	150[b]			156	(69)	169	(76)	185	(85)	200	(93)	217	(103)	237	(114)
	180[b]			161	(72)	176	(80)	194	(90)	210	(99)	228	(109)	248	(120)
	210[b]			165	(74)	183	(84)	202	(94)	220	(104)	239	(115)	259	(126)
	240			170	(77)	190	(88)	210	(99)	230	(110)	250	(121)	270	(132)

Table 2—Well-Simulation Test Schedules for Curing Compressive Strength Specimens (Continued)

1	2	3		4		5		6		7		8		9	
	Elapsed Time (min)	Pressure		Temperature Gradient, °F/100 ft depth (°C/100 m depth)[a] Temperature, °F (°C)											
				°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
Schedule		psi	(kPa)	0.9	(1.6)	1.1	(2)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
7Sg	15	3,000	(20,700)	98	(37)	102	(39)	107	(42)	111	(44)	116	(47)	120	(49)
12,000 ft	30			115	(46)	124	(51)	133	(56)	143	(62)	152	(67)	161	(72)
(3,660 m)	45			133	(56)	146	(63)	160	(71)	174	(79)	188	(87)	201	(94)
	60[b]			148	(64)	166	(74)	184	(84)	202	(94)	220	(104)	237	(114)
	90[b]			155	(68)	173	(78)	192	(89)	211	(99)	230	(110)	249	(121)
	120[b]			162	(72)	181	(83)	201	(94)	221	(105)	241	(116)	261	(127)
	150[b]			168	(76)	189	(87)	210	(99)	231	(111)	252	(122)	272	(133)
	180[b]			175	(79)	197	(92)	219	(104)	241	(116)	263	(128)	284	(140)
	210[b]			181	(83)	204	(96)	227	(108)	250	(121)	273	(134)	296	(147)
	240			188	(87)	212	(100)	236	(113)	260	(127)	284	(140)	308	(153)
8Sg	15	3,000	(20,700)	99	(37)	104	(40)	109	(43)	114	(46)	119	(48)	123	(51)
14,000 ft	30			118	(48)	128	(53)	138	(59)	147	(64)	157	(69)	167	(75)
(4,270 m)	45			137	(58)	152	(67)	167	(75)	181	(83)	196	(91)	210	(99)
	60			156	(69)	175	(79)	195	(91)	215	(102)	235	(113)	254	(123)
	75[b]			166	(74)	188	(87)	210	(99)	231	(111)	254	(123)	275	(135)
	90[b]			170	(77)	192	(89)	215	(102)	237	(114)	259	(126)	281	(138)
	120[b]			177	(81)	200	(93)	224	(107)	247	(119)	271	(133)	294	(146)
	150[b]			184	(84)	209	(98)	234	(112)	258	(126)	283	(139)	307	(153)
	180[b]			192	(89)	217	(103)	243	(117)	269	(132)	295	(146)	320	(160)
	210[b]			199	(93)	226	(108)	253	(123)	279	(137)	306	(152)	333	(167)
	240			206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	346	(174)
9Sg	15	3,000	(20,700)	101	(38)	106	(41)	111	(44)	116	(47)	121	(49)	126	(52)
16,000 ft	30			121	(49)	131	(55)	142	(61)	152	(67)	163	(73)	173	(78)
(4,880 m)	45			142	(61)	157	(69)	173	(78)	188	(87)	204	(96)	219	(104)
	60			163	(73)	183	(84)	204	(96)	224	(107)	245	(118)	266	(130)
	75[b]			182	(83)	207	(97)	233	(112)	258	(126)	284	(140)	309	(154)
	90[b]			186	(86)	212	(100)	238	(114)	264	(129)	291	(144)	316	(158)
	120[b]			194	(90)	221	(105)	248	(120)	275	(135)	303	(151)	330	(166)
	150[b]			201	(94)	229	(109)	258	(126)	286	(141)	315	(157)	343	(173)
	180[b]			209	(98)	238	(114)	268	(131)	298	(148)	327	(164)	357	(181)
	210[b]			216	(102)	247	(119)	278	(137)	309	(154)	340	(171)	370	(188)
	240			224	(107)	256	(124)	288	(142)	320	(160)	352	(178)	384	(196)
10Sg	15	3,000	(20,700)	102	(39)	108	(42)	113	(45)	119	(48)	124	(51)	129	(54)
18,000 ft	30			124	(51)	135	(57)	146	(63)	157	(69)	168	(76)	179	(82)
(5,490 m)	45			146	(63)	163	(73)	179	(82)	196	(91)	212	(100)	228	(109)
	60			169	(76)	190	(88)	212	(100)	234	(112)	256	(124)	278	(137)
	75			191	(88)	218	(103)	246	(119)	273	(134)	300	(149)	327	(164)
	90[b]			203	(95)	233	(112)	264	(129)	294	(146)	324	(162)	354	(179)
	120[b]			211	(99)	242	(117)	274	(134)	305	(1520	337	(169)	367	(186)

Table 2—Well-Simulation Test Schedules for Curing Compressive Strength Specimens (Continued)

1	2	3		4		5		6		7		8		9	
	Elapsed Time (min)	Pressure		Temperature Gradient, °F/100 ft depth (°C/100 m depth)[a] Temperature, °F (°C)											
				°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
Schedule		psi	(kPa)	0.9	(1.6)	1.1	(2)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	150[b]			219	(104)	251	(122)	284	(140)	316	(158)	349	(176)	381	(194)
	180[b]			226	(108)	260	(127)	294	(146)	328	(164)	361	(183)	395	(202)
	210[b]			234	(112)	269	(132)	304	(151)	339	(171)	374	(190)	408	(209)
	240			242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	422	(217)
11Sg	15	3,000	(20,700)	104	(40)	109	(43)	115	(46)	121	(49)	127	(53)	133	(56)
20,000 ft	30			127	(53)	139	(59)	150	(66)	162	(72)	173	(78)	185	(85)
(6,100 m)	45			151	(66)	168	(76)	186	(86)	203	(95)	220	(104)	238	(114)
	60			175	(79)	197	(92)	221	(105)	244	(118)	267	(131)	290	(143)
	75			198	(92)	227	(108)	256	(124)	285	(141)	313	(156)	343	(173)
	90[b]			222	(106)	256	(124)	291	(144)	326	(163)	360	(182)	395	(202)
	120[b]			230	(110)	265	(129)	301	(149)	337	(169)	372	(189)	408	(209)
	150[b]			237	(114)	274	(134)	311	(155)	348	(176)	384	(196)	421	(216)
	180[b]			245	(118)	282	(139)	320	(160)	358	(181)	396	(202)	434	(223)
	210[b]			252	(122)	291	(144)	330	(166)	369	(187)	408	(209)	447	(231)
	240			260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	460	(238)
12Sg	15	3,000	(20,700)	105	(41)	111	(44)	117	(47)	123	(51)	130	(54)	136	(58)
22,000 ft	30			130	(54)	142	(61)	155	(68)	167	(75)	179	(82)	191	(88)
(6,710 m)	45			155	(68)	174	(79)	192	(89)	210	(99)	229	(109)	247	(119)
	60			180	(82)	205	(96)	229	(109)	254	(123)	278	(137)	303	(151)
	75			206	(97)	236	(113)	267	(131)	297	(147)	328	(164)	359	(182)
	90			231	(111)	267	(131)	304	(151)	341	(172)	378	(192)	414	(212)
	105[b]			246	(119)	286	(141)	326	(163)	366	(186)	406	(208)	447	(231)
	120[b]			249	(121)	290	(143)	331	(166)	371	(188)	412	(211)	452	(233)
	150[b]			256	(124)	298	(148)	339	(171)	381	(194)	422	(217)	464	(240)
	180[b]			264	(129)	306	(152)	348	(176)	391	(199)	433	(223)	475	(246)
	210[b]			271	(133)	314	(157)	357	(181)	400	(204)	443	(228)	487	(253)
	240			278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	498	(259)

[a]Temperature gradient (CS) = $\frac{BHST - 80°F}{Depth / 100 ft.}$ or $\frac{BHST - 27°C}{Depth / 100 m}$

(*BHST* = Bottom-Hole Static Temperature.)

[b]The temperature should be increased in equal amounts at 15 minute intervals until the 4-hour (240-minute) temperature is reached. The 4-hour temperature should be maintained until completion of test.

Notes:

1. The test pressure shall be applied as soon as specimens are placed in the pressure vessel and maintained at the given pressure within the following limits for the duration of the curing period:
   - Schedule 1Sg..800, ±100 psi (5,500, ±700 KPa).
   - Schedule 2Sg.......................................1,600, ±200 psi (11,000, ±1,400 KPa).
   - Schedule 11Sg....................................3,000, ±500 psi (20,700, ±3,400 KPa).
2. Final temperature shall be maintained ±3°F (±2°C) throughout the remainder of the curing period.

8 Non-Destructive Sonic Testing of Cement

8.1 GENERAL

This section presents testing procedures for the non-destructive sonic testing of cement. Non-destructive sonic testing of cement is not required for compliance with API Specification 10A.

8.2 APPARATUS

The testing apparatus consists of a curing cell which can be subjected to controlled temperature and pressure for curing the cement slurry. The apparatus transmits a sonic signal through the cement. The signal transit time may be correlated to cement properties such as the time and extent of strength development.

8.2.1 Temperature Measuring System

The temperature measuring system should be calibrated to an accuracy of ±3°F (±1.7°C). Calibration should be no less frequent than monthly and may be performed according to the procedure described in Appendix B, API Recommended Practice 10B.

8.2.2 Sonic Signal Measuring System

The sonic measuring system should be calibrated according to manufacturer's instructions.

8.3 SAMPLING

Samples of the cement, additives, and mix water should be obtained according to Section 4 of API Recommended Practice 10B.

8.4 PREPARATION OF SLURRY

The slurry should be prepared according to Section 5 of API Recommended Practice 10B.

Note: Excessive free fluid can impair the accuracy of this test. Free fluid in a slurry may cause cement not to be in contact with the top cell cover and affect the signal being sent through the cement. Free fluid may be determined according to Section 15 of API Recommended Practice 10B.

8.5 PROCEDURE

Detailed operating instructions and safety precautions furnished by the manufacturer should be followed.

8.6 CURING TIME

The curing period begins with the recording of the transit time and the application of temperature and pressure and continues until the test is terminated. Recording of transit time data should begin within five (5) minutes after application of temperature and pressure.

8.7 CURING SCHEDULES

Cement samples may be cured according to pressure/temperature schedules provided in Section 7 or a schedule designed to simulate specific well conditions.

Note: Planned or unplanned changes in temperature or pressure alter the transit time.

8.8 DATA REPORTING

The transit time is continuously monitored. The strength is obtained from transit time correlations.

Note: After removal of the sample from the curing cell it is occasionally surfaced and crushed. The result obtained is not comparable to crush results obtained under Section 7, API Recommended Practice 10B and should not be reported as API compressive strength.

9 Well Simulation Thickening Time Tests

9.1 GENERAL

Recommended procedures for determining the well-simulation thickening time of a cement slurry are provided in this section. The results of the laboratory thickening time test provide an indication of the length of time that a cement slurry will remain pumpable in a well. The laboratory test conditions should represent the time, temperature and pressure to which a cement slurry will be exposed during pumping operations. Well simulation thickening time tests are not required for compliance with API Specification for Well Cements (Specification 10A).

9.2 APPARATUS

A pressurized consistometer is required (see Figure 6). The most commonly used apparatus incorporates a rotating cylindrical slurry container equipped with a stationary paddle assembly, all enclosed in a pressure vessel capable of withstanding the well-simulation pressures and temperatures. The space between the slurry container and the walls of the pressure vessel should be completely filled with hydrocarbon oil. The selected oil should have the following physical properties:

Viscosity	= 49 – 350 SSU @ 100°F (7 – 75 cSt)
Specific Heat	= 0.5 – 0.58 Btu/lb x °F [2.1 – 2.4 kJ/9kg x K)]
Thermal Conductivity	= 0.0685 – 0.0770 Btu/h x ft^2 x °F/ft) [0.119 – 0.133 W/(m x K)]
Specific Gravity	= 0.85 – 0.91

Only if the test temperature exceeds the flash point of the hydrocarbon oil should a synthetic oil with suitable properties be used.

A heating system capable of raising the temperature of the oil bath at a rate of at least 5°F (2.8°C per minute) is required. Temperature measuring systems should be provided for determining the temperature of the cement slurry and also, optionally, the oil bath.

Note: See Appendix B, "Calibration Procedures for Thermocouples and Temperature Measuring Systems."

The slurry container is rotated as a speed of 150, ±15 rpm (2.5, ±0.25 rev/s). The consistency of the cement slurry (as defined in 9.3.1) should be measured. The paddle and all parts of the slurry container exposed to the slurry should be constructed of corrosion-resistant materials.

Alternate equipment used to conduct well-simulation thickening time tests is described in Appendix D.

9.3 CALIBRATION

Measurement of the thickening time of a cement slurry requires calibration and maintenance of operating systems of the pressurized consistometer including consistency measurement, temperature measuring systems, temperature controllers, motor speed, timer, and pressure gauges.

9.3.1 Consistency

Consistency of a cement slurry is expressed in Bearden units of consistency (B_c). This value is measured by a potentiometer mechanism and voltage measurement circuit. These should be calibrated monthly, and whenever the calibration spring, resistor or contact arm is adjusted or replaced. One of the following methods should be used.

9.3.1.1 A weight loaded device (see Figure 7 for typical potentiometer calibrating device) to produce a series of torque equivalent values for consistency shall be used for calibration, defined by the following equation:

$$T = 78.2 + 20.02\ B_c$$

Where:

T = torque in g•cm.

B_c = Bearden units of consistency.

Weights are used to apply torque to the potentiometer spring, using the radius of the potentiometer frame as a lever arm. As weight is added, the contact arm is deflected and resulting DC voltage is recorded and used to determine B_c as per Table 3 (see manufacturer's instruction manual for procedure). Some units display B_c directly.

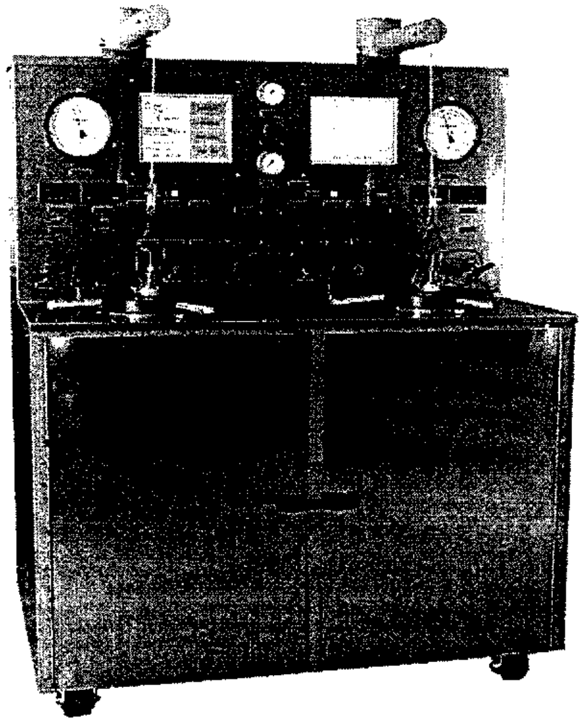


Figure 6—Typical Pressurized Consistometer (Dual Consitometer Shown)

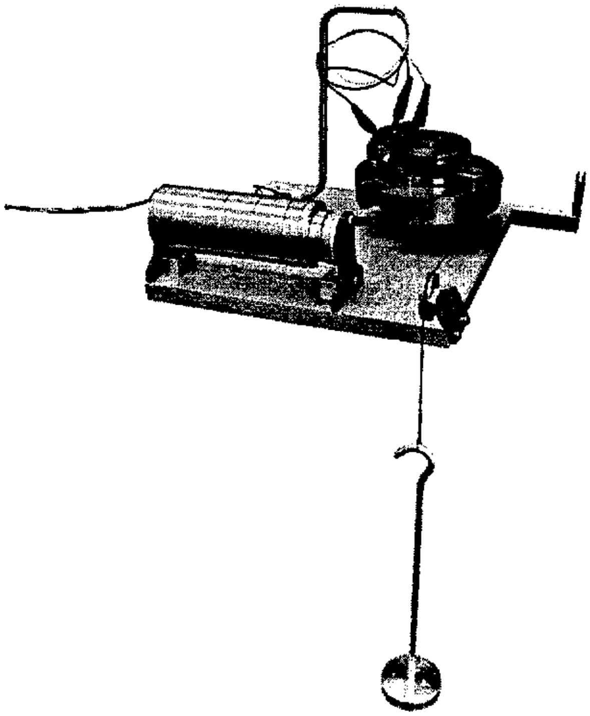


Figure 7—Typical Calibrating Device for Pressurized Consistometer

Table 3—Slurry Consistency Versus Equivalent Torque

(For a potentiometer mechanism with a radius of 52, ±1 mm)

Calculated Torque Equivalent g-cm	Weight Grams	Calculated Slurry Consistency in B_c
260	50, ±0.1	9
520	100, ±0.1	22
780	150, ±0.1	35
1,040	200, ±0.1	48
1,300	250, ±0.1	61
1,560	300, ±0.1	74
1,820	350, ±0.1	87
2,080	400, ±0.1	100

Note: For a potentiometer mechanism with another radius, an appropriate table with equivalent tolerances should be developed.

9.3.1.2 An alternate method for calibrating the potentiometer mechanism is by the using calibration oil, the viscosity-temperature relationship of which is known over a range of 5 to 100 Bearden units of consistency (the calibration oil should be discarded after use).

9.3.2 Temperature Measuring System

The temperature measuring device system should be calibrated to an accuracy of ±3°F (±1.7°C). Calibration should be no less frequent than monthly and may be performed according to the procedure described in Appendix B.

9.3.3 Motor Speed

Rotation of the slurry container should be 150, ±15 rpm (2.5, ±0.25 rev/sec) and should be checked no less frequently than quarterly.

9.3.4 Timer

Timers should be checked for accuracy semiannually. They must be accurate within ±30 seconds per hour.

9.3.5 Pressure Measuring Devices

Calibration should be conducted annually against a deadweight tester or master gauge to 0.25 percent of full range at a minimum of 25 percent, 50 percent, and 75 percent of full scale.

9.4 TEST PROCEDURE

9.4.1 Operating Instructions

Detailed operating instructions, as furnished by the equipment manufacturer, are applicable under this method and should be followed, provided they conform to the procedure contained herein. In case of conflict, this procedure should supersede. Do not exceed manufacturer's safety limits.

CAUTION: This procedure requires the handling of hot, pressurized equipment and materials that are hazardous and can cause injury. *Only trained personnel should run these tests.*

9.4.2 Assembling and Filling the Slurry Container

Assemble and fill the slurry container as follows:

a. Clean and lubricate cup threads.

b. Inspect diaphragm.

c. Assemble paddle shaft assembly and secure it in the cup sleeve with flange ring.

d. Make sure the paddle turns freely.

e. Invert the slurry cup assembly and fill to within 1/4 inch of the top.

Note: Slurry segregation may occur during the filling operation. This may be reduced by stirring the slurry in the mixing container with a spatula while pouring. Segregation will be less of a problem if the time from cessation of mixing to completing the filling operation is kept to a minimum.

f. Strike to remove air.

g. Screw in base plate and make sure slurry is extruded through the center hole.

h. Screw in center plug (pivot bearing) into the container.

i. Wipe all cement from the outer surfaces.

j. Recheck the paddle to make sure it turns smoothly.

k. Load the cup assembly into the consistometer.

9.4.3 Initiation of Test

Engage the slurry container on the drive table in the pressure vessel, start rotation of the slurry container and secure the potentiometer mechanism so as to engage the paddle shaft drive bar. At this point, the paddle shaft should not be rotating. Begin filling the vessel with oil and close the head assembly. Insert the temperature sensing device through the hole in the head assembly and partially engage the threads. After the pressure vessel is completely filled with oil, tighten the threads of the temperature sensing device. The test should be started within 5 minutes of the cessation of mixing.

9.4.4 Temperature and Pressure Control

During the test period, the temperature and pressure of the cement slurry in the slurry container should be increased in accordance with the appropriate well-simulation test schedule (see 9.5). Schedules may be calculated or taken from tables. Temperature of the cement slurry should be determined by use of a Type J thermocouple (ASTM classification, special) located in the center of the slurry container.

Note: See Appendix B, "Calibration Procedures for Thermocouples and Temperature Measuring Systems."

9.4.5 Thickening Time

The thickening time is the elapsed time 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 or 100 B_c). The slurry consistency at which the thickening time test was terminated should be documented.

9.5 DETERMINATION OF TEST SCHEDULE

Well-simulation thickening time test schedules may be taken from the tables or calculated from equations as described in 9.5.1 through 9.5.3.13. Background and supporting information for these schedules is contained in Appendix C.

The schedules are based upon nominally vertical wells. The choice of table is based upon well depth. The choice of column within a table is based upon thermal gradient.

9.5.1 Casing Cementing Tabular Schedules

Tabular well-simulation thickening time schedules for casing cementing operations are provided in Table 4, Schedules 9.2 through 9.13. Once reached, the final temperature and pressure conditions shown in the schedules should be maintained until the thickening time test is completed.

9.5.2 Liner Cementing Tabular Schedules

Tabular well-simulation thickening time schedules for liner cementing operations are provided in Table 5, Schedules 9.14 through 9.25. Once reached, the final temperature and pressure conditions shown in the schedules should be maintained until the thickening time test is completed.

9.5.3 Tailored Casing and Liner Schedules

Casing and liner thickening time test schedules may be developed using projected job parameters to tailor the test schedule to a specific well cementing operation. The equations and guidelines in this section may be used to tailor a thickening time test schedule to a specific set of well conditions. Once reached, the final temperature and pressure conditions shown in the schedules should be maintained until the thickening time test is completed.

9.5.3.1 Surface Mixing of the Slurry

If batch mixing is used for the cementing operation, the slurry may be stirred in the consistometer to simulate the time and temperature. The time and surface slurry temperature (SST) may be estimated depending upon the expected conditions at the well site.

The batch mixing simulation is done prior to the start of the thickening time test. The batch mixing time should be reported separately from the thickening time of the slurry.

For example:

Simulated Batch Mixing Time: 1:00
Thickening Time (does not include batch mixing simulation): 3:30

9.5.3.2 Time to Displace Leading Edge of Cement Slurry to Bottom

$$t_{disp} = \frac{\text{Pipe Capacity, bbl}}{Q} \quad (1)$$

Where:

t_{disp} = time to displace leading edge of cement slurry to bottom, minutes.
Q = fluid pump rate, bbl/min.

9.5.3.3 Correlation for Predicted Bottom-Hole Circulating Temperatures (PBHCT) for Casing or Liner Jobs at Depths Deeper than 10,000 Feet

$$PBHCT = 80°F + \frac{(0.006061 \times TVD \times PsTG) - 10.0915}{1.0 - (0.1505 \times 10^{-4} \times TVD)} \quad (2)$$

Where:

$PBHCT$ = predicted bottom-hole circulating temperature, °F.
$PsTG$ = pseudo temperature gradient, °F/100 ft.
TVD = true vertical depth, ft.
80°F = assumed surface temperature.

Note: The correlation is valid only for the units shown.

Note: *This correlation should not be used to predict PBHCT for depths of 10,000 feet or shallower because it can give significantly higher PBHCT than the PHBCT found in Table 4, Schedules 9.2 through 9.7 (inclusive) and Table 5, Schedules 9.14 thorough 9.19 (inclusive).* A different correlation is used for the predicted squeeze temperature (PSqT). This correlation can be found in 9.5.5.1 of this document.
Although the PBHCT correlation is based upon field measurements, there can be error associated with its use for predicting the circulating temperature in a well. The error range between this correlation and the field measured data from which the correlation was derived is shown in Appendix C. The standard deviation is 16.6°F. *Whenever possible, measurements of downhole temperatures are preferred over calculated estimates.*

9.5.3.4 Heat-Up Rate to Predicted Bottom-Hole Circulating Temperature

The temperature of the cement slurry should be increased from the slurry surface temperature (SST) to the predicted bottom-hole circulating temperature (PBHCT) in the time required to displace the leading edge of cement slurry to bottom. The heat-up rate may be calculated using the following equation:

$$H_{ur} = \frac{PBHCT - SST}{t_{disp}} \quad (3)$$

Where:

H_{ur} = heat-up rate, °F/min (°C/min).
PBHCT = predicted bottom-hole circulating temperature, °F (°C).
SST = slurry surface temperature, °F (°C).

9.5.3.5 Bottom-Hole Pressure

$$BHP = (0.052)(\rho_m)(TVD) \quad (4a)$$

Where:

BHP = bottom-hole pressure, psi.
ρ_m = density of drilling fluid, lb/gal.
TVD = true vertical depth, ft.

or:

$$BHP = 9.764(\rho_m)(TVD) \quad (4b)$$

Where:

BHP = bottom-hole pressure, kPa.
ρ_m = specific gravity of drilling fluid.
TVD = true vertical depth, meters.

Note: The bottom-hole pressure may be calculated to account for contributions of other fluids (spacers, weighted pills, etc.) in the annulus.

9.5.3.6 Starting Pressure

The starting pressure (SP) is the estimated pressure to which the leading edge of cement slurry is subjected as it leaves the cementing head.

9.5.3.7 Pressure-Up Rate to Bottom-Hole Pressure

Pressure on the cement slurry should be increased to the bottom-hole pressure during the test at a pressure-up rate calculated as follows:

$$P_{ur} = \frac{BHP - SP}{t_{disp}} \quad (5)$$

Where:

P_{ur} = pressure-up rate (psi/min).
BHP = bottom-hole pressure, psi.
SP = starting pressure, psi.
t_{disp} = time to displace first sack of cement to bottom, minutes.

9.5.3.8 Time at PBHCT and BHP

If no measured data are available for the top of cement column temperature (TOCT), the PBHCT and BHP should be maintained until the completion of the thickening time test. Skip steps 9.5.3.9 through 9.5.3.13 below.

If reliable TOCT data are available, the cement slurry may be held at the PBHCT and BHP for a given period, such as 30 minutes, as a built in safety factor. After a holding period at PBHCT and BHP, the temperature and pressure on the cement slurry may be changed to the TOCT and top of cement pressure (TOCP) using steps 7.5.3.9 through 7.5.3.13

9.5.3.9 Time to Displace the Cemented Annular Volume

$$t_a = \frac{\text{Annular volume to be cemented, bbl}}{Q} \quad (6)$$

Where:

t_a = time to displace the leading edge of cement slurry from bottom of the casing to the top of the annular cement column, minutes.
Q = fluid pump rate, bbl/min.

9.5.3.10 Rate of Temperature Change to TOCT

The temperature of the cement slurry may be changed to the TOCT at a rate calculated by the following equation:

$$\Delta_r = \frac{TOCT - PBHCT}{t_a} \quad (7)$$

Where:

Δ_r = rate of temperature change to *TOCT* in °F/min.
PBHCT = the bottom-hole circulating temperature, °F.
TCCT = top of cement circulating temperature, °F.
t_a = time to displace the leading edge of the cement slurry from bottom of the casing to the top of the annular cement column, minutes.

Note: A positive Δ_r indicates heatup. A negative Δ_r indicates cooldown.

9.5.3.11 Pressure at the Top of Cement Column

$$TOCP = (0.052)(\rho_m)(TCTVD) \quad (8a)$$

Where:

TOCP = pressure at the top of the cement column in the annulus, psi.
ρ_m = density of drilling fluid, lb/gal.
TCTVD = true vertical depth at top of cement column, ft.

$$TOCP = 9.764(\rho_m)(TCTVD) \quad (8b)$$

Where:

TOCP = pressure at the top of the cement column in the annulus, kPa.
ρ_m = specific gravity of drilling fluid.
TCTVD = true vertical depth at top of cement column, meters.

The top of cement pressure may be calculated to account for contributions of other fluids (spacers, weighted pills, etc.) in the annulus.

9.5.3.12 Pressure-own Rate to TOCP

$$P_{dr} = \frac{BHP - TOCP}{t_a} \qquad (9)$$

Where:

P_{dr} = pressure-down rate, psi/min (kPa/min).

$TOCP$ = pressure at the top of the cement the column in the annulus, psi (kPa).

BHP = bottom-hole pressure, psi (kPa).

t_a = time to displace the leading edge of cement slurry from bottom of the casing to the top of the annular cement column, minutes.

9.5.3.13 Completion of Test with Simulated Temperature Change

The cement slurry should be held at the TOCT and TOCP pressure until the thickening time test is completed.

9.5.4 Squeeze Cementing Tabular Schedules

9.5.4.1 Continuous Pumping Squeeze Schedules

Tabular well-simulation thickening time schedules for continuous pumping squeeze cementing operations are provided in Table 6, Schedules 9.26 through 9.37. Once reached, the final temperature and pressure conditions shown in the schedules should be maintained until the thickening time test is completed.

9.5.4.2 Hesitation Squeeze Schedules

Tabular well-simulation thickening time schedules for hesitation pumping squeeze cementing operations are provided in Table 7, Schedules 9.38 through 9.49. The difference between the hesitation and continuous pumping schedules are: 1) there is a second temperature ramp to static temperature and 2) stirring of the slurry is cycled on and off during the second temperature ramp.

9.5.5 Tailored Squeeze Schedules

9.5.5.1 Correlation to Predict Squeeze Temperatures

The correlation developed for predicting squeeze temperatures is given by:

$$PSqT = 80°\text{F} + \frac{(0.0076495 \times TVD \times PsTG) - 8.2021}{1.0 - (0.807 \times 10^{-5} \times TVD)} \qquad (10)$$

Where:

$PSqT$ = predicted bottom-hole circulating temperature, °F.

$PsTG$ = pseudo temperature gradient, °F/100 ft.

TVD = true vertical depth, ft.

80°F = assumed surface temperature.

Note: This correlation is valid only for the units shown.

Although the PSqT correlation is based upon field measurements, there can be error associated with its use for predicting the squeeze temperature in a well. The error range between this correlation and the field measured data from which the correlation was derived is shown in Appendix C. The standard deviation is 13.0°F. Whenever possible, measurements of down hole temperatures are preferred over calculated estimates.

9.5.5.2 Tailored Schedule Equations

Equations 1 through 5 under 9.5.3 should be used. These equations can be used to calculate the heat-up rate (H_{ur}) and pressure-up rate (P_{ur}) for a squeeze simulation thickening time test. In Equation 3, the predicted squeeze temperature, PSqT, should be substituted for the PBHCT. After reaching the PSqT and BHP, the temperature and pressure profile should follow the anticipated temperature and pressure profile for the remainder of the squeeze operation. Additionally, it is recommended that the stirring of the slurry be cycled, using an appropriate sequence, to simulate a hesitation technique if this is anticipated for the squeeze cementing operation.

9.5.6 Plug Cementing Tailored Schedules

Equations 1 through 5 under 9.5.3 can be used. These equations can be used to calculate the heat-up rate (H_{ur}) and pressure-up rate (P_{ur}) for a plug cementing simulation thickening time test. Because of the short cement columns typically used in plug cementing, no temperature change or pressure-down rates to the top of the cement column should be used. Therefore, steps 9.5.3.9 through 9.5.3.13 should not be used.

Table 4—Casing Well-Simulation Tests

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.2							
	Depth	1,000 ft	(305 m)								Mud density: 8.7 lb/gal (1.04 kg/L)			
0	250	(1700)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	300	(2100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
4	400	(2800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
6	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
8	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
10	600	(4100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
12	700	(4800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
13	700	(4800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
Heating Rate - Deg/min			0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
Pressure Rate (per min)			35 psi (238 kPa)											
Time to Final Conditions			13 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.3							
	Depth	2,000 ft	(610 m)								Mud density: 8.9 lb/gal (1.07 kg/L)			
0	300	(2100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	400	(2800)	81	(27)	81	(27)	81	(27)	81	(27)	81	(27)	81	(27)
4	500	(3400)	82	(28)	82	(28)	82	(28)	82	(28)	83	(28)	83	(28)
6	600	(4100)	83	(28)	83	(28)	84	(29)	84	(29)	84	(29)	84	(29)
8	700	(4800)	84	(29)	84	(29)	85	(29)	85	(29)	85	(29)	85	(29)
10	800	(5500)	85	(29)	85	(29)	86	(30)	86	(30)	86	(30)	86	(30)
12	900	(6200)	86	(30)	86	(30)	87	(31)	87	(31)	88	(31)	88	(31)
14	1000	(6900)	87	(31)	87	(31)	88	(31)	88	(31)	89	(32)	89	(32)
16	1100	(7600)	88	(31)	88	(31)	89	(32)	89	(32)	90	(32)	90	(32)
17	1200	(8300)	89	(32)	89	(32)	90	(32)	90	(32)	91	(33)	91	(33)
Heating Rate - Deg/min			0.53	(0.29)	0.53	(0.29)	0.59	(0.33)	0.59	(0.33)	0.65	(0.36)	0.65	(0.36)
Pressure Rate (per min)			53 psi (365 kPa)											
Time to Final Conditions			17 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.4											
	Depth	4,000 ft	(1220 m)								Mud density: 9.4 lb/gal (1.13 kg/L)			
0	350	(2400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	500	(3400)	82	(28)	82	(28)	82	(28)	82	(28)	82	(28)	82	(28)
4	700	(4800)	83	(28)	83	(28)	83	(28)	84	(29)	84	(29)	84	(29)
6	800	(5500)	85	(29)	85	(29)	85	(29)	85	(29)	86	(30)	86	(30)
8	1000	(6900)	86	(30)	86	(30)	87	(31)	87	(31)	87	(31)	88	(31)
10	1100	(7600)	88	(31)	88	(31)	88	(31)	89	(32)	89	(32)	90	(32)
12	1300	(9000)	89	(32)	90	(32)	90	(32)	91	(33)	91	(33)	92	(33)
14	1400	(9700)	91	(33)	91	(33)	92	(33)	92	(33)	93	(34)	93	(34)
16	1600	(11000)	92	(33)	93	(34)	93	(34)	94	(34)	95	(35)	95	(35)
18	1800	(12400)	94	(34)	94	(34)	95	(35)	96	(36)	97	(36)	97	(36)
20	1900	(13100)	95	(35)	96	(36)	97	(36)	98	(37)	98	(37)	99	(37)
22	2100	(14500)	97	(36)	98	(37)	98	(37)	99	(37)	100	(38)	101	(38)
24	2200	(15200)	98	(37)	99	(37)	100	(38)	101	(38)	102	(39)	103	(39)
25	2300	(15900)	99	(37)	100	(38)	101	(38)	102	(39)	103	(39)	104	(40)
Heating Rate - Deg/min			0.76	(0.42)	0.80	(0.44)	0.84	(0.47)	0.88	(0.49)	0.92	(0.51)	0.96	(0.53)
Pressure Rate (per min)			78 psi (540 kPa)											
Time to Final Conditions			25 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.5											
	Depth	6,000 ft	(1830 m)								Mud density: 9.9 lb/gal (1.19 kg/L)			
0	450	(3100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	600	(4100)	82	(28)	82	(28)	82	(28)	82	(28)	82	(28)	83	(28)
4	800	(5500)	84	(29)	84	(29)	84	(29)	85	(29)	85	(29)	86	(30)
6	1000	(6900)	86	(30)	86	(30)	87	(31)	87	(31)	87	(31)	88	(31)
8	1200	(8300)	88	(31)	88	(31)	89	(32)	89	(32)	90	(32)	91	(33)
10	1400	(9700)	90	(32)	90	(32)	91	(33)	92	(33)	92	(33)	94	(34)
12	1600	(11000)	92	(33)	92	(33)	93	(34)	94	(34)	95	(35)	97	(36)
14	1700	(11700)	94	(34)	94	(34)	95	(35)	96	(36)	97	(36)	100	(38)
16	1900	(13100)	96	(36)	96	(36)	97	(36)	98	(37)	99	(37)	102	(39)
18	2100	(14500)	97	(36)	99	(37)	100	(38)	101	(38)	102	(39)	105	(41)
20	2300	(15900)	99	(37)	101	(38)	102	(39)	103	(39)	104	(40)	108	(42)
22	2500	(17200)	101	(38)	103	(39)	104	(40)	105	(41)	107	(42)	111	(44)
24	2700	(18600)	103	(39)	105	(41)	106	(41)	108	(42)	109	(43)	113	(45)
26	2900	(20000)	105	(41)	107	(42)	108	(42)	110	(43)	112	(44)	116	(47)
28	3000	(20700)	107	(42)	109	(43)	111	(44)	112	(44)	114	(46)	119	(48)
30	3200	(22100)	109	(43)	111	(44)	113	(45)	115	(46)	116	(47)	122	(50)
32	3400	(23400)	111	(44)	113	(45)	115	(46)	117	(47)	119	(48)	125	(52)
33	3500	(24100)	112	(44)	114	(46)	116	(47)	118	(48)	120	(49)	126	(52)
Heating Rate - Deg/min			0.97	(0.54)	1.03	(0.57)	1.09	(0.61)	1.15	(0.64)	1.21	(0.67)	1.39	(0.77)
Pressure Rate (per min)			92 psi (636 kPa)											
Time to Final Conditions			33 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.6							
	Depth	8,000 ft	(2440 m)								Mud density: 10.4 lb/gal (1.25 kg/L)			
0	550	(3800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	800	(5500)	82	(28)	82	(28)	83	(28)	83	(28)	83	(28)	84	(29)
4	1000	(6900)	84	(29)	85	(29)	85	(29)	86	(30)	86	(30)	88	(31)
6	1200	(8300)	87	(31)	87	(31)	88	(31)	89	(32)	90	(32)	92	(33)
8	1400	(9700)	89	(32)	90	(32)	91	(33)	92	(33)	93	(34)	96	(36)
10	1600	(11000)	91	(33)	92	(33)	93	(34)	95	(35)	96	(36)	100	(38)
12	1800	(12400)	93	(34)	94	(34)	96	(36)	98	(37)	99	(37)	103	(39)
14	2000	(13800)	96	(36)	97	(36)	99	(37)	100	(38)	103	(39)	107	(42)
16	2200	(15200)	98	(37)	99	(37)	101	(38)	103	(39)	106	(41)	111	(44)
18	2500	(17200)	100	(38)	102	(39)	104	(40)	106	(41)	109	(43)	115	(46)
20	2700	(18600)	102	(39)	104	(40)	107	(42)	109	(43)	112	(44)	119	(48)
22	2900	(20000)	105	(41)	106	(41)	110	(43)	112	(44)	115	(46)	123	(51)
24	3100	(21400)	107	(42)	109	(43)	112	(44)	115	(46)	119	(48)	127	(53)
26	3300	(22800)	109	(43)	111	(44)	115	(46)	118	(48)	122	(50)	131	(55)
28	3500	(24100)	111	(44)	113	(45)	118	(48)	121	(49)	125	(52)	135	(57)
30	3700	(25500)	114	(46)	116	(47)	120	(49)	124	(51)	128	(53)	139	(59)
32	3900	(26900)	116	(47)	118	(48)	123	(51)	127	(53)	132	(56)	142	(61)
34	4200	(29000)	118	(48)	121	(49)	126	(52)	130	(54)	135	(57)	146	(63)
36	4400	(30300)	120	(49)	123	(51)	128	(53)	133	(56)	138	(59)	150	(66)
38	4600	(31700)	123	(51)	125	(52)	131	(55)	136	(58)	141	(61)	154	(68)
40	4800	(33100)	125	(52)	128	(53)	134	(57)	139	(59)	144	(62)	158	(70)
41	4900	(33800)	126	(52)	129	(54)	135	(57)	140	(60)	146	(63)	160	(71)
Heating Rate - Deg/min			1.12	(0.62)	1.20	(0.67)	1.34	(0.74)	1.46	(0.81)	1.61	(0.89)	1.95	(1.08)
Pressure Rate (per min)			106 psi (732 kPa)											
Time to Final Conditions			41 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.7							
	Depth	10,000 ft	(3050 m)								Mud density: 10.9 lb/gal (1.31 kg/L)			
0	650	(4500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	900	(6200)	82	(28)	83	(28)	83	(28)	83	(28)	84	(29)	85	(29)
4	1100	(7600)	85	(29)	85	(29)	86	(30)	87	(31)	88	(31)	90	(32)
6	1300	(9000)	87	(31)	88	(31)	89	(32)	90	(32)	92	(33)	94	(34)
8	1600	(11000)	90	(32)	91	(33)	92	(33)	94	(34)	96	(36)	99	(37)
10	1800	(12400)	92	(33)	93	(34)	96	(36)	97	(36)	100	(38)	104	(40)
12	2000	(13800)	95	(35)	96	(36)	99	(37)	101	(38)	104	(40)	109	(43)
14	2200	(15200)	97	(36)	98	(37)	102	(39)	104	(40)	108	(42)	114	(46)
16	2500	(17200)	100	(38)	101	(38)	105	(41)	108	(42)	112	(44)	118	(48)
18	2700	(18600)	102	(39)	104	(40)	108	(42)	111	(44)	116	(47)	123	(51)
20	2900	(20000)	104	(40)	106	(41)	111	(44)	115	(46)	120	(49)	128	(53)
22	3100	(21400)	107	(42)	109	(43)	114	(46)	118	(48)	124	(51)	133	(56)
24	3400	(23400)	109	(43)	112	(44)	117	(47)	122	(50)	128	(53)	138	(59)
26	3600	(24800)	112	(44)	114	(46)	121	(49)	125	(52)	132	(56)	142	(61)
28	3800	(26200)	114	(46)	117	(47)	124	(51)	129	(54)	136	(58)	147	(64)
30	4000	(27600)	117	(47)	120	(49)	127	(53)	132	(56)	140	(60)	152	(67)
32	4300	(29600)	119	(48)	122	(50)	130	(54)	136	(58)	144	(62)	157	(69)
34	4500	(31000)	121	(49)	125	(52)	133	(56)	139	(59)	148	(64)	162	(72)
36	4700	(32400)	124	(51)	128	(53)	136	(58)	143	(62)	152	(67)	166	(74)
38	4900	(33800)	126	(52)	130	(54)	139	(59)	146	(63)	156	(69)	171	(77)
40	5200	(35900)	129	(54)	133	(56)	142	(61)	150	(66)	160	(71)	176	(80)
42	5400	(37200)	131	(55)	135	(57)	146	(63)	153	(67)	164	(73)	181	(83)
44	5600	(38600)	134	(57)	138	(59)	149	(65)	157	(69)	168	(76)	186	(86)
46	5800	(40000)	136	(58)	141	(61)	152	(67)	160	(71)	172	(78)	190	(88)
48	6100	(42100)	139	(59)	143	(62)	155	(68)	164	(73)	176	(80)	195	(91)
50	6300	(43400)	141	(61)	146	(63)	158	(70)	167	(75)	180	(82)	200	(93)
Heating Rate - Deg/min			1.22	(0.68)	1.32	(0.73)	1.56	(0.87)	1.74	(0.97)	2.00	(1.11)	2.40	(1.33)
Pressure Rate (per min)			113 psi (778 kPa)											
Time to Final Conditions			50 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.8											
	Depth	12,000 ft	(3660 m)								Mud density: 11.3 lb/gal (1.35 kg/L)			
0	700	(4800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	900	(6200)	82	(28)	83	(28)	84	(29)	84	(29)	85	(29)	85	(29)
4	1200	(8300)	85	(29)	86	(30)	87	(31)	88	(31)	90	(32)	91	(33)
6	1400	(9700)	87	(31)	89	(32)	91	(33)	92	(33)	94	(34)	96	(36)
8	1700	(11700)	89	(32)	92	(33)	94	(34)	97	(36)	99	(37)	102	(39)
10	1900	(13100)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)
12	2100	(14500)	94	(34)	98	(37)	101	(38)	105	(41)	109	(43)	112	(44)
14	2400	(16500)	96	(36)	101	(38)	105	(41)	109	(43)	113	(45)	118	(48)
16	2600	(17900)	99	(37)	104	(40)	108	(42)	113	(45)	118	(48)	123	(51)
18	2900	(20000)	101	(38)	106	(41)	112	(44)	117	(47)	123	(51)	129	(54)
20	3100	(21400)	103	(39)	109	(43)	116	(47)	122	(50)	128	(53)	134	(57)
22	3400	(23400)	106	(41)	112	(44)	119	(48)	126	(52)	133	(56)	139	(59)
24	3600	(24800)	108	(42)	115	(46)	123	(51)	130	(54)	137	(58)	145	(63)
26	3800	(26200)	110	(43)	118	(48)	126	(52)	134	(57)	142	(61)	150	(66)
28	4100	(28300)	113	(45)	121	(49)	130	(54)	138	(59)	147	(64)	155	(68)
30	4300	(29600)	115	(46)	124	(51)	133	(56)	142	(61)	152	(67)	161	(72)
32	4600	(31700)	117	(47)	127	(53)	137	(58)	147	(64)	156	(69)	166	(74)
34	4800	(33100)	120	(49)	130	(54)	140	(60)	151	(66)	161	(72)	172	(78)
36	5000	(34500)	122	(50)	133	(56)	144	(62)	155	(68)	166	(74)	177	(81)
38	5300	(36500)	124	(51)	136	(58)	148	(64)	159	(71)	171	(77)	182	(83)
40	5500	(37900)	127	(53)	139	(59)	151	(66)	163	(73)	176	(80)	188	(87)
42	5800	(40000)	129	(54)	142	(61)	155	(68)	167	(75)	180	(82)	193	(89)
44	6000	(41400)	131	(55)	145	(63)	158	(70)	172	(78)	185	(85)	199	(93)
46	6300	(43400)	134	(57)	148	(64)	162	(72)	176	(80)	190	(88)	204	(96)
48	6500	(44800)	136	(58)	151	(66)	165	(74)	180	(82)	195	(91)	209	(98)
50	6700	(46200)	138	(59)	154	(68)	169	(76)	184	(84)	199	(93)	215	(102)
52	7000	(48300)	141	(61)	156	(69)	172	(78)	188	(87)	204	(96)	220	(104)
54	7200	(49600)	143	(62)	159	(71)	176	(80)	192	(89)	209	(98)	226	(108)
56	7500	(51700)	145	(63)	162	(72)	180	(82)	197	(92)	214	(101)	231	(111)
58	7700	(53100)	148	(64)	165	(74)	183	(84)	201	(94)	219	(104)	236	(113)
Heating Rate - Deg/min			1.17	(0.65)	1.47	(0.82)	1.78	(0.99)	2.09	(1.16)	2.40	(1.33)	2.69	(1.49)
Pressure Rate (per min)			121 psi (833 kPa)											
Time to Final Conditions			58 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.9							
	Depth	14,000 ft	(4270 m)								Mud density: 11.8 lb/gal (1.41 kg/L)			
0	800	(5500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1100	(7600)	83	(28)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)
4	1300	(9000)	85	(29)	86	(30)	88	(31)	89	(32)	90	(32)	92	(33)
6	1600	(11000)	88	(31)	90	(32)	92	(33)	93	(34)	95	(35)	97	(36)
8	1800	(12400)	90	(32)	93	(34)	95	(35)	98	(37)	101	(38)	103	(39)
10	2100	(14500)	93	(34)	96	(36)	99	(37)	102	(39)	106	(41)	109	(43)
12	2400	(16500)	95	(35)	99	(37)	103	(39)	107	(42)	111	(44)	115	(46)
14	2600	(17900)	98	(37)	102	(39)	107	(42)	111	(44)	116	(47)	121	(49)
16	2900	(20000)	100	(38)	106	(41)	111	(44)	116	(47)	121	(49)	126	(52)
18	3100	(21400)	103	(39)	109	(43)	115	(46)	120	(49)	126	(52)	132	(56)
20	3400	(23400)	105	(41)	112	(44)	118	(48)	125	(52)	132	(56)	138	(59)
22	3700	(25500)	108	(42)	115	(46)	122	(50)	129	(54)	137	(58)	144	(62)
24	3900	(26900)	111	(44)	118	(48)	126	(52)	134	(57)	142	(61)	150	(66)
26	4200	(29000)	113	(45)	122	(50)	130	(54)	138	(59)	147	(64)	155	(68)
28	4400	(30300)	116	(47)	125	(52)	134	(57)	143	(62)	152	(67)	161	(72)
30	4700	(32400)	118	(48)	128	(53)	138	(59)	147	(64)	157	(69)	167	(75)
32	5000	(34500)	121	(49)	131	(55)	142	(61)	152	(67)	162	(72)	173	(78)
34	5200	(35900)	123	(51)	134	(57)	145	(63)	156	(69)	168	(76)	179	(82)
36	5500	(37900)	126	(52)	138	(59)	149	(65)	161	(72)	173	(78)	184	(84)
38	5800	(40000)	128	(53)	141	(61)	153	(67)	165	(74)	178	(81)	190	(88)
40	6000	(41400)	131	(55)	144	(62)	157	(69)	170	(77)	183	(84)	196	(91)
42	6300	(43400)	133	(56)	147	(64)	161	(72)	174	(79)	188	(87)	202	(94)
44	6500	(44800)	136	(58)	150	(66)	165	(74)	179	(82)	193	(89)	208	(98)
46	6800	(46900)	139	(59)	154	(68)	168	(76)	183	(84)	198	(92)	213	(101)
48	7100	(49000)	141	(61)	157	(69)	172	(78)	188	(87)	204	(96)	219	(104)
50	7300	(50300)	144	(62)	160	(71)	176	(80)	192	(89)	209	(98)	225	(107)
52	7600	(52400)	146	(63)	163	(73)	180	(82)	197	(92)	214	(101)	231	(111)
54	7800	(53800)	149	(65)	166	(74)	184	(84)	201	(94)	219	(104)	237	(114)
56	8100	(55800)	151	(66)	169	(76)	188	(87)	206	(97)	224	(107)	242	(117)
58	8400	(57900)	154	(68)	173	(78)	192	(89)	210	(99)	229	(109)	248	(120)
60	8600	(59300)	156	(69)	176	(80)	195	(91)	215	(102)	235	(113)	254	(123)
62	8900	(61400)	159	(71)	179	(82)	199	(93)	219	(104)	240	(116)	260	(127)
64	9100	(62700)	161	(72)	182	(83)	203	(95)	224	(107)	245	(118)	266	(130)
66	9400	(64800)	164	(73)	185	(85)	207	(97)	228	(109)	250	(121)	271	(133)
Heating Rate - Deg/min			1.27	(0.71)	1.59	(0.88)	1.92	(1.07)	2.24	(1.24)	2.58	(1.43)	2.89	(1.61)
Pressure Rate (per min)			130 psi (898 kPa)											
Time to Final Conditions			66 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.10							
	Depth	16,000 ft	(4880 m)								Mud density: 12.3 lb/gal (1.47) kg/L)			
0	900	(6200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1200	(8300)	83	(28)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)
4	1500	(10300)	85	(29)	87	(31)	88	(31)	90	(32)	91	(33)	92	(33)
6	1700	(11700)	88	(31)	90	(32)	92	(33)	94	(34)	97	(36)	99	(37)
8	2000	(13800)	91	(33)	94	(34)	97	(36)	99	(37)	102	(39)	105	(41)
10	2300	(15900)	94	(34)	97	(36)	101	(38)	104	(40)	108	(42)	111	(44)
12	2600	(17900)	96	(36)	101	(38)	105	(41)	109	(43)	113	(45)	117	(47)
14	2800	(19300)	99	(37)	104	(40)	109	(43)	114	(46)	119	(48)	123	(51)
16	3100	(21400)	102	(39)	108	(42)	113	(45)	119	(48)	124	(51)	130	(54)
18	3400	(23400)	105	(41)	111	(44)	117	(47)	123	(51)	130	(54)	136	(58)
20	3700	(25500)	107	(42)	114	(46)	121	(49)	128	(53)	135	(57)	142	(61)
22	3900	(26900)	110	(43)	118	(48)	125	(52)	133	(56)	141	(61)	148	(64)
24	4200	(29000)	113	(45)	121	(49)	130	(54)	138	(59)	146	(63)	154	(68)
26	4500	(31000)	116	(47)	125	(52)	134	(57)	143	(62)	152	(67)	161	(72)
28	4800	(33100)	118	(48)	128	(53)	138	(59)	147	(64)	157	(69)	167	(75)
30	5000	(34500)	121	(49)	132	(56)	142	(61)	152	(67)	163	(73)	173	(78)
32	5300	(36500)	124	(51)	135	(57)	146	(63)	157	(69)	168	(76)	179	(82)
34	5600	(38600)	127	(53)	138	(59)	150	(66)	162	(72)	174	(79)	185	(85)
36	5900	(40700)	129	(54)	142	(61)	154	(68)	167	(75)	179	(82)	192	(89)
38	6100	(42100)	132	(56)	145	(63)	158	(70)	172	(78)	185	(85)	198	(92)
40	6400	(44100)	135	(57)	149	(65)	163	(73)	176	(80)	190	(88)	204	(96)
42	6700	(46200)	138	(59)	152	(67)	167	(75)	181	(83)	196	(91)	210	(99)
44	7000	(48300)	140	(60)	156	(69)	171	(77)	186	(86)	201	(94)	216	(102)
46	7200	(49600)	143	(62)	159	(71)	175	(79)	191	(88)	207	(97)	223	(106)
48	7500	(51700)	146	(63)	163	(73)	179	(82)	196	(91)	212	(100)	229	(109)
50	7800	(53800)	149	(65)	166	(74)	183	(84)	200	(93)	218	(103)	235	(113)
52	8100	(55800)	151	(66)	169	(76)	187	(86)	205	(96)	223	(106)	241	(116)
54	8300	(57200)	154	(68)	173	(78)	191	(88)	210	(99)	229	(109)	247	(119)
56	8600	(59300)	157	(69)	176	(80)	196	(91)	215	(102)	234	(112)	254	(123)
58	8900	(61400)	160	(71)	180	(82)	200	(93)	220	(104)	240	(116)	260	(127)
60	9200	(63400)	162	(72)	183	(84)	204	(96)	225	(107)	245	(118)	266	(130)
62	9400	(64800)	165	(74)	187	(86)	208	(98)	229	(109)	251	(122)	272	(133)
64	9700	(66900)	168	(76)	190	(88)	212	(100)	234	(112)	256	(124)	278	(137)
66	10000	(68900)	171	(77)	193	(89)	216	(102)	239	(115)	262	(128)	285	(141)
68	10300	(71000)	173	(78)	197	(92)	220	(104)	244	(118)	267	(131)	291	(144)
70	10500	(72400)	176	(80)	200	(93)	225	(107)	249	(121)	273	(134)	297	(147)
72	10800	(74500)	179	(82)	204	(96)	229	(109)	253	(123)	278	(137)	303	(151)
74	11100	(76500)	182	(83)	207	(97)	233	(112)	258	(126)	284	(140)	309	(154)
Heating Rate - Deg/min			1.38	(0.77)	1.72	(0.96)	2.07	(1.15)	2.41	(1.34)	2.76	(1.53)	3.09	(1.72)
Pressure Rate (per min)			138 psi (950 kPa)											
Time to Final Conditions			74 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.11											
	Depth	18,000 ft	(5490 m)								Mud density: 12.8 lb/gal (1.53 kg/L)			
0	1000	(6900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1300	(9000)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	87	(31)
4	1600	(11000)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	93	(34)
6	1900	(13100)	89	(32)	91	(33)	93	(34)	95	(35)	98	(37)	100	(38)
8	2200	(15200)	92	(33)	95	(35)	98	(37)	101	(38)	103	(39)	106	(41)
10	2500	(17200)	95	(35)	98	(37)	102	(39)	106	(41)	109	(43)	113	(45)
12	2800	(19300)	98	(37)	102	(39)	106	(41)	111	(44)	115	(46)	120	(49)
14	3000	(20700)	101	(38)	106	(41)	111	(44)	116	(47)	121	(49)	126	(52)
16	3300	(22800)	104	(40)	109	(43)	115	(46)	121	(49)	127	(53)	133	(56)
18	3600	(24800)	107	(42)	113	(45)	120	(49)	126	(52)	133	(56)	139	(59)
20	3900	(26900)	109	(43)	117	(47)	124	(51)	131	(55)	139	(59)	146	(63)
22	4200	(29000)	112	(44)	120	(49)	128	(53)	137	(58)	145	(63)	153	(67)
24	4500	(31000)	115	(46)	124	(51)	133	(56)	142	(61)	150	(66)	159	(71)
26	4800	(33100)	118	(48)	128	(53)	137	(58)	147	(64)	156	(69)	166	(74)
28	5100	(35200)	121	(49)	131	(55)	142	(61)	152	(67)	162	(72)	172	(78)
30	5400	(37200)	124	(51)	135	(57)	146	(63)	157	(69)	168	(76)	179	(82)
32	5700	(39300)	127	(53)	139	(59)	151	(66)	162	(72)	174	(79)	186	(86)
34	6000	(41400)	130	(54)	143	(62)	155	(68)	167	(75)	180	(82)	192	(89)
36	6300	(43400)	133	(56)	146	(63)	159	(71)	172	(78)	186	(86)	199	(93)
38	6600	(45500)	136	(58)	150	(66)	164	(73)	178	(81)	191	(88)	205	(96)
40	6900	(47600)	139	(59)	154	(68)	168	(76)	183	(84)	197	(92)	212	(100)
42	7100	(49000)	142	(61)	157	(69)	173	(78)	188	(87)	203	(95)	219	(104)
44	7400	(51000)	145	(63)	161	(72)	177	(81)	193	(89)	209	(98)	225	(107)
46	7700	(53100)	148	(64)	165	(74)	181	(83)	198	(92)	215	(102)	232	(111)
48	8000	(55200)	151	(66)	168	(76)	186	(86)	203	(95)	221	(105)	238	(114)
50	8300	(57200)	154	(68)	172	(78)	190	(88)	208	(98)	227	(108)	245	(118)
52	8600	(59300)	157	(69)	176	(80)	195	(91)	214	(101)	233	(112)	252	(122)
54	8900	(61400)	160	(71)	179	(82)	199	(93)	219	(104)	238	(114)	258	(126)
56	9200	(63400)	163	(73)	183	(84)	203	(95)	224	(107)	244	(118)	265	(129)
58	9500	(65500)	165	(74)	187	(86)	208	(98)	229	(109)	250	(121)	271	(133)
60	9800	(67600)	168	(76)	190	(88)	212	(100)	234	(112)	256	(124)	278	(137)
62	10100	(69600)	171	(77)	194	(90)	217	(103)	239	(115)	262	(128)	285	(141)
64	10400	(71700)	174	(79)	198	(92)	221	(105)	244	(118)	268	(131)	291	(144)
66	10700	(73800)	177	(81)	201	(94)	225	(107)	250	(121)	274	(134)	298	(148)
68	11000	(75800)	180	(82)	205	(96)	230	(110)	255	(124)	279	(137)	304	(151)
70	11200	(77200)	183	(84)	209	(98)	234	(112)	260	(127)	285	(141)	311	(155)
72	11500	(79300)	186	(86)	212	(100)	239	(115)	265	(129)	291	(144)	317	(158)
74	11800	(81400)	189	(87)	216	(102)	243	(117)	270	(132)	297	(147)	324	(162)
76	12100	(83400)	192	(89)	220	(104)	247	(119)	275	(135)	303	(151)	331	(166)
78	12400	(85500)	195	(91)	223	(106)	252	(122)	280	(138)	309	(154)	337	(169)
80	12700	(87600)	198	(92)	227	(108)	256	(124)	285	(141)	315	(157)	344	(173)
82	13000	(89600)	201	(94)	231	(111)	261	(127)	291	(144)	321	(161)	350	(177)
Heating Rate - Deg/min			1.48	(0.82)	1.84	(1.02)	2.21	(1.23)	2.57	(1.43)	2.94	(1.63)	3.29	(1.83)
Pressure Rate (per min)			146 psi (1009 kPa)											
Time to Final Conditions			82 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.12							
	Depth	20,000 ft	(6100 m)								Mud density: 13.3 lb/gal (1.59 kg/L)			
0	1050	(7200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1400	(9700)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	87	(31)
4	1700	(11700)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	94	(34)
6	2000	(13800)	89	(32)	92	(33)	94	(34)	96	(36)	99	(37)	101	(38)
8	2300	(15900)	93	(34)	96	(36)	99	(37)	102	(39)	105	(41)	108	(42)
10	2600	(17900)	96	(36)	100	(38)	103	(39)	107	(42)	111	(44)	115	(46)
12	2900	(20000)	99	(37)	104	(40)	108	(42)	113	(45)	117	(47)	122	(50)
14	3200	(22100)	102	(39)	107	(42)	113	(45)	118	(48)	124	(51)	129	(54)
16	3500	(24100)	105	(41)	111	(44)	118	(48)	124	(51)	130	(54)	136	(58)
18	3800	(26200)	108	(42)	115	(46)	122	(50)	129	(54)	136	(58)	143	(62)
20	4100	(28300)	111	(44)	119	(48)	127	(53)	135	(57)	142	(61)	150	(66)
22	4400	(30300)	115	(46)	123	(51)	132	(56)	140	(60)	149	(65)	157	(69)
24	4700	(32400)	118	(48)	127	(53)	136	(58)	146	(63)	155	(68)	164	(73)
26	5100	(35200)	121	(49)	131	(55)	141	(61)	151	(66)	161	(72)	171	(77)
28	5400	(37200)	124	(51)	135	(57)	146	(63)	156	(69)	167	(75)	178	(81)
30	5700	(39300)	127	(53)	139	(59)	150	(66)	162	(72)	173	(78)	185	(85)
32	6000	(41400)	130	(54)	143	(62)	155	(68)	167	(75)	180	(82)	192	(89)
34	6300	(43400)	134	(57)	147	(64)	160	(71)	173	(78)	186	(86)	199	(93)
36	6600	(45500)	137	(58)	151	(66)	164	(73)	178	(81)	192	(89)	206	(97)
38	6900	(47600)	140	(60)	154	(68)	169	(76)	184	(84)	198	(92)	213	(101)
40	7200	(49600)	143	(62)	158	(70)	174	(79)	189	(87)	205	(96)	220	(104)
42	7500	(51700)	146	(63)	162	(72)	178	(81)	195	(91)	211	(99)	227	(108)
44	7800	(53800)	149	(65)	166	(74)	183	(84)	200	(93)	217	(103)	234	(112)
46	8100	(55800)	152	(67)	170	(77)	188	(87)	206	(97)	223	(106)	241	(116)
48	8400	(57900)	156	(69)	174	(79)	193	(89)	211	(99)	230	(110)	248	(120)
50	8700	(60000)	159	(71)	178	(81)	197	(92)	217	(103)	236	(113)	255	(124)
52	9100	(62700)	162	(72)	182	(83)	202	(94)	222	(106)	242	(117)	262	(128)
54	9400	(64800)	165	(74)	186	(86)	207	(97)	227	(108)	248	(120)	269	(132)
56	9700	(66900)	168	(76)	190	(88)	211	(99)	233	(112)	254	(123)	276	(136)
58	10000	(68900)	171	(77)	194	(90)	216	(102)	238	(114)	261	(127)	283	(139)
60	10300	(71000)	174	(79)	198	(92)	221	(105)	244	(118)	267	(131)	290	(143)
62	10600	(73100)	178	(81)	201	(94)	225	(107)	249	(121)	273	(134)	297	(147)
64	10900	(75200)	181	(83)	205	(96)	230	(110)	255	(124)	279	(137)	304	(151)
66	11200	(77200)	184	(84)	209	(98)	235	(113)	260	(127)	286	(141)	311	(155)
68	11500	(79300)	187	(86)	213	(101)	239	(115)	266	(130)	292	(144)	318	(159)
70	11800	(81400)	190	(88)	217	(103)	244	(118)	271	(133)	298	(148)	325	(163)
72	12100	(83400)	193	(89)	221	(105)	249	(121)	277	(136)	304	(151)	332	(167)
74	12400	(85500)	196	(91)	225	(107)	254	(123)	282	(139)	311	(155)	339	(171)
76	12700	(87600)	200	(93)	229	(109)	258	(126)	287	(142)	317	(158)	346	(174)
78	13100	(90300)	203	(95)	233	(112)	263	(128)	293	(145)	323	(162)	353	(178)
80	13400	(92400)	206	(97)	237	(114)	268	(131)	298	(148)	329	(165)	360	(182)
82	13700	(94500)	209	(98)	241	(116)	272	(133)	304	(151)	335	(168)	367	(186)
84	14000	(96500)	212	(100)	245	(118)	277	(136)	309	(154)	342	(172)	374	(190)
86	14300	(98600)	215	(102)	248	(120)	282	(139)	315	(157)	348	(176)	381	(194)
88	14600	(100700)	219	(104)	252	(122)	286	(141)	320	(160)	354	(179)	388	(198)
90	14900	(102700)	222	(106)	256	(124)	291	(144)	326	(163)	360	(182)	395	(202)
Heating Rate - Deg/min			1.58	(0.88)	1.96	(1.09)	2.34	(1.30)	2.73	(1.52)	3.11	(1.73)	3.50	(1.94)
Pressure Rate (per min)			154 psi (1061 kPa)											
Time to Final Conditions			90 Minutes											

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.13											
	Depth	22,000 ft	(6710 m)								Mud density: 13.8 lb/gal (1.65kg/L)			
0	1150	(7900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1500	(10300)	83	(28)	84	(29)	85	(29)	86	(30)	87	(31)	87	(31)
4	1800	(12400)	87	(31)	88	(31)	90	(32)	92	(33)	93	(34)	95	(35)
6	2100	(14500)	90	(32)	93	(34)	95	(35)	97	(36)	100	(38)	102	(39)
8	2400	(16500)	93	(34)	97	(36)	100	(38)	103	(39)	106	(41)	110	(43)
10	2800	(19300)	97	(36)	101	(38)	105	(41)	109	(43)	113	(45)	117	(47)
12	3100	(21400)	100	(38)	105	(41)	110	(43)	115	(46)	120	(49)	125	(52)
14	3400	(23400)	103	(39)	109	(43)	115	(46)	121	(49)	126	(52)	132	(56)
16	3700	(25500)	107	(42)	113	(45)	120	(49)	126	(52)	133	(56)	139	(59)
18	4000	(27600)	110	(43)	118	(48)	125	(52)	132	(56)	139	(59)	147	(64)
20	4400	(30300)	114	(46)	122	(50)	130	(54)	138	(59)	146	(63)	154	(68)
22	4700	(32400)	117	(47)	126	(52)	135	(57)	144	(62)	153	(67)	162	(72)
24	5000	(34500)	120	(49)	130	(54)	140	(60)	150	(66)	159	(71)	169	(76)
26	5300	(36500)	124	(51)	134	(57)	145	(63)	155	(68)	166	(74)	176	(80)
28	5700	(39300)	127	(53)	138	(59)	150	(66)	161	(72)	173	(78)	184	(84)
30	6000	(41400)	130	(54)	143	(62)	155	(68)	167	(75)	179	(82)	191	(88)
32	6300	(43400)	134	(57)	147	(64)	160	(71)	173	(78)	186	(86)	199	(93)
34	6600	(45500)	137	(58)	151	(66)	165	(74)	179	(82)	192	(89)	206	(97)
36	6900	(47600)	140	(60)	155	(68)	170	(77)	184	(84)	199	(93)	214	(101)
38	7300	(50300)	144	(62)	159	(71)	175	(79)	190	(88)	206	(97)	221	(105)
40	7600	(52400)	147	(64)	163	(73)	180	(82)	196	(91)	212	(100)	228	(109)
42	7900	(54500)	150	(66)	168	(76)	185	(85)	202	(94)	219	(104)	236	(113)
44	8200	(56500)	154	(68)	172	(78)	190	(88)	207	(97)	225	(107)	243	(117)
46	8500	(58600)	157	(69)	176	(80)	195	(91)	213	(101)	232	(111)	251	(122)
48	8900	(61400)	160	(71)	180	(82)	200	(93)	219	(104)	239	(115)	258	(126)
50	9200	(63400)	164	(73)	184	(84)	205	(96)	225	(107)	245	(118)	266	(130)
52	9500	(65500)	167	(75)	188	(87)	210	(99)	231	(111)	252	(122)	273	(134)
54	9800	(67600)	171	(77)	193	(89)	214	(101)	236	(113)	258	(126)	280	(138)
56	10200	(70300)	174	(79)	197	(92)	219	(104)	242	(117)	265	(129)	288	(142)
58	10500	(72400)	177	(81)	201	(94)	224	(107)	248	(120)	272	(133)	295	(146)
60	10800	(74500)	181	(83)	205	(96)	229	(109)	254	(123)	278	(137)	303	(151)
62	11100	(76500)	184	(84)	209	(98)	234	(112)	260	(127)	285	(141)	310	(154)
64	11400	(78600)	187	(86)	213	(101)	239	(115)	265	(129)	291	(144)	318	(159)
66	11800	(81400)	191	(88)	218	(103)	244	(118)	271	(133)	298	(148)	325	(163)

Table 4—Casing Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)								Schedule 9.13 (Continued)			
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
68	12100	(83400)	194	(90)	222	(106)	249	(121)	277	(136)	305	(152)	332	(167)
70	12400	(85500)	197	(92)	226	(108)	254	(123)	283	(139)	311	(155)	340	(171)
72	12700	(87600)	201	(94)	230	(110)	259	(126)	289	(143)	318	(159)	347	(175)
74	13000	(89600)	204	(96)	234	(112)	264	(129)	294	(146)	325	(163)	355	(179)
76	13400	(92400)	207	(97)	238	(114)	269	(132)	300	(149)	331	(166)	362	(183)
78	13700	(94500)	211	(99)	243	(117)	274	(134)	306	(152)	338	(170)	369	(187)
80	14000	(96500)	214	(101)	247	(119)	279	(137)	312	(156)	344	(173)	377	(192)
82	14300	(98600)	218	(103)	251	(122)	284	(140)	318	(159)	351	(177)	384	(196)
84	14700	(101400)	221	(105)	255	(124)	289	(143)	323	(162)	358	(181)	392	(200)
86	15000	(103400)	224	(107)	259	(126)	294	(146)	329	(165)	364	(184)	399	(204)
88	15300	(105500)	228	(109)	263	(128)	299	(148)	335	(168)	371	(188)	407	(208)
90	15600	(107600)	231	(111)	268	(131)	304	(151)	341	(172)	377	(192)	414	(212)
92	15900	(109600)	234	(112)	272	(133)	309	(154)	347	(175)	384	(196)	421	(216)
94	16300	(112400)	238	(114)	276	(136)	314	(157)	352	(178)	391	(199)	429	(221)
96	16600	(114500)	241	(116)	280	(138)	319	(159)	358	(181)	397	(203)	436	(224)
98	16900	(116500)	244	(118)	284	(140)	324	(162)	364	(184)	404	(207)	444	(229)
Heating Rate - Deg/min			1.67	(0.93)	2.08	(1.16)	2.49	(1.38)	2.90	(1.61)	3.31	(1.84)	3.71	(2.06)
Pressure Rate (per min)			161 psi (1108 kPa)											
Time to Final Conditions			98 Minutes											

Table 5—Liner Well-Simulation Tests

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.14											
	Depth	1,000 ft	(305 m)								Mud density: 8.7 lb/gal (1.04 kg/L)			
0	250	(1700)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	300	(2100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
4	400	(2800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
6	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
8	600	(4100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
10	700	(4800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
11	700	(4800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
Heating Rate - Deg/min			0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
Pressure Rate (per min)			41 psi (282 kPa)											
Time to Final Conditions			11 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.15											
	Depth	2,000 ft	(610 m)								Mud density: 8.9 lb/gal (1.07 kg/L)			
0	300	(2100)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	400	(2800)	81	(27)	81	(27)	81	(27)	81	(27)	82	(28)	82	(28)
4	600	(4100)	83	(28)	83	(28)	83	(28)	83	(28)	83	(28)	83	(28)
6	700	(4800)	84	(29)	84	(29)	84	(29)	84	(29)	85	(29)	85	(29)
8	800	(5500)	85	(29)	85	(29)	86	(30)	86	(30)	86	(30)	86	(30)
10	900	(6200)	86	(30)	86	(30)	87	(31)	87	(31)	88	(31)	88	(31)
12	1100	(7600)	88	(31)	88	(31)	89	(32)	89	(32)	89	(32)	89	(32)
14	1200	(8300)	89	(32)	89	(32)	90	(32)	90	(32)	91	(33)	91	(33)
Heating Rate - Deg/min			0.64	(0.36)	0.64	(0.36)	0.71	(0.39)	0.71	(0.39)	0.79	(0.44)	0.79	(0.44)
Pressure Rate (per min)			64 psi (443 kPa)											
Time to Final Conditions			14 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.16											
	Depth	4,000 ft	(1220 m)								Mud density: 9.4 lb/gal (1.13 kg/L)			
0	400	(2800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	600	(4100)	82	(28)	82	(28)	82	(28)	82	(28)	82	(28)	82	(28)
4	800	(5500)	84	(29)	84	(29)	84	(29)	84	(29)	85	(29)	85	(29)
6	1000	(6900)	86	(30)	86	(30)	86	(30)	87	(31)	87	(31)	87	(31)
8	1200	(8300)	88	(31)	88	(31)	88	(31)	89	(32)	89	(32)	90	(32)
10	1400	(9700)	90	(32)	90	(32)	91	(33)	91	(33)	92	(33)	92	(33)
12	1600	(11000)	91	(33)	92	(33)	93	(34)	93	(34)	94	(34)	94	(34)
14	1800	(12400)	93	(34)	94	(34)	95	(35)	95	(35)	96	(36)	97	(36)
16	2000	(13800)	95	(35)	96	(36)	97	(36)	98	(37)	98	(37)	99	(37)
18	2200	(15200)	97	(36)	98	(37)	99	(37)	100	(38)	101	(38)	102	(39)
20	2400	(16500)	99	(37)	100	(38)	101	(38)	102	(39)	103	(39)	104	(40)
Heating Rate - Deg/min			0.95	(0. 53)	1.00	(0. 56)	1.05	(0. 58)	1.10	(0. 61)	1.15	(0. 64)	1.20	(0. 67)
Pressure Rate (per min)			100 psi (685 kPa)											
Time to Final Conditions			20 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.17											
	Depth	6,000 ft	(1830 m)								Mud density: 9.9 lb/gal (1.19 kg/L)			
0	550	(3800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	800	(5500)	82	(28)	83	(28)	83	(28)	83	(28)	83	(28)	84	(29)
4	1000	(6900)	85	(29)	85	(29)	86	(30)	86	(30)	86	(30)	87	(31)
6	1300	(9000)	87	(31)	88	(31)	88	(31)	89	(32)	89	(32)	91	(33)
8	1500	(10300)	90	(32)	90	(32)	91	(33)	92	(33)	92	(33)	94	(34)
10	1700	(11700)	92	(33)	93	(34)	94	(34)	95	(35)	95	(35)	98	(37)
12	2000	(13800)	95	(35)	96	(36)	97	(36)	98	(37)	98	(37)	101	(38)
14	2200	(15200)	97	(36)	98	(37)	99	(37)	100	(38)	102	(39)	105	(41)
16	2400	(16500)	100	(38)	101	(38)	102	(39)	103	(39)	105	(41)	108	(42)
18	2700	(18600)	102	(39)	104	(40)	105	(41)	106	(41)	108	(42)	112	(44)
20	2900	(20000)	105	(41)	106	(41)	108	(42)	109	(43)	111	(44)	115	(46)
22	3100	(21400)	107	(42)	109	(43)	110	(43)	112	(44)	114	(46)	119	(48)
24	3400	(23400)	110	(43)	111	(44)	113	(45)	115	(46)	117	(47)	122	(50)
26	3600	(24800)	112	(44)	114	(46)	116	(47)	118	(48)	120	(49)	126	(52)
Heating Rate - Deg/min			1.23	(0.68)	1.31	(0.73)	1.38	(0.77)	1.46	(0.81)	1.54	(0.86)	1.77	(0.98)
Pressure Rate (per min)			117 psi (808 kPa)											
Time to Final Conditions			26 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.18							
	Depth	8,000 ft	(2440 m)								Mud density: 10.4 lb/gal (1.25 kg/L)			
0	650	(4500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	900	(6200)	83	(28)	83	(28)	83	(28)	84	(29)	84	(29)	85	(29)
4	1200	(8300)	86	(30)	86	(30)	87	(31)	88	(31)	88	(31)	90	(32)
6	1500	(10300)	89	(32)	89	(32)	90	(32)	91	(33)	92	(33)	95	(35)
8	1700	(11700)	92	(33)	92	(33)	94	(34)	95	(35)	97	(36)	100	(38)
10	2000	(13800)	94	(34)	95	(35)	97	(36)	99	(37)	101	(38)	105	(41)
12	2300	(15900)	97	(36)	98	(37)	101	(38)	103	(39)	105	(41)	110	(43)
14	2600	(17900)	100	(38)	101	(38)	104	(40)	106	(41)	109	(43)	115	(46)
16	2800	(19300)	103	(39)	105	(41)	108	(42)	110	(43)	113	(45)	120	(49)
18	3100	(21400)	106	(41)	108	(42)	111	(44)	114	(46)	117	(47)	125	(52)
20	3400	(23400)	109	(43)	111	(44)	114	(46)	118	(48)	121	(49)	130	(54)
22	3600	(24800)	112	(44)	114	(46)	118	(48)	121	(49)	125	(52)	135	(57)
24	3900	(26900)	115	(46)	117	(47)	121	(49)	125	(52)	130	(54)	140	(60)
26	4200	(29000)	117	(47)	120	(49)	125	(52)	129	(54)	134	(57)	145	(63)
28	4500	(31000)	120	(49)	123	(51)	128	(53)	133	(56)	138	(59)	150	(66)
30	4700	(32400)	123	(51)	126	(52)	132	(56)	136	(58)	142	(61)	155	(68)
32	5000	(34500)	126	(52)	129	(54)	135	(57)	140	(60)	146	(63)	160	(71)
Heating Rate - Deg/min			1.44	(0.80)	1.53	(0.85)	1.72	(0.96)	1.88	(1.04)	2.06	(1.14)	2.50	(1.39)
Pressure Rate (per min)			136 psi (938 kPa)											
Time to Final Conditions			32 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.19											
	Depth	10,000 ft	(3050 m)								Mud density: 10.9 lb/gal (1.31 kg/L)			
0	800	(5500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1100	(7600)	83	(28)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)
4	1400	(9700)	86	(30)	87	(31)	88	(31)	89	(32)	91	(33)	93	(34)
6	1700	(11700)	90	(32)	90	(32)	92	(33)	94	(34)	96	(36)	99	(37)
8	2000	(13800)	93	(34)	94	(34)	96	(36)	98	(37)	101	(38)	105	(41)
10	2300	(15900)	96	(36)	97	(36)	101	(38)	103	(39)	106	(41)	112	(44)
12	2600	(17900)	99	(37)	101	(38)	105	(41)	107	(42)	112	(44)	118	(48)
14	2900	(20000)	102	(39)	104	(40)	109	(43)	112	(44)	117	(47)	124	(51)
16	3200	(22100)	106	(41)	108	(42)	113	(45)	117	(47)	122	(50)	131	(55)
18	3500	(24100)	109	(43)	111	(44)	117	(47)	121	(49)	127	(53)	137	(58)
20	3800	(26200)	112	(44)	115	(46)	121	(49)	126	(52)	133	(56)	143	(62)
22	4100	(28300)	115	(46)	118	(48)	125	(52)	130	(54)	138	(59)	149	(65)
24	4400	(30300)	119	(48)	122	(50)	129	(54)	135	(57)	143	(62)	156	(69)
26	4700	(32400)	122	(50)	125	(52)	133	(56)	140	(60)	148	(64)	162	(72)
28	5000	(34500)	125	(52)	129	(54)	137	(58)	144	(62)	154	(68)	168	(76)
30	5300	(36500)	128	(53)	132	(56)	142	(61)	149	(65)	159	(71)	175	(79)
32	5600	(38600)	131	(55)	136	(58)	146	(63)	153	(67)	164	(73)	181	(83)
34	5900	(40700)	135	(57)	139	(59)	150	(66)	158	(70)	169	(76)	187	(86)
36	6200	(42700)	138	(59)	143	(62)	154	(68)	162	(72)	175	(79)	194	(90)
38	6500	(44800)	141	(61)	146	(63)	158	(70)	167	(75)	180	(82)	200	(93)
Heating Rate - Deg/min			1.61	(0.89)	1.74	(0.97)	2.05	(1.14)	2.29	(1.27)	2.63	(1.46)	3.16	(1.76)
Pressure Rate (per min)			150 psi (1034 kPa)											
Time to Final Conditions			38 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.20											
	Depth	12,000 ft	(3660 m)								Mud density: 11.3 lb/gal (1.36 kg/L)			
0	900	(6200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1200	(8300)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)	87	(31)
4	1600	(11000)	86	(30)	88	(31)	90	(32)	91	(33)	93	(34)	95	(35)
6	1900	(13100)	89	(32)	92	(33)	94	(34)	97	(36)	99	(37)	102	(39)
8	2200	(15200)	93	(34)	96	(36)	99	(37)	102	(39)	106	(41)	109	(43)
10	2500	(17200)	96	(36)	100	(38)	104	(40)	108	(42)	112	(44)	116	(47)
12	2900	(20000)	99	(37)	104	(40)	109	(43)	114	(46)	119	(48)	124	(51)
14	3200	(22100)	102	(39)	108	(42)	114	(46)	119	(48)	125	(52)	131	(55)
16	3500	(24100)	105	(41)	112	(44)	118	(48)	125	(52)	132	(56)	138	(59)
18	3800	(26200)	108	(42)	116	(47)	123	(51)	131	(55)	138	(59)	145	(63)
20	4200	(29000)	111	(44)	120	(49)	128	(53)	136	(58)	144	(62)	153	(67)
22	4500	(31000)	115	(46)	124	(51)	133	(56)	142	(61)	151	(66)	160	(71)
24	4800	(33100)	118	(48)	128	(53)	138	(59)	147	(64)	157	(69)	167	(75)
26	5100	(35200)	121	(49)	132	(56)	142	(61)	153	(67)	164	(73)	175	(79)
28	5500	(37900)	124	(51)	136	(58)	147	(64)	159	(71)	170	(77)	182	(83)
30	5800	(40000)	127	(53)	140	(60)	152	(67)	164	(73)	177	(81)	189	(87)
32	6100	(42100)	130	(54)	143	(62)	157	(69)	170	(77)	183	(84)	196	(91)
34	6400	(44100)	133	(56)	147	(64)	162	(72)	176	(80)	190	(88)	204	(96)
36	6800	(46900)	137	(58)	151	(66)	166	(74)	181	(83)	196	(91)	211	(99)
38	7100	(49000)	140	(60)	155	(68)	171	(77)	187	(86)	202	(94)	218	(103)
40	7400	(51000)	143	(62)	159	(71)	176	(80)	192	(89)	209	(98)	225	(107)
42	7700	(53100)	146	(63)	163	(73)	181	(83)	198	(92)	215	(102)	233	(112)
43	7900	(54500)	148	(64)	165	(74)	183	(84)	201	(94)	219	(104)	236	(113)
Heating Rate - Deg/min			1.58	(0.88)	1.98	(1.10)	2.40	(1.33)	2.81	(1.56)	3.23	(1.79)	3.63	(2.02)
Pressure Rate (per min)			163 psi (1123 kPa)											
Time to Final Conditions			43 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.21											
	Depth	14,000 ft	(4270 m)								Mud density: 11.8 lb/gal (1.41 kg/L)			
0	1050	(7200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1400	(9700)	83	(28)	84	(29)	85	(29)	86	(30)	87	(31)	88	(31)
4	1700	(11700)	87	(31)	89	(32)	90	(32)	92	(33)	94	(34)	96	(36)
6	2100	(14500)	90	(32)	93	(34)	96	(36)	98	(37)	101	(38)	103	(39)
8	2400	(16500)	94	(34)	97	(36)	101	(38)	104	(40)	108	(42)	111	(44)
10	2800	(19300)	97	(36)	102	(39)	106	(41)	110	(43)	115	(46)	119	(48)
12	3100	(21400)	101	(38)	106	(41)	111	(44)	116	(47)	122	(50)	127	(53)
14	3500	(24100)	104	(40)	110	(43)	116	(47)	122	(50)	129	(54)	135	(57)
16	3800	(26200)	107	(42)	114	(46)	121	(49)	128	(53)	136	(58)	143	(62)
18	4200	(29000)	111	(44)	119	(48)	127	(53)	135	(57)	142	(61)	150	(66)
20	4500	(31000)	114	(46)	123	(51)	132	(56)	141	(61)	149	(65)	158	(70)
22	4900	(33800)	118	(48)	127	(53)	137	(58)	147	(64)	156	(69)	166	(74)
24	5200	(35900)	121	(49)	132	(56)	142	(61)	153	(67)	163	(73)	174	(79)
26	5600	(38600)	125	(52)	136	(58)	147	(64)	159	(71)	170	(77)	182	(83)
28	5900	(40700)	128	(53)	140	(60)	153	(67)	165	(74)	177	(81)	189	(87)
30	6300	(43400)	131	(55)	145	(63)	158	(70)	171	(77)	184	(84)	197	(92)
32	6600	(45500)	135	(57)	149	(65)	163	(73)	177	(81)	191	(88)	205	(96)
34	7000	(48300)	138	(59)	153	(67)	168	(76)	183	(84)	198	(92)	213	(101)
36	7300	(50300)	142	(61)	157	(69)	173	(78)	189	(87)	205	(96)	221	(105)
38	7700	(53100)	145	(63)	162	(72)	178	(81)	195	(91)	212	(100)	228	(109)
40	8000	(55200)	149	(65)	166	(74)	184	(84)	201	(94)	219	(104)	236	(113)
42	8400	(57900)	152	(67)	170	(77)	189	(87)	207	(97)	226	(108)	244	(118)
44	8700	(60000)	155	(68)	175	(79)	194	(90)	213	(101)	233	(112)	252	(122)
46	9100	(62700)	159	(71)	179	(82)	199	(93)	219	(104)	240	(116)	260	(127)
48	9400	(64800)	162	(72)	183	(84)	204	(96)	225	(107)	247	(119)	268	(131)
49	9600	(66200)	164	(73)	185	(85)	207	(97)	228	(109)	250	(121)	271	(133)
Heating Rate - Deg/min			1.71	(0.95)	2.14	(1.19)	2.59	(1.44)	3.02	(1.68)	3.47	(1.93)	3.90	(2.17)
Pressure Rate (per min)			174 psi (1204 kPa)											
Time to Final Conditions			49 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.22							
	Depth	16,000 ft	(4880 m)								Mud density: 12.3 lb/gal (1.47 kg/L)			
0	1200	(8300)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1600	(11000)	84	(29)	85	(29)	86	(30)	86	(30)	87	(31)	88	(31)
4	1900	(13100)	87	(31)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)
6	2300	(15900)	91	(33)	94	(34)	97	(36)	99	(37)	102	(39)	105	(41)
8	2700	(18600)	95	(35)	99	(37)	102	(39)	106	(41)	110	(43)	113	(45)
10	3100	(21400)	98	(37)	103	(39)	108	(42)	112	(44)	117	(47)	122	(50)
12	3400	(23400)	102	(39)	108	(42)	113	(45)	119	(48)	124	(51)	130	(54)
14	3800	(26200)	106	(41)	112	(44)	119	(48)	125	(52)	132	(56)	138	(59)
16	4200	(29000)	110	(43)	117	(47)	124	(51)	132	(56)	139	(59)	147	(64)
18	4500	(31000)	113	(45)	122	(50)	130	(54)	138	(59)	147	(64)	155	(68)
20	4900	(33800)	117	(47)	126	(52)	136	(58)	145	(63)	154	(68)	163	(73)
22	5300	(36500)	121	(49)	131	(55)	141	(61)	151	(66)	162	(72)	172	(78)
24	5700	(39300)	124	(51)	136	(58)	147	(64)	158	(70)	169	(76)	180	(82)
26	6000	(41400)	128	(53)	140	(60)	152	(67)	164	(73)	176	(80)	188	(87)
28	6400	(44100)	132	(56)	145	(63)	158	(70)	171	(77)	184	(84)	197	(92)
30	6800	(46900)	135	(57)	149	(65)	163	(73)	177	(81)	191	(88)	205	(96)
32	7100	(49000)	139	(59)	154	(68)	169	(76)	184	(84)	199	(93)	213	(101)
34	7500	(51700)	143	(62)	159	(71)	174	(79)	190	(88)	206	(97)	222	(106)
36	7900	(54500)	147	(64)	163	(73)	180	(82)	197	(92)	213	(101)	230	(110)
38	8200	(56500)	150	(66)	168	(76)	186	(86)	203	(95)	221	(105)	239	(115)
40	8600	(59300)	154	(68)	173	(78)	191	(88)	210	(99)	228	(109)	247	(119)
42	9000	(62100)	158	(70)	177	(81)	197	(92)	216	(102)	236	(113)	255	(124)
44	9400	(64800)	161	(72)	182	(83)	202	(94)	223	(106)	243	(117)	264	(129)
46	9700	(66900)	165	(74)	186	(86)	208	(98)	229	(109)	251	(122)	272	(133)
48	10100	(69600)	169	(76)	191	(88)	213	(101)	236	(113)	258	(126)	280	(138)
50	10500	(72400)	172	(78)	196	(91)	219	(104)	242	(117)	265	(129)	289	(143)
52	10800	(74500)	176	(80)	200	(93)	224	(107)	249	(121)	273	(134)	297	(147)
54	11200	(77200)	180	(82)	205	(96)	230	(110)	255	(124)	280	(138)	305	(152)
55	11400	(78600)	182	(83)	207	(97)	233	(112)	258	(126)	284	(140)	309	(154)
Heating Rate - Deg/min			1.85	(1.03)	2.31	(1.28)	2.78	(1.54)	3.24	(1.80)	3.71	(2.06)	4.16	(2.31)
Pressure Rate (per min)			185 psi (1278 kPa)											
Time to Final Conditions			55 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.23											
	Depth	18,000 ft	(5490 m)								Mud density: 12.8 lb/gal (1.53 kg/L)			
0	1300	(9000)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1700	(11700)	84	(29)	85	(29)	86	(30)	87	(31)	88	(31)	89	(32)
4	2100	(14500)	88	(31)	90	(32)	92	(33)	94	(34)	96	(36)	98	(37)
6	2500	(17200)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)
8	2900	(20000)	96	(36)	100	(38)	104	(40)	108	(42)	112	(44)	115	(46)
10	3300	(22800)	100	(38)	105	(41)	110	(43)	115	(46)	119	(48)	124	(51)
12	3700	(25500)	104	(40)	110	(43)	116	(47)	121	(49)	127	(53)	133	(56)
14	4100	(28300)	108	(42)	115	(46)	121	(49)	128	(53)	135	(57)	142	(61)
16	4400	(30300)	112	(44)	120	(49)	127	(53)	135	(57)	143	(62)	151	(66)
18	4800	(33100)	116	(47)	124	(51)	133	(56)	142	(61)	151	(66)	160	(71)
20	5200	(35900)	120	(49)	129	(54)	139	(59)	149	(65)	159	(71)	169	(76)
22	5600	(38600)	124	(51)	134	(57)	145	(63)	156	(69)	167	(75)	178	(81)
24	6000	(41400)	128	(53)	139	(59)	151	(66)	163	(73)	175	(79)	186	(86)
26	6400	(44100)	132	(56)	144	(62)	157	(69)	170	(77)	183	(84)	195	(91)
28	6800	(46900)	135	(57)	149	(65)	163	(73)	177	(81)	190	(88)	204	(96)
30	7200	(49600)	139	(59)	154	(68)	169	(76)	184	(84)	198	(92)	213	(101)
32	7600	(52400)	143	(62)	159	(71)	175	(79)	190	(88)	206	(97)	222	(106)
34	8000	(55200)	147	(64)	164	(73)	181	(83)	197	(92)	214	(101)	231	(111)
36	8400	(57900)	151	(66)	169	(76)	187	(86)	204	(96)	222	(106)	240	(116)
38	8800	(60700)	155	(68)	174	(79)	193	(89)	211	(99)	230	(110)	248	(120)
40	9200	(63400)	159	(71)	179	(82)	198	(92)	218	(103)	238	(114)	257	(125)
42	9600	(66200)	163	(73)	184	(84)	204	(96)	225	(107)	246	(119)	266	(130)
44	10000	(68900)	167	(75)	189	(87)	210	(99)	232	(111)	254	(123)	275	(135)
46	10300	(71000)	171	(77)	194	(90)	216	(102)	239	(115)	261	(127)	284	(140)
48	10700	(73800)	175	(79)	199	(93)	222	(106)	246	(119)	269	(132)	293	(145)
50	11100	(76500)	179	(82)	204	(96)	228	(109)	253	(123)	277	(136)	302	(150)
52	11500	(79300)	183	(84)	209	(98)	234	(112)	260	(127)	285	(141)	311	(155)
54	11900	(82000)	187	(86)	213	(101)	240	(116)	266	(130)	293	(145)	319	(159)
56	12300	(84800)	191	(88)	218	(103)	246	(119)	273	(134)	301	(149)	328	(164)
58	12700	(87600)	195	(91)	223	(106)	252	(122)	280	(138)	309	(154)	337	(169)
60	13100	(90300)	199	(93)	228	(109)	258	(126)	287	(142)	317	(158)	346	(174)
61	13300	(91700)	201	(94)	231	(111)	261	(127)	291	(144)	321	(161)	350	(177)
Heating Rate - Deg/min			1.98	(1.10)	2.48	(1.38)	2.97	(1.65)	3.46	(1.92)	3.95	(2.19)	4.43	(2.46)
Pressure Rate (per min)			197 psi (1356 kPa)											
Time to Final Conditions			61 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.24											
	Depth	20,000 ft	(6100 m)								Mud density: 13.3 lb/gal (1.59 kg/L)			
0	1450	(10000)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	1900	(13100)	84	(29)	85	(29)	86	(30)	87	(31)	88	(31)	89	(32)
4	2300	(15900)	88	(31)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)
6	2700	(18600)	93	(34)	96	(36)	99	(37)	102	(39)	105	(41)	108	(42)
8	3100	(21400)	97	(36)	101	(38)	105	(41)	109	(43)	113	(45)	118	(48)
10	3500	(24100)	101	(38)	106	(41)	111	(44)	117	(47)	122	(50)	127	(53)
12	3900	(26900)	105	(41)	112	(44)	118	(48)	124	(51)	130	(54)	136	(58)
14	4300	(29600)	110	(43)	117	(47)	124	(51)	131	(55)	139	(59)	146	(63)
16	4800	(33100)	114	(46)	122	(50)	130	(54)	139	(59)	147	(64)	155	(68)
18	5200	(35900)	118	(48)	127	(53)	137	(58)	146	(63)	155	(68)	165	(74)
20	5600	(38600)	122	(50)	133	(56)	143	(62)	153	(67)	164	(73)	174	(79)
22	6000	(41400)	127	(53)	138	(59)	149	(65)	161	(72)	172	(78)	183	(84)
24	6400	(44100)	131	(55)	143	(62)	156	(69)	168	(76)	180	(82)	193	(89)
26	6800	(46900)	135	(57)	148	(64)	162	(72)	175	(79)	189	(87)	202	(94)
28	7200	(49600)	139	(59)	154	(68)	168	(76)	183	(84)	197	(92)	212	(100)
30	7700	(53100)	143	(62)	159	(71)	174	(79)	190	(88)	206	(97)	221	(105)
32	8100	(55800)	148	(64)	164	(73)	181	(83)	197	(92)	214	(101)	230	(110)
34	8500	(58600)	152	(67)	169	(76)	187	(86)	205	(96)	222	(106)	240	(116)
36	8900	(61400)	156	(69)	175	(79)	193	(89)	212	(100)	231	(111)	249	(121)
38	9300	(64100)	160	(71)	180	(82)	200	(93)	219	(104)	239	(115)	259	(126)
40	9700	(66900)	165	(74)	185	(85)	206	(97)	227	(108)	247	(119)	268	(131)
42	10100	(69600)	169	(76)	191	(88)	212	(100)	234	(112)	256	(124)	278	(137)
44	10500	(72400)	173	(78)	196	(91)	219	(104)	241	(116)	264	(129)	287	(142)
46	11000	(75800)	177	(81)	201	(94)	225	(107)	249	(121)	273	(134)	296	(147)
48	11400	(78600)	181	(83)	206	(97)	231	(111)	256	(124)	281	(138)	306	(152)
50	11800	(81400)	186	(86)	212	(100)	237	(114)	263	(128)	289	(143)	315	(157)
52	12200	(84100)	190	(88)	217	(103)	244	(118)	271	(133)	298	(148)	325	(163)
54	12600	(86900)	194	(90)	222	(106)	250	(121)	278	(137)	306	(152)	334	(168)
56	13000	(89600)	198	(92)	227	(108)	256	(124)	285	(141)	314	(157)	343	(173)
58	13400	(92400)	203	(95)	233	(112)	263	(128)	293	(145)	323	(162)	353	(178)
60	13900	(95800)	207	(97)	238	(114)	269	(132)	300	(149)	331	(166)	362	(183)
62	14300	(98600)	211	(99)	243	(117)	275	(135)	307	(153)	339	(171)	372	(189)
64	14700	(101400)	215	(102)	248	(120)	282	(139)	315	(157)	348	(176)	381	(194)
66	15100	(104100)	220	(104)	254	(123)	288	(142)	322	(161)	356	(180)	390	(199)
67	15300	(105500)	222	(106)	256	(124)	291	(144)	326	(163)	360	(182)	395	(202)
Heating Rate - Deg/min			2.12	(1.18)	2.63	(1.46)	3.15	(1.75)	3.67	(2.04)	4.18	(2.32)	4.70	(2.61)
Pressure Rate (per min)			207 psi (1425 kPa)											
Time to Final Conditions			67 Minutes											

Table 5—Liner Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.25											
	Depth	22,000 ft	(6710 m)								Mud density: 13.8 lb/gal (1.65 kg/L)			
0	1550	(10700)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
2	2000	(13800)	85	(29)	86	(30)	87	(31)	88	(31)	89	(32)	90	(32)
4	2400	(16500)	89	(32)	91	(33)	93	(34)	96	(36)	98	(37)	100	(38)
6	2800	(19300)	94	(34)	97	(36)	100	(38)	103	(39)	107	(42)	110	(43)
8	3300	(22800)	98	(37)	102	(39)	107	(42)	111	(44)	115	(46)	120	(49)
10	3700	(25500)	103	(39)	108	(42)	113	(45)	119	(48)	124	(51)	130	(54)
12	4100	(28300)	107	(42)	114	(46)	120	(49)	127	(53)	133	(56)	140	(60)
14	4600	(31700)	112	(44)	119	(48)	127	(53)	134	(57)	142	(61)	150	(66)
16	5000	(34500)	116	(47)	125	(52)	133	(56)	142	(61)	151	(66)	160	(71)
18	5400	(37200)	121	(49)	130	(54)	140	(60)	150	(66)	160	(71)	170	(77)
20	5900	(40700)	125	(52)	136	(58)	147	(64)	158	(70)	169	(76)	180	(82)
22	6300	(43400)	130	(54)	142	(61)	154	(68)	166	(74)	178	(81)	190	(88)
24	6700	(46200)	134	(57)	147	(64)	160	(71)	173	(78)	186	(86)	200	(93)
26	7200	(49600)	139	(59)	153	(67)	167	(75)	181	(83)	195	(91)	210	(99)
28	7600	(52400)	143	(62)	158	(70)	174	(79)	189	(87)	204	(96)	219	(104)
30	8000	(55200)	148	(64)	164	(73)	180	(82)	197	(92)	213	(101)	229	(109)
32	8500	(58600)	152	(67)	170	(77)	187	(86)	204	(96)	222	(106)	239	(115)
34	8900	(61400)	157	(69)	175	(79)	194	(90)	212	(100)	231	(111)	249	(121)
36	9300	(64100)	161	(72)	181	(83)	200	(93)	220	(104)	240	(116)	259	(126)
38	9700	(66900)	166	(74)	186	(86)	207	(97)	228	(109)	249	(121)	269	(132)
40	10200	(70300)	170	(77)	192	(89)	214	(101)	236	(113)	257	(125)	279	(137)
42	10600	(73100)	175	(79)	197	(92)	220	(104)	243	(117)	266	(130)	289	(143)
44	11000	(75800)	179	(82)	203	(95)	227	(108)	251	(122)	275	(135)	299	(148)
46	11500	(79300)	184	(84)	209	(98)	234	(112)	259	(126)	284	(140)	309	(154)
48	11900	(82000)	188	(87)	214	(101)	240	(116)	267	(131)	293	(145)	319	(159)
50	12300	(84800)	193	(89)	220	(104)	247	(119)	274	(134)	302	(150)	329	(165)
52	12800	(88300)	197	(92)	225	(107)	254	(123)	282	(139)	311	(155)	339	(171)
54	13200	(91000)	202	(94)	231	(111)	261	(127)	290	(143)	320	(160)	349	(176)
56	13600	(93800)	206	(97)	237	(114)	267	(131)	298	(148)	328	(164)	359	(182)
58	14100	(97200)	211	(99)	242	(117)	274	(134)	306	(152)	337	(169)	369	(187)
60	14500	(100000)	215	(102)	248	(120)	281	(138)	313	(156)	346	(174)	379	(193)
62	14900	(102700)	220	(104)	253	(123)	287	(142)	321	(161)	355	(179)	389	(198)
64	15400	(106200)	224	(107)	259	(126)	294	(146)	329	(165)	364	(184)	399	(204)
66	15800	(108900)	229	(109)	265	(129)	301	(149)	337	(169)	373	(189)	409	(209)
68	16200	(111700)	233	(112)	270	(132)	307	(153)	345	(174)	382	(194)	419	(215)
70	16700	(115100)	238	(114)	276	(136)	314	(157)	352	(178)	391	(199)	429	(221)
72	17100	(117900)	242	(117)	281	(138)	321	(161)	360	(182)	399	(204)	439	(226)
73	17300	(119300)	244	(118)	284	(140)	324	(162)	364	(184)	404	(207)	444	(229)
Heating Rate - Deg/min			2.25	(1.25)	2.79	(1.55)	3.34	(1.86)	3.89	(2.16)	4.44	(2.47)	4.99	(2.77)
Pressure Rate (per min)			216 psi (1488 kPa)											
Time to Final Conditions			73 Minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.26											
	Depth	1,000 ft	(305 m)								Mud density: 9.2 lb/gal (1.10 kg/L)			
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	500	(3400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
2	520	(3600)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
3	540	(3700)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
4	560	(3900)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
5	580	(4000)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
6	600	(4100)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
7	620	(4300)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
8	640	(4400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
9	660	(4600)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
10	680	(4700)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
11	700	(4800)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
12	720	(5000)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
13	740	(5100)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
14	760	(5200)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
15	780	(5400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)
Ramp (Deg/min)			0.00	(0.00)	0.00	(0.00)	2.00	(1.11)	3.00	(1.67)	5.00	(2.78)	6.00	(3.33)
Ramp Time			1 Minute											
Temp. Dwell			14 Minutes											
Pressure Rate (per min)			0 psi (0 kPa) for 1 minute, then 20 psi (143 kPa) for 14 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.27											
	Depth	2,000 ft	(610 m)						Mud density: 9.40 lb/gal (1.13 kg/L)					
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	600	(4100)	82	(28)	82	(28)	83	(28)	84	(29)	85	(29)	86	(30)
2	700	(4800)	84	(29)	85	(29)	86	(30)	88	(31)	89	(32)	91	(33)
3	800	(5500)	85	(30)	87	(31)	89	(31)	91	(33)	94	(34)	96	(36)
4	900	(6200)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
5	940	(6500)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
6	980	(6800)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
7	1020	(7000)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
8	1060	(7300)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
9	1100	(7600)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
10	1140	(7900)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
11	1180	(8100)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
12	1220	(8400)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
13	1260	(8700)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
14	1300	(9000)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
15	1340	(9200)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
16	1380	(9500)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
17	1420	(9800)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
18	1460	(10100)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
19	1500	(10300)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
20	1540	(10600)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)
Ramp (Deg/min)			1.50	(0.83)	2.25	(1.25)	3.00	(1.67)	3.75	(2.08)	4.50	(2.50)	5.25	(2.92)
Ramp Time			4 Minutes											
Temp. Dwell			16 Minutes											
Pressure Rate (per min)			100 psi (700 kPa) for 4 minutes, then 40 psi (275 kPa) for 16 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.28							
	Depth	4,000 ft	(1220 m)								Mud density: 9.7 lb/gal (1.16 kg/L)			
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	660	(4600)	82	(28)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)
2	820	(5700)	84	(29)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)
3	980	(6800)	87	(31)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)
4	1140	(7900)	89	(32)	92	(33)	95	(35)	97	(36)	100	(38)	103	(39)
5	1300	(9000)	91	(33)	94	(34)	98	(37)	102	(39)	105	(41)	109	(43)
6	1460	(10100)	93	(34)	97	(36)	102	(39)	106	(41)	110	(43)	115	(46)
7	1620	(11200)	96	(36)	100	(38)	106	(41)	110	(43)	115	(46)	120	(49)
8	1780	(12300)	98	(37)	103	(39)	109	(43)	115	(46)	120	(49)	126	(52)
9	1940	(13400)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
10	2005	(13800)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
11	2070	(14300)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
12	2135	(14700)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
13	2200	(15200)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
14	2265	(15600)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
15	2330	(16100)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
16	2395	(16500)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
17	2460	(17000)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
18	2525	(17400)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
19	2590	(17900)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
20	2655	(18300)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
21	2720	(18800)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
22	2785	(19200)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
23	2850	(19700)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
24	2915	(20100)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
25	2980	(20500)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)
Ramp (Deg/min)			2.22	(1.23)	2.89	(1.61)	3.67	(2.04)	4.33	(2.41)	5.00	(2.78)	5.78	(3.21)
Ramp Time			9 Minutes											
Temp. Dwell			16 Minutes											
Pressure Rate (per min)			160 psi (1111 kPa) for 9 minutes, then 65 psi (444 kPa) for 16 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.29							
	Depth	6,000 ft	(1830 m)								Mud density: 10.2 lb/gal (1.22 kg/L)			
0	800	(5500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	970	(6700)	83	(28)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)
2	1140	(7900)	85	(29)	86	(30)	88	(31)	89	(32)	90	(32)	92	(33)
3	1310	(9000)	88	(31)	89	(32)	92	(33)	94	(34)	96	(36)	98	(37)
4	1480	(10200)	90	(32)	93	(34)	95	(35)	98	(37)	101	(38)	104	(40)
5	1650	(11400)	93	(34)	96	(36)	99	(37)	103	(39)	106	(41)	110	(43)
6	1820	(12500)	95	(35)	99	(37)	103	(39)	107	(42)	111	(44)	116	(47)
7	1990	(13700)	98	(37)	102	(39)	107	(42)	112	(44)	116	(47)	122	(50)
8	2160	(14900)	100	(38)	105	(41)	111	(44)	117	(47)	122	(50)	127	(53)
9	2330	(16100)	103	(39)	108	(42)	115	(46)	121	(49)	127	(53)	133	(56)
10	2500	(17200)	105	(41)	111	(44)	119	(48)	126	(52)	132	(56)	139	(59)
11	2670	(18400)	108	(42)	115	(46)	122	(50)	130	(54)	137	(58)	145	(63)
12	2840	(19600)	110	(43)	118	(48)	126	(52)	135	(57)	143	(62)	151	(66)
13	3010	(20800)	113	(45)	121	(49)	130	(54)	139	(59)	148	(64)	157	(69)
14	3180	(21900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
15	3250	(22400)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
16	3320	(22900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
17	3390	(23400)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
18	3460	(23900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
19	3530	(24300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
20	3600	(24800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
21	3670	(25300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
22	3740	(25800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
23	3810	(26300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
24	3880	(26800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
25	3950	(27200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
26	4020	(27700)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
27	4090	(28200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
28	4160	(28700)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
29	4230	(29200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
30	4300	(29600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
31	4370	(30100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
32	4440	(30600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
33	4510	(31100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
34	4580	(31600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
35	4650	(32100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)
Ramp (Deg/min)			2.50	(1.39)	3.14	(1.74)	3.86	(2.14)	4.57	(2.54)	5.21	(2.89)	5.93	(3.29)
Ramp Time			14 Minutes											
Temp. Dwell			21 Minutes											
Pressure Rate (per min)			170 psi (1171 kPa) for 14 minutes, then 70 psi (486 kPa) for 21 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.30							
	Depth	8,000 ft	(2440 m)								Mud density: 10.8 lb/gal (1.29 kg/L)			
0	1000	(6900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	1185	(8200)	83	(28)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)
2	1370	(9400)	85	(29)	87	(31)	88	(31)	89	(32)	91	(33)	92	(33)
3	1555	(10700)	88	(31)	90	(32)	92	(33)	94	(34)	96	(36)	98	(37)
4	1740	(12000)	91	(33)	93	(34)	96	(36)	99	(37)	101	(38)	104	(40)
5	1925	(13300)	93	(34)	97	(36)	100	(38)	103	(39)	107	(42)	111	(44)
6	2110	(14500)	96	(36)	100	(38)	104	(40)	108	(42)	112	(44)	117	(47)
7	2295	(15800)	98	(37)	103	(39)	108	(42)	113	(45)	118	(48)	123	(51)
8	2480	(17100)	101	(38)	107	(42)	112	(44)	117	(47)	123	(51)	129	(54)
9	2665	(18400)	104	(40)	110	(43)	116	(47)	122	(50)	128	(53)	135	(57)
10	2850	(19700)	106	(41)	113	(45)	120	(49)	127	(53)	134	(57)	141	(61)
11	3035	(20900)	109	(43)	117	(47)	124	(51)	131	(56)	139	(59)	147	(64)
12	3220	(22200)	112	(44)	120	(49)	128	(53)	136	(58)	144	(62)	153	(67)
13	3405	(23500)	114	(46)	123	(51)	132	(56)	141	(61)	150	(66)	159	(71)
14	3590	(24800)	117	(47)	126	(52)	136	(58)	146	(63)	155	(68)	165	(74)
15	3775	(26000)	119	(48)	130	(54)	140	(60)	150	(66)	161	(72)	172	(78)
16	3960	(27300)	122	(50)	133	(56)	144	(62)	155	(68)	166	(74)	178	(81)
17	4145	(28600)	125	(52)	136	(58)	148	(64)	160	(71)	171	(77)	184	(84)
18	4330	(29900)	127	(53)	140	(60)	152	(67)	164	(73)	177	(81)	190	(88)
19	4515	(31100)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
20	4600	(31700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
21	4685	(32300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
22	4770	(32900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
23	4855	(33500)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
24	4940	(34100)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
25	5025	(34600)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
26	5110	(35200)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
27	5195	(35800)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
28	5280	(36400)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
29	5365	(37000)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
30	5450	(37600)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
31	5535	(38200)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
32	5620	(38700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
33	5705	(39300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
34	5790	(39900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
35	5875	(40500)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
36	5960	(41100)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
37	6045	(41700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
38	6130	(42300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
39	6215	(42900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
40	6300	(43400)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)
Ramp (Deg/min)			2.63	(1.46)	3.32	(1.84)	4.00	(2.22)	4.68	(2.60)	5.37	(2.98)	6.11	(3.39)
Ramp Time			19 Minutes											
Temp. Dwell			21 Minutes											
Pressure Rate (per min)			185 psi (1274 kPa) for 19 minutes, then 85 psi (586 kPa) for 21 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.31											
	Depth	10,000 ft	(3050 m)								Mud density: 11.5 lb/gal (1.38 kg/L)			
0	1300	(9000)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	1500	(10300)	83	(28)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)
2	1700	(11700)	86	(30)	87	(31)	88	(31)	90	(32)	91	(33)	92	(33)
3	1900	(13100)	88	(31)	90	(32)	92	(33)	95	(35)	97	(36)	99	(37)
4	2100	(14500)	91	(33)	94	(34)	97	(36)	99	(37)	102	(39)	105	(41)
5	2300	(15900)	94	(34)	97	(36)	101	(38)	104	(40)	108	(42)	111	(44)
6	2500	(17200)	97	(36)	101	(38)	105	(41)	109	(43)	113	(45)	117	(47)
7	2700	(18600)	99	(37)	104	(40)	109	(43)	114	(46)	119	(48)	123	(51)
8	2900	(20000)	102	(39)	108	(42)	113	(45)	119	(48)	124	(51)	130	(54)
9	3100	(21400)	105	(41)	111	(44)	117	(47)	123	(51)	130	(54)	136	(58)
10	3300	(22800)	108	(42)	115	(46)	121	(49)	128	(53)	135	(57)	142	(61)
11	3500	(24100)	110	(43)	118	(48)	125	(52)	133	(56)	141	(61)	148	(64)
12	3700	(25500)	113	(45)	122	(50)	130	(54)	138	(59)	146	(64)	155	(68)
13	3900	(26900)	116	(47)	125	(52)	134	(57)	143	(62)	152	(67)	161	(72)
14	4100	(28300)	119	(48)	128	(53)	138	(59)	148	(64)	158	(70)	167	(75)
15	4300	(29600)	121	(49)	132	(56)	142	(61)	152	(67)	163	(73)	173	(78)
16	4500	(31000)	124	(51)	135	(57)	146	(63)	157	(69)	169	(76)	179	(82)
17	4700	(32400)	127	(53)	139	(59)	150	(66)	162	(72)	174	(79)	186	(86)
18	4900	(33800)	130	(54)	142	(61)	154	(68)	167	(75)	180	(82)	192	(89)
19	5100	(35200)	132	(56)	146	(63)	158	(70)	172	(78)	185	(85)	198	(92)
20	5300	(36500)	135	(57)	149	(65)	163	(73)	177	(81)	191	(88)	204	(96)
21	5500	(37900)	138	(59)	153	(67)	167	(75)	181	(83)	196	(91)	210	(99)
22	5700	(39300)	141	(61)	156	(69)	171	(77)	186	(86)	202	(94)	217	(103)
23	5900	(40700)	143	(62)	160	(71)	175	(79)	191	(88)	207	(97)	223	(106)
24	6100	(42100)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
25	6195	(42700)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
26	6290	(43400)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
27	6385	(44000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
28	6480	(44700)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
29	6575	(45300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
30	6670	(46000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
31	6765	(46600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
32	6860	(47300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
33	6955	(48000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
34	7050	(48600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
35	7145	(49300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
36	7240	(49900)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
37	7335	(50600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
38	7430	(51200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
39	7525	(51900)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
40	7620	(52500)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
41	7715	(53200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
42	7810	(53800)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
43	7905	(54500)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
44	8000	(55200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
45	8095	(55800)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)
Ramp (Deg/min)			2.75	(1.53)	3.46	(1.92)	4.13	(2.29)	4.83	(2.68)	5.54	(3.08)	6.21	(3.45)
Ramp Time			24 Minutes											
Temp. Dwell			21 Minutes											
Pressure Rate (per min)			200 psi (1379 kPa) for 24 minutes, then 95 psi (652 kPa) for 21 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.32											
	Depth	12,000 ft	(3660 m)								Mud density: 12.4 lb/gal (1.49 kg/L)			
0	1500	(10300)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	1720	(11900)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	86	(30)
2	1940	(13400)	86	(30)	87	(31)	88	(31)	90	(32)	91	(33)	93	(34)
3	2160	(14900)	88	(31)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)
4	2380	(16400)	91	(33)	94	(34)	97	(36)	100	(38)	103	(39)	105	(41)
5	2600	(17900)	94	(34)	98	(37)	101	(38)	105	(41)	108	(42)	112	(44)
6	2820	(19400)	97	(36)	101	(38)	105	(41)	110	(43)	114	(46)	118	(48)
7	3040	(21000)	100	(38)	105	(41)	110	(43)	115	(46)	120	(49)	124	(51)
8	3260	(22500)	103	(39)	108	(42)	114	(46)	119	(48)	125	(52)	131	(55)
9	3480	(24000)	105	(41)	112	(44)	118	(48)	124	(51)	131	(55)	137	(58)
10	3700	(25500)	108	(42)	116	(47)	122	(50)	129	(54)	137	(58)	143	(62)
11	3920	(27000)	111	(44)	119	(48)	127	(53)	134	(57)	142	(61)	150	(66)
12	4140	(28500)	114	(46)	123	(51)	131	(55)	139	(59)	148	(64)	156	(69)
13	4360	(30100)	117	(47)	126	(52)	135	(57)	144	(62)	154	(68)	162	(72)
14	4580	(31600)	120	(49)	130	(54)	139	(59)	149	(65)	159	(71)	169	(76)
15	4800	(33100)	122	(50)	133	(56)	144	(62)	154	(68)	165	(74)	175	(79)
16	5020	(34600)	125	(52)	137	(58)	148	(64)	159	(71)	170	(77)	182	(83)
17	5240	(36100)	128	(53)	140	(60)	152	(67)	164	(73)	176	(80)	188	(87)
18	5460	(37600)	131	(55)	144	(62)	156	(69)	169	(76)	182	(83)	194	(90)
19	5680	(39200)	134	(57)	147	(64)	161	(72)	174	(79)	187	(86)	201	(94)
20	5900	(40700)	137	(58)	151	(66)	165	(74)	179	(82)	193	(89)	207	(97)
21	6120	(42200)	139	(59)	155	(68)	169	(76)	184	(84)	199	(93)	213	(101)
22	6340	(43700)	142	(61)	158	(70)	173	(78)	188	(87)	204	(96)	220	(104)
23	6560	(45200)	145	(63)	162	(72)	178	(81)	193	(89)	210	(99)	226	(108)
24	6780	(46700)	148	(64)	165	(74)	182	(83)	198	(92)	216	(102)	232	(111)
25	7000	(48300)	151	(66)	169	(76)	186	(86)	203	(95)	221	(105)	239	(115)
26	7220	(49800)	154	(68)	172	(78)	190	(88)	208	(98)	227	(108)	245	(118)
27	7440	(51300)	156	(69)	176	(80)	195	(91)	213	(101)	233	(112)	251	(122)
28	7660	(52800)	159	(71)	179	(82)	199	(93)	218	(103)	238	(114)	258	(126)
29	7880	(54300)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
30	7985	(55100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
31	8090	(55800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
32	8195	(56500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
33	8300	(57200)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
34	8405	(58000)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
35	8510	(58700)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth)											
			Temperature, °F (°C)								Schedule 9.32 (Continued)			
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
36	8615	(59400)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
37	8720	(60100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
38	8825	(60800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
39	8930	(61600)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
40	9035	(62300)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
41	9140	(63000)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
42	9245	(63700)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
43	9350	(64500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
44	9455	(65200)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
45	9560	(65900)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
46	9665	(66600)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
47	9770	(67400)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
48	9875	(68100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
49	9980	(68800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
50	10085	(69500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)
Ramp (Deg/min)			2.83	(1.57)	3.55	(1.97)	4.24	(2.36)	4.93	(2.74)	5.66	(3.14)	6.34	(3.52)
Ramp Time			29 Minutes											
Temp. Dwell			21 Minutes											
Pressure Rate (per min)			220 psi (1517 kPa) for 29 minutes, then 105 (724 kPa) psi for 21 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.33											
	Depth	14,000 ft	(4270 m)								Mud density: 13.3 lb/gal (1.59 kg/L)			
0	1800	(12400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	2035	(14000)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	86	(30)
2	2270	(15700)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	93	(34)
3	2505	(17300)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)
4	2740	(18900)	92	(33)	95	(35)	97	(36)	100	(38)	103	(39)	106	(41)
5	2975	(20500)	95	(35)	98	(37)	102	(39)	105	(41)	109	(43)	112	(44)
6	3210	(22100)	97	(36)	102	(39)	106	(41)	110	(43)	115	(46)	119	(48)
7	3445	(23800)	100	(38)	106	(41)	110	(43)	115	(46)	120	(49)	125	(52)
8	3680	(25400)	103	(39)	109	(43)	115	(46)	120	(49)	126	(52)	132	(56)
9	3915	(27000)	106	(41)	113	(45)	119	(48)	126	(52)	132	(56)	138	(59)
10	4150	(28600)	109	(43)	116	(47)	124	(51)	131	(55)	138	(59)	145	(63)
11	4385	(30200)	112	(44)	120	(49)	128	(53)	136	(58)	143	(62)	151	(66)
12	4620	(31900)	115	(46)	124	(51)	132	(56)	141	(61)	149	(65)	158	(70)
13	4855	(33500)	118	(48)	127	(53)	137	(58)	146	(63)	155	(68)	164	(73)
14	5090	(35100)	121	(49)	131	(55)	141	(61)	151	(66)	161	(72)	171	(77)
15	5325	(36700)	124	(51)	135	(57)	145	(63)	156	(69)	166	(74)	177	(81)
16	5560	(38300)	127	(53)	138	(59)	150	(66)	161	(72)	172	(78)	184	(84)
17	5795	(40000)	130	(54)	142	(61)	154	(68)	166	(74)	178	(81)	190	(88)
18	6030	(41600)	132	(56)	146	(63)	158	(70)	171	(77)	184	(84)	196	(91)
19	6265	(43200)	135	(57)	149	(65)	163	(73)	176	(80)	190	(88)	203	(95)
20	6500	(44800)	138	(59)	153	(67)	167	(75)	181	(83)	195	(91)	209	(98)
21	6735	(46400)	141	(61)	157	(69)	171	(77)	186	(86)	201	(94)	216	(102)
22	6970	(48100)	144	(62)	160	(71)	176	(80)	191	(88)	207	(97)	222	(106)
23	7205	(49700)	147	(64)	164	(73)	180	(82)	196	(91)	213	(101)	229	(109)
24	7440	(51300)	150	(66)	168	(76)	184	(84)	201	(94)	218	(103)	235	(113)
25	7675	(52900)	153	(67)	171	(77)	189	(87)	206	(97)	224	(107)	242	(117)
26	7910	(54500)	156	(69)	175	(79)	193	(89)	212	(100)	230	(110)	248	(120)
27	8145	(56200)	159	(71)	178	(81)	198	(92)	217	(103)	236	(113)	255	(124)
28	8380	(57800)	162	(72)	182	(83)	202	(94)	222	(106)	241	(116)	261	(127)
29	8615	(59400)	164	(73)	186	(86)	206	(97)	227	(108)	247	(119)	268	(131)
30	8850	(61000)	167	(75)	189	(87)	211	(99)	232	(111)	253	(123)	274	(134)
31	9085	(62600)	170	(77)	193	(89)	215	(102)	237	(114)	259	(126)	281	(138)
32	9320	(64300)	173	(78)	197	(92)	219	(104)	242	(117)	264	(129)	287	(142)
33	9555	(65900)	176	(80)	200	(93)	224	(107)	247	(119)	270	(132)	294	(146)
34	9790	(67500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
35	9895	(68200)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
36	10000	(69000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
37	10105	(69700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
38	10210	(70400)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
39	10315	(71100)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
40	10420	(71800)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.33 (Continued)	
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
41	10525	(72600)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
42	10630	(73300)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
43	10735	(74000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
44	10840	(74700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
45	10945	(75500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
46	11050	(76200)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
47	11155	(76900)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
48	11260	(77600)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
49	11365	(78400)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
50	11470	(79100)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
51	11575	(79800)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
52	11680	(80500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
53	11785	(81300)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
54	11890	(82000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
55	11995	(82700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)
Ramp (Deg/min)			2.91	(1.62)	3.65	(2.03)	4.35	(2.42)	5.06	(2.81)	5.76	(3.2)	6.47	(3.59)
Ramp Time			34 Minutes											
Temp. Dwell			21 Minutes											
Pressure Rate (per min)			235 psi (1621 kPa) for 34 minutes, then 105 psi (724 kPa) for 21 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.34											
	Depth	16,000 ft	(4880 m)						Mud density: 14.4 lb/gal (1.73 kg/L)					
0	2000	(13800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	2255	(15500)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	87	(31)
2	2510	(17300)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	93	(34)
3	2765	(19100)	89	(32)	91	(33)	93	(34)	95	(35)	98	(37)	100	(38)
4	3020	(20800)	92	(33)	95	(35)	98	(37)	101	(38)	103	(39)	106	(41)
5	3275	(22600)	95	(35)	99	(37)	102	(39)	106	(41)	109	(43)	113	(45)
6	3530	(24300)	98	(37)	102	(39)	107	(42)	111	(44)	115	(46)	120	(49)
7	3785	(26100)	101	(38)	106	(41)	111	(44)	116	(47)	121	(49)	126	(52)
8	4040	(27900)	104	(40)	110	(43)	115	(46)	121	(49)	127	(27)	133	(56)
9	4295	(29600)	107	(42)	113	(45)	120	(49)	126	(52)	133	(56)	140	(60)
10	4550	(31400)	110	(43)	117	(47)	124	(51)	132	(56)	139	(59)	146	(63)
11	4805	(33100)	113	(45)	121	(49)	129	(54)	137	(58)	145	(63)	153	(67)
12	5060	(34900)	116	(47)	125	(52)	133	(56)	142	(61)	150	(66)	159	(71)
13	5315	(36600)	119	(48)	128	(53)	138	(59)	147	(64)	156	(69)	166	(74)
14	5570	(38400)	122	(50)	132	(56)	142	(61)	152	(67)	162	(72)	173	(78)
15	5825	(40200)	125	(52)	136	(58)	147	(64)	157	(69)	168	(76)	179	(82)
16	6080	(41900)	128	(53)	139	(59)	151	(66)	162	(72)	174	(79)	186	(86)
17	6335	(43700)	131	(55)	143	(62)	155	(68)	168	(76)	180	(82)	192	(89)
18	6590	(45400)	134	(57)	147	(64)	160	(71)	173	(78)	186	(86)	199	(93)
19	6845	(47200)	137	(58)	151	(66)	164	(73)	178	(81)	192	(89)	206	(97)
20	7100	(49000)	140	(60)	154	(68)	169	(76)	183	(84)	197	(92)	212	(100)
21	7355	(50700)	143	(62)	158	(70)	173	(78)	188	(87)	203	(95)	219	(104)
22	7610	(52500)	146	(63)	162	(72)	178	(81)	193	(89)	209	(98)	226	(108)
23	7865	(54200)	149	(65)	166	(74)	182	(83)	199	(93)	215	(102)	232	(111)
24	8120	(56000)	152	(67)	169	(76)	186	(86)	204	(96)	221	(105)	239	(115)
25	8375	(57700)	155	(68)	173	(78)	191	(88)	209	(98)	227	(108)	245	(118)
26	8530	(59500)	158	(70)	177	(81)	195	(91)	214	(101)	233	(112)	252	(122)
27	8885	(61300)	161	(72)	180	(82)	200	(93)	219	(104)	239	(115)	259	(126)
28	9140	(63000)	164	(73)	184	(84)	204	(96)	224	(107)	244	(118)	265	(129)
29	9395	(64800)	167	(75)	188	(87)	209	(98)	229	(109)	250	(121)	272	(133)
30	9650	(66500)	170	(77)	192	(89)	213	(101)	235	(113)	256	(124)	278	(137)
31	9905	(68300)	173	(78)	195	(91)	218	(103)	240	(116)	262	(128)	285	(141)
32	10160	(70100)	176	(80)	199	(93)	222	(106)	245	(118)	268	(131)	292	(144)
33	10415	(71800)	179	(82)	203	(95)	226	(108)	250	(121)	274	(134)	298	(148)
34	10670	(73600)	182	(83)	206	(97)	231	(111)	255	(124)	280	(138)	305	(152)
35	10925	(75300)	185	(85)	210	(99)	235	(113)	260	(127)	286	(141)	312	(156)
36	11180	(77100)	188	(87)	214	(101)	240	(116)	266	(130)	291	(144)	318	(159)
37	11435	(78800)	191	(88)	218	(103)	244	(118)	271	(133)	297	(147)	325	(163)
38	11690	(80600)	194	(90)	221	(105)	249	(121)	276	(136)	303	(151)	331	(166)
39	11945	(82400)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
40	12085	(83300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
41	12225	(84300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)								Schedule 9.34 (Continued)			
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
42	12365	(85300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
43	12505	(86200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
44	12645	(87200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
45	12785	(88200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
46	12925	(89100)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
47	13065	(90100)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
48	13205	(91000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
49	13345	(92000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
50	13485	(93000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
51	13625	(93900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
52	13765	(94900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
53	13905	(95900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
54	14045	(96800)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
55	14185	(97800)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)
Ramp (Deg/min)			3.00	(1.67)	3.72	(2.07)	4.44	(2.47)	5.15	(2.86)	5.87	(3.26)	6.62	(3.68)
Ramp Time			39 Minutes											
Temp. Dwell			16 Minutes											
Pressure Rate (per min)			255 psi (1759 kPa) for 39 minutes, then 140 psi (963 kPa) for 16 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.35							
	Depth	18,000 ft	(5490 m)								Mud density: 15.6 lb/gal (1.87 kg/L)			
0	2200	(15200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	2475	(17100)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	87	(31)
2	2750	(19000)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	93	(34)
3	3025	(20900)	89	(32)	91	(33)	94	(34)	96	(36)	98	(37)	100	(38)
4	3300	(22800)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)
5	3575	(24600)	95	(35)	99	(37)	103	(39)	106	(41)	110	(43)	114	(46)
6	3850	(26500)	98	(37)	103	(39)	107	(42)	112	(44)	116	(47)	120	(49)
7	4125	(28400)	101	(38)	107	(42)	112	(44)	117	(47)	122	(50)	127	(53)
8	4400	(30300)	105	(41)	111	(44)	116	(47)	122	(50)	128	(53)	134	(57)
9	4675	(32200)	108	(42)	114	(46)	121	(49)	127	(53)	134	(57)	141	(61)
10	4950	(34100)	111	(44)	118	(48)	125	(52)	133	(56)	140	(60)	147	(64)
11	5225	(36000)	114	(46)	122	(50)	130	(54)	138	(59)	146	(63)	154	(68)
12	5500	(37900)	117	(47)	126	(52)	135	(57)	143	(62)	152	(67)	161	(72)
13	5775	(39800)	120	(49)	130	(54)	139	(59)	149	(65)	158	(70)	167	(75)
14	6050	(41700)	123	(51)	133	(56)	144	(62)	154	(68)	164	(73)	174	(79)
15	6325	(43600)	126	(52)	137	(58)	148	(64)	159	(71)	170	(77)	181	(83)
16	6600	(45500)	129	(54)	141	(61)	153	(67)	164	(73)	176	(80)	188	(87)
17	6875	(47400)	132	(56)	145	(63)	157	(69)	170	(77)	182	(83)	194	(90)
18	7150	(49300)	135	(57)	149	(65)	162	(72)	175	(79)	188	(87)	201	(94)
19	7425	(51200)	138	(59)	153	(67)	166	(74)	180	(82)	194	(90)	208	(98)
20	7700	(53100)	141	(61)	156	(69)	171	(77)	185	(85)	200	(93)	215	(102)
21	7975	(55000)	144	(62)	160	(71)	175	(79)	191	(88)	206	(97)	221	(105)
22	8250	(56900)	148	(64)	164	(73)	180	(82)	196	(91)	212	(100)	228	(109)
23	8525	(58800)	151	(66)	168	(76)	185	(85)	201	(94)	218	(103)	235	(113)
24	8800	(60700)	154	(68)	172	(78)	189	(87)	207	(97)	224	(107)	241	(116)
25	9075	(62600)	157	(69)	175	(79)	194	(90)	212	(100)	230	(110)	248	(120)
26	9350	(64500)	160	(71)	179	(82)	198	(92)	217	(103)	236	(113)	255	(124)
27	9625	(66400)	163	(73)	183	(84)	203	(95)	222	(106)	242	(117)	262	(128)
28	9900	(68300)	166	(74)	187	(86)	207	(97)	228	(109)	248	(120)	268	(131)
29	10175	(70200)	169	(76)	191	(88)	212	(100)	233	(112)	254	(123)	275	(135)
30	10450	(72100)	172	(78)	195	(91)	216	(102)	238	(114)	260	(127)	282	(139)
31	10725	(73900)	175	(79)	198	(92)	221	(105)	243	(117)	266	(130)	289	(143)
32	11000	(75800)	178	(81)	202	(94)	225	(107)	249	(121)	272	(133)	295	(146)
33	11275	(77700)	181	(83)	206	(97)	230	(110)	254	(123)	278	(137)	302	(150)
34	11550	(79600)	184	(84)	210	(99)	235	(113)	259	(126)	284	(140)	309	(154)
35	11825	(81500)	187	(86)	214	(101)	239	(115)	265	(129)	290	(143)	315	(157)
36	12100	(83400)	190	(88)	217	(103)	244	(118)	270	(132)	296	(147)	322	(161)
37	12375	(85300)	194	(90)	221	(105)	248	(120)	275	(135)	302	(150)	329	(165)
38	12650	(87200)	197	(92)	225	(107)	253	(123)	280	(138)	308	(153)	336	(169)
39	12925	(89100)	200	(93)	229	(109)	257	(125)	286	(141)	314	(157)	342	(172)
40	13200	(91000)	203	(95)	233	(112)	262	(128)	291	(144)	320	(160)	349	(176)
41	13475	(92900)	206	(97)	237	(114)	266	(130)	296	(147)	326	(163)	356	(180)
42	13750	(94800)	209	(98)	240	(116)	271	(133)	301	(149)	332	(167)	363	(184)
43	14025	(96700)	212	(100)	244	(118)	275	(135)	307	(153)	338	(170)	369	(187)
44	14300	(98600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
45	14435	(99500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
46	14570	(100500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.35 (Continued)	
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
47	14705	(101400)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
48	14840	(102300)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
49	14975	(103300)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
50	15110	(104200)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
51	15245	(105100)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
52	15380	(106000)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
53	15515	(107000)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
54	15650	(107900)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
55	15785	(108800)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
56	15920	(109800)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
57	16055	(110700)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
58	16190	(111600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
59	16325	(112600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
60	16460	(113500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)
Ramp (Deg/min)			3.07	(1.71)	3.82	(2.12)	4.55	(2.53)	5.27	(2.93)	6.00	(3.33)	6.73	(3.74)
Ramp Time			44 Minutes											
Temp. Dwell			16 Minutes											
Pressure Rate (per min)			275 psi (1895 kPa) for 44 minutes, then 135 psi (931 kPa) for 16 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)											
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
							Schedule 9.36							
	Depth	20,000 ft	(6095 m)								Mud density: 16.9 lb/gal (2.03 kg/L)			
0	2400	(16500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	2695	(18600)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	87	(31)
2	2990	(20600)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	94	(34)
3	3285	(22700)	89	(32)	92	(33)	94	(34)	96	(36)	98	(37)	101	(38)
4	3580	(24700)	93	(34)	96	(36)	99	(37)	102	(39)	104	(40)	108	(42)
5	3875	(26700)	96	(36)	99	(37)	103	(39)	107	(42)	111	(44)	114	(46)
6	4170	(28800)	99	(37)	103	(39)	108	(42)	112	(44)	117	(47)	121	(49)
7	4465	(30800)	102	(39)	107	(42)	112	(44)	118	(48)	123	(51)	128	(53)
8	4760	(32800)	105	(41)	111	(44)	117	(47)	123	(51)	129	(54)	135	(57)
9	5055	(34900)	108	(42)	115	(46)	122	(50)	128	(53)	135	(57)	142	(61)
10	5350	(36900)	111	(44)	119	(48)	126	(52)	134	(57)	141	(61)	149	(65)
11	5645	(38900)	115	(46)	123	(51)	131	(55)	139	(59)	147	(64)	156	(69)
12	5940	(41000)	118	(48)	127	(53)	136	(58)	145	(63)	153	(67)	163	(73)
13	6235	(43000)	121	(49)	131	(55)	140	(60)	150	(66)	160	(71)	169	(76)
14	6530	(45000)	124	(51)	135	(57)	145	(63)	155	(68)	166	(74)	176	(80)
15	6825	(47100)	127	(53)	138	(59)	149	(65)	161	(72)	172	(78)	183	(84)
16	7120	(49100)	130	(54)	142	(61)	154	(68)	166	(74)	178	(81)	190	(88)
17	7415	(51100)	133	(56)	146	(63)	159	(71)	172	(78)	184	(84)	197	(92)
18	7710	(53200)	137	(58)	150	(66)	163	(73)	177	(81)	190	(88)	204	(96)
19	8005	(55200)	140	(60)	154	(68)	168	(76)	182	(83)	196	(91)	211	(99)
20	8300	(57200)	143	(62)	158	(70)	173	(78)	188	(87)	202	(94)	218	(103)
21	8595	(59300)	146	(63)	162	(72)	177	(81)	193	(89)	209	(98)	224	(107)
22	8890	(61300)	149	(65)	166	(74)	182	(83)	199	(93)	215	(102)	231	(111)
23	9185	(63300)	152	(67)	170	(77)	187	(86)	204	(96)	221	(105)	238	(114)
24	9480	(65400)	155	(68)	174	(79)	191	(88)	209	(98)	227	(108)	245	(118)
25	9775	(67400)	159	(71)	177	(81)	196	(91)	215	(102)	233	(112)	252	(122)
26	10070	(69400)	162	(72)	181	(83)	200	(93)	220	(104)	239	(115)	259	(126)
27	10365	(71500)	165	(74)	185	(85)	205	(96)	225	(107)	245	(118)	266	(130)
28	10660	(73500)	168	(76)	189	(87)	210	(99)	231	(111)	251	(122)	273	(134)
29	10955	(75500)	171	(77)	193	(89)	214	(101)	236	(113)	258	(126)	279	(137)
30	11250	(77600)	174	(79)	197	(92)	219	(104)	242	(117)	264	(129)	286	(141)
31	11545	(79600)	177	(81)	201	(94)	224	(107)	247	(119)	270	(132)	293	(145)
32	11840	(81600)	181	(83)	205	(96)	228	(109)	252	(122)	276	(136)	300	(149)
33	12135	(83700)	184	(84)	209	(98)	233	(112)	258	(126)	282	(139)	307	(153)
34	12430	(85700)	187	(86)	213	(101)	238	(114)	263	(128)	288	(142)	314	(157)
35	12725	(87700)	190	(88)	216	(102)	242	(117)	269	(132)	294	(146)	321	(161)
36	13020	(89800)	193	(89)	220	(104)	247	(119)	274	(134)	300	(149)	328	(164)
37	13315	(91800)	196	(91)	224	(107)	251	(122)	279	(137)	307	(153)	334	(168)
38	13610	(93800)	199	(93)	228	(109)	256	(124)	285	(141)	313	(156)	341	(172)
39	13905	(95900)	203	(95)	232	(111)	261	(127)	290	(143)	319	(159)	348	(176)
40	14200	(97900)	206	(97)	236	(113)	265	(129)	296	(147)	325	(163)	355	(179)
41	14495	(99900)	209	(98)	240	(116)	270	(132)	301	(149)	331	(166)	362	(183)
42	14790	(102000)	212	(100)	244	(118)	275	(135)	306	(152)	337	(169)	369	(187)
43	15085	(104000)	215	(102)	248	(120)	279	(137)	312	(156)	343	(173)	376	(191)
44	15380	(106000)	218	(103)	252	(122)	284	(140)	317	(158)	349	(176)	383	(195)
45	15675	(108100)	221	(105)	255	(124)	288	(142)	322	(161)	356	(180)	389	(198)
46	15970	(110100)	225	(107)	259	(126)	293	(145)	328	(164)	362	(183)	396	(202)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

Temperature Gradient, °F/100 ft depth (°C/100 m depth)
Temperature, °F (°C)

Schedule 9.36 (Continued)

1	2		3		4		5		6		7		8	
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
47	16265	(112100)	228	(109)	263	(128)	298	(148)	333	(167)	368	(187)	403	(206)
48	16560	(114200)	231	(111)	267	(131)	302	(150)	339	(171)	374	(190)	410	(210)
49	16855	(116200)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
50	17030	(117400)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
51	17205	(118600)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
52	17380	(119800)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
53	17555	(121000)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
54	17730	(122200)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
55	17905	(123500)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
56	18080	(124700)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
57	18255	(125900)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
58	18430	(127100)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
59	18605	(128300)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
60	18780	(129500)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)
Ramp (Deg/min)			3.14	(1.74)	3.90	(2.17)	4.63	(2.57)	5.39	(2.99)	6.12	(3.40)	6.88	(3.82)
Ramp Time			49 Minutes											
Temp. Dwell			11 Minutes											
Pressure Rate (per min)			295 psi (2035 kPa) for 49 minutes, then 175 psi (1209 kPa) for 11 minutes											

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth)											
			Temperature, °F (°C)								Schedule 9.37 (Continued)			
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
			Schedule 9.37											
	Depth	22,000 ft	(6705 m)								Mud density: 18.2 lb/gal (2.18 kg/L)			
0	2600	(17900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)
1	2910	(20100)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)	87	(31)
2	3220	(22200)	86	(30)	88	(31)	89	(32)	91	(33)	93	(34)	94	(34)
3	3530	(24300)	90	(32)	92	(33)	94	(34)	97	(36)	99	(37)	101	(38)
4	3840	(26500)	93	(34)	96	(36)	99	(37)	102	(39)	105	(41)	108	(42)
5	4150	(28600)	96	(36)	100	(38)	104	(40)	108	(42)	111	(44)	115	(46)
6	4460	(30800)	99	(37)	104	(40)	108	(42)	113	(45)	118	(48)	122	(50)
7	4770	(32900)	103	(39)	108	(42)	113	(45)	119	(48)	124	(51)	129	(54)
8	5080	(35000)	106	(41)	112	(44)	118	(48)	124	(51)	130	(54)	136	(58)
9	5390	(37200)	109	(43)	116	(47)	123	(51)	130	(54)	136	(58)	143	(62)
10	5700	(39300)	112	(44)	120	(49)	127	(53)	135	(57)	143	(62)	150	(66)
11	6010	(41400)	115	(46)	124	(51)	132	(56)	141	(61)	149	(65)	157	(69)
12	6320	(43600)	119	(48)	128	(53)	137	(58)	146	(63)	155	(68)	164	(73)
13	6630	(45700)	122	(50)	132	(56)	142	(61)	152	(67)	161	(72)	171	(77)
14	6940	(47900)	125	(52)	136	(58)	146	(63)	157	(69)	168	(76)	178	(81)
15	7250	(50000)	128	(53)	140	(60)	151	(66)	163	(73)	174	(79)	185	(85)
16	7560	(52100)	132	(56)	144	(62)	156	(69)	168	(76)	180	(82)	192	(89)
17	7870	(54300)	135	(57)	148	(64)	161	(72)	174	(79)	186	(86)	199	(93)
18	8180	(56400)	138	(59)	152	(67)	165	(74)	179	(82)	193	(89)	206	(97)
19	8490	(58500)	141	(61)	156	(69)	170	(77)	185	(85)	199	(93)	213	(101)
20	8800	(60700)	144	(62)	160	(71)	175	(79)	190	(88)	205	(96)	220	(104)
21	9110	(62800)	148	(64)	164	(73)	180	(82)	196	(91)	211	(99)	227	(108)
22	9420	(65000)	151	(66)	168	(76)	184	(84)	201	(94)	218	(103)	234	(112)
23	9730	(67100)	154	(68)	172	(78)	189	(87)	207	(97)	224	(107)	241	(116)
24	10040	(69200)	157	(69)	176	(80)	194	(90)	212	(100)	230	(110)	248	(120)
25	10350	(71400)	161	(72)	180	(82)	199	(93)	218	(103)	236	(113)	255	(124)
26	10660	(73500)	164	(73)	184	(84)	203	(95)	223	(106)	243	(117)	262	(128)
27	10970	(75600)	167	(75)	188	(87)	208	(98)	229	(109)	249	(121)	270	(132)
28	11280	(77800)	170	(77)	191	(88)	213	(101)	234	(112)	255	(124)	277	(136)
29	11590	(79900)	173	(78)	195	(91)	217	(103)	240	(116)	262	(128)	284	(140)
30	11900	(82100)	177	(81)	199	(93)	222	(106)	245	(118)	268	(131)	291	(144)
31	12210	(84200)	180	(82)	203	(95)	227	(108)	251	(122)	274	(134)	298	(148)
32	12520	(86300)	183	(84)	207	(97)	232	(111)	256	(124)	280	(138)	305	(152)
33	12830	(88500)	186	(86)	211	(99)	236	(113)	262	(128)	287	(142)	312	(156)
34	13140	(90600)	190	(88)	215	(102)	241	(116)	267	(131)	293	(145)	319	(159)
35	13450	(92700)	193	(89)	219	(104)	246	(119)	273	(134)	299	(148)	326	(163)
36	13760	(94900)	196	(91)	223	(106)	251	(122)	278	(137)	305	(152)	333	(167)
37	14070	(97000)	199	(93)	227	(108)	255	(124)	284	(140)	312	(156)	340	(171)
38	14380	(99200)	202	(94)	231	(111)	260	(127)	289	(143)	318	(159)	347	(175)
39	14690	(101300)	206	(97)	235	(113)	265	(129)	295	(146)	324	(162)	354	(179)
40	15000	(103400)	209	(98)	239	(115)	270	(132)	300	(149)	330	(166)	361	(183)
41	15310	(105600)	212	(100)	243	(117)	274	(134)	306	(152)	337	(169)	368	(187)
42	15620	(107700)	215	(102)	247	(119)	279	(137)	311	(155)	343	(173)	375	(191)
43	15930	(109800)	219	(104)	251	(122)	284	(140)	317	(158)	349	(176)	382	(194)
44	16240	(112000)	222	(106)	255	(124)	289	(143)	322	(161)	355	(179)	389	(198)
45	16550	(114100)	225	(107)	259	(126)	293	(145)	328	(164)	362	(183)	396	(202)
46	16860	(116200)	228	(109)	263	(128)	298	(148)	333	(167)	368	(187)	403	(206)
47	17170	(118400)	231	(111)	267	(131)	303	(151)	339	(171)	374	(190)	410	(210)
48	17480	(120500)	235	(113)	271	(133)	308	(153)	344	(173)	380	(193)	417	(214)
49	17790	(122700)	238	(114)	275	(135)	312	(156)	350	(177)	387	(197)	424	(218)

Table 6—Continuous Pumping Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.37 (Continued)	
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)
50	18100	(124800)	241	(116)	279	(137)	317	(158)	355	(179)	393	(201)	431	(222)
51	18410	(126900)	244	(118)	283	(139)	322	(161)	361	(183)	399	(204)	438	(226)
52	18720	(129100)	248	(120)	287	(142)	327	(164)	366	(186)	405	(207)	445	(229)
53	19030	(131200)	251	(122)	291	(144)	331	(166)	372	(189)	412	(211)	452	(233)
54	19340	(133300)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
55	19515	(134600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
56	19690	(135800)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
57	19865	(137000)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
58	20040	(138200)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
59	20215	(139400)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
60	20390	(140600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
61	20565	(141800)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
62	20740	(143000)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
63	20915	(144200)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
64	21090	(145400)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
65	21265	(146600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)
Ramp (Deg/min)			3.22	(1.79)	3.98	(2.21)	4.74	(2.63)	5.50	(3.06)	6.26	(3.48)	7.02	(3.90)
Ramp Time			54 Minutes											
Temp. Dwell			11 Minutes											
Pressure Rate (per min)			310 psi (2137 kPa) for 54 minutes, then 175 psi (1209 kPa) for 11 minutes											

Table 7—Hesitation Squeeze Well-Simulation Tests

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	Stirring
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	
			Schedule 9.38												
	Depth	1,000 ft	(305 m)								Mud density: 9.2 lb/gal (1.10 kg/L)				
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	500	(3400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
2	520	(3600)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
3	540	(3700)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
4	560	(3900)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
5	580	(4000)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
6	600	(4100)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
7	620	(4300)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
8	640	(4400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
9	660	(4600)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
10	680	(4700)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
11	700	(4800)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
12	720	(5000)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
13	740	(5100)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
14	760	(5200)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	On
15	780	(5400)	80	(27)	80	(27)	82	(28)	83	(28)	85	(29)	86	(30)	Off
25	780	(5400)	82	(28)	82	(28)	84	(29)	85	(29)	87	(31)	88	(31)	On
30	780	(5400)	83	(28)	83	(28)	85	(29)	86	(30)	88	(31)	89	(32)	Off
40	780	(5400)	85	(29)	85	(29)	87	(31)	88	(31)	90	(32)	91	(33)	On
45	780	(5400)	86	(30)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	Off
55	780	(5400)	88	(31)	88	(31)	90	(32)	91	(33)	93	(34)	94	(34)	On
60	780	(5400)	89	(32)	89	(32)	91	(33)	92	(33)	94	(34)	95	(35)	Off
70	780	(5400)	89	(32)	91	(33)	93	(34)	94	(34)	96	(36)	97	(36)	On
75	780	(5400)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	98	(37)	Off
85	780	(5400)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	On
90	780	(5400)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	Off
100	780	(5400)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	On
105	780	(5400)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	Off

Segment 1:												
Ramp (Deg/min)	0.00	(0.00)	0.00	(0.00)	2.00	(1.11)	3.00	(1.67)	5.00	(2.78)	6.00	(3.33)
Ramp Time	1 Minute											
Temp. Dwell	14 Minutes											
Pressure Rate (per min)	0 psi (0 kPa) for 1 minute, then 20 psi (143 kPa) for 14 minutes											
Segment 2:												
Ramp (Deg/min)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	45	Minutes	55	Minutes	55	Minutes	60	Minutes	60	Minutes	65	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
			Schedule 9.39												
	Depth	2,000 ft	(610 m)								Mud density: 9.40 lb/gal (1.13 kg/L)				
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	600	(4100)	82	(28)	82	(28)	83	(28)	84	(29)	85	(29)	85	(29)	On
2	700	(4800)	83	(28)	85	(29)	86	(30)	88	(31)	89	(32)	91	(33)	On
3	800	(5500)	85	(29)	87	(31)	89	(31)	91	(33)	94	(34)	96	(36)	On
4	900	(6200)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
5	940	(6500)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
6	980	(6800)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
7	1020	(7000)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
8	1060	(7300)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
9	1100	(7600)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
10	1140	(7900)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
11	1180	(8100)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
12	1220	(8400)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
13	1260	(8700)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
14	1300	(9000)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
15	1340	(9200)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
16	1380	(9500)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
17	1420	(9800)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
18	1460	(10100)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
19	1500	(10300)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	On
20	1540	(10600)	86	(30)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	Off
30	1540	(10600)	88	(31)	91	(33)	94	(34)	97	(36)	100	(38)	103	(39)	On
35	1540	(10600)	89	(32)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	Off
45	1540	(10600)	91	(33)	94	(34)	97	(36)	100	(38)	103	(39)	106	(41)	On
50	1540	(10600)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)	Off
60	1540	(10600)	94	(34)	97	(36)	100	(38)	103	(39)	106	(41)	109	(43)	On
65	1540	(10600)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)	110	(43)	Off
75	1540	(10600)	97	(36)	100	(38)	103	(39)	106	(41)	109	(43)	112	(44)	On
80	1540	(10600)	98	(37)	101	(38)	104	(40)	107	(42)	110	(43)	113	(45)	Off
90	1540	(10600)	98	(37)	102	(39)	106	(41)	109	(43)	112	(44)	115	(46)	On
95	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	113	(45)	116	(47)	Off
105	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	On
110	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	Off
120	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	On
125	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	Off
135	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	On
140	1540	(10600)	98	(37)	102	(39)	106	(41)	110	(43)	114	(46)	118	(48)	Off
Segment 1:															
Ramp (Deg/min)			1.50	(0.83)	2.25	(1.25)	3.00	(1.67)	3.75	(2.08)	4.50	(2.50)	5.25	(2.92)	
Ramp Time			4 Minutes												
Temp. Dwell			16 Minutes												
Pressure Rate (per min)			100 psi (700 kPa) for 4 minutes, then 40 psi (275 kPa) for 16 minutes												
Segment 2:															
Ramp (Deg/min)			0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	
Ramp Time			60	Minutes	65	Minutes	70	Minutes	75	Minutes	80	Minutes	85	Minutes	

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.40								
	Depth	4,000 ft	(1220 m)								Mud density: 9.7 lb/gal (1.16 kg/L)				
0	500	(3400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	660	(4600)	82	(28)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	On
2	820	(5700)	84	(29)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	On
3	980	(6800)	87	(31)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	On
4	1140	(7900)	89	(32)	92	(33)	95	(35)	97	(36)	100	(38)	103	(39)	On
5	1300	(9000)	91	(33)	94	(34)	98	(37)	102	(39)	105	(41)	109	(43)	On
6	1460	(10100)	93	(34)	97	(36)	102	(39)	106	(41)	110	(43)	115	(46)	On
7	1620	(11200)	96	(36)	100	(38)	106	(41)	110	(43)	115	(46)	120	(49)	On
8	1780	(12300)	98	(37)	103	(39)	109	(43)	115	(46)	120	(49)	126	(52)	On
9	1940	(13400)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
10	2005	(13800)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
11	2070	(14300)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
12	2135	(14700)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
13	2200	(15200)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
14	2265	(15600)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
15	2330	(16100)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
16	2395	(16500)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
17	2460	(17000)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
18	2525	(17400)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
19	2590	(17900)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
20	2655	(18300)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
21	2720	(18800)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
22	2785	(19200)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
23	2850	(19700)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
24	2915	(20100)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	On
25	2980	(20500)	100	(38)	106	(41)	113	(45)	119	(48)	125	(52)	132	(56)	Off
35	2980	(20500)	102	(39)	108	(42)	115	(46)	121	(49)	127	(53)	134	(57)	On
40	2980	(20500)	103	(39)	109	(43)	116	(47)	122	(50)	128	(53)	135	(57)	Off
50	2980	(20500)	105	(41)	111	(44)	118	(48)	124	(51)	130	(54)	137	(58)	On
55	2980	(20500)	106	(41)	112	(44)	119	(48)	125	(52)	131	(55)	138	(59)	Off
65	2980	(20500)	108	(42)	114	(46)	121	(49)	127	(53)	133	(56)	140	(60)	On
70	2980	(20500)	109	(43)	115	(46)	122	(50)	128	(53)	134	(57)	141	(61)	Off
80	2980	(20500)	111	(44)	117	(47)	124	(51)	130	(54)	136	(58)	143	(62)	On
85	2980	(20500)	112	(44)	118	(48)	125	(52)	131	(55)	137	(58)	144	(62)	Off
95	2980	(20500)	114	(46)	120	(49)	127	(53)	133	(56)	139	(59)	146	(63)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.40 (Continued)		
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
100	2980	(20500)	115	(46)	121	(49)	128	(53)	134	(57)	140	(60)	147	(64)	Off
110	2980	(20500)	116	(47)	123	(51)	130	(54)	136	(58)	142	(61)	149	(65)	On
115	2980	(20500)	116	(47)	124	(51)	131	(55)	137	(58)	143	(62)	150	(66)	Off
125	2980	(20500)	116	(47)	124	(51)	132	(56)	139	(59)	145	(63)	152	(67)	Off
130	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	146	(63)	153	(67)	On
140	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	155	(68)	Off
145	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	156	(69)	On
155	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	156	(69)	Off
160	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	156	(69)	On
170	2980	(20500)	116	(47)	124	(51)	132	(56)	140	(60)	148	(64)	156	(69)	Off

Segment 1:												
Ramp (Deg/min)	2.22	(1.23)	2.89	(1.61)	3.67	(2.04)	4.33	(2.41)	5.00	(2.78)	5.78	(3.21)
Ramp Time	9 Minutes											
Temp. Dwell	16 Minutes											
Pressure Rate (per min)	160 psi (1111 kPa) for 9 minutes, then 65 psi (444 kPa) for 16 minutes											
Segment 2:												
Ramp (Deg/min)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	80	Minutes	90	Minutes	95	Minutes	105	Minutes	115	Minutes	120	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.41								
	Depth	6,000 ft	(1830 m)								Mud density: 10.2 lb/gal (1.22 kg/L)				
0	800	(5500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	970	(6700)	83	(28)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	On
2	1140	(7900)	85	(29)	86	(30)	88	(31)	89	(32)	90	(32)	92	(33)	On
3	1310	(9000)	88	(31)	89	(32)	92	(33)	94	(34)	96	(36)	98	(37)	On
4	1480	(10200)	90	(32)	93	(34)	95	(35)	98	(37)	101	(38)	104	(40)	On
5	1650	(11400)	93	(34)	96	(36)	99	(37)	103	(39)	106	(41)	110	(43)	On
6	1820	(12500)	95	(35)	99	(37)	103	(39)	107	(42)	111	(44)	116	(47)	On
7	1990	(13700)	98	(37)	102	(39)	107	(42)	112	(44)	117	(47)	122	(50)	On
8	2160	(14900)	100	(38)	105	(41)	111	(44)	117	(47)	122	(50)	127	(53)	On
9	2330	(16100)	103	(39)	108	(42)	115	(46)	121	(49)	127	(53)	133	(56)	On
10	2500	(17200)	105	(41)	111	(44)	119	(48)	126	(52)	132	(56)	139	(59)	On
11	2670	(18400)	108	(42)	115	(46)	122	(50)	130	(54)	137	(58)	145	(63)	On
12	2840	(19600)	110	(43)	118	(48)	126	(52)	135	(57)	143	(62)	151	(66)	On
13	3010	(20800)	113	(45)	121	(49)	130	(54)	139	(59)	148	(64)	157	(69)	On
14	3180	(21900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
15	3250	(22400)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
16	3320	(22900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
17	3390	(23400)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
18	3460	(23900)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
19	3530	(24300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
20	3600	(24800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
21	3670	(25300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
22	3740	(25800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
23	3810	(26300)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
24	3880	(26800)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
25	3950	(27200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
26	4020	(27700)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
27	4090	(28200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
28	4160	(28700)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
29	4230	(29200)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
30	4300	(29600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
31	4370	(30100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
32	4440	(30600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
33	4510	(31100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
34	4580	(31600)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
35	4650	(32100)	115	(46)	124	(51)	134	(57)	144	(62)	153	(67)	163	(73)	On
45	4650	(32100)	117	(47)	126	(52)	136	(58)	146	(63)	155	(68)	165	(74)	Off
50	4650	(32100)	118	(48)	127	(53)	137	(58)	147	(64)	156	(69)	166	(74)	On
60	4650	(32100)	120	(49)	129	(54)	139	(59)	149	(65)	158	(70)	168	(76)	Off
65	4650	(32100)	121	(49)	130	(54)	140	(60)	150	(66)	159	(71)	169	(76)	On
75	4650	(32100)	123	(51)	132	(56)	142	(61)	152	(67)	161	(72)	171	(77)	Off
80	4650	(32100)	124	(51)	133	(56)	143	(62)	153	(67)	162	(72)	172	(78)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.41 (Continued)		
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
90	4650	(32100)	126	(52)	135	(57)	145	(63)	155	(68)	164	(73)	174	(79)	Off
95	4650	(32100)	127	(53)	136	(58)	146	(63)	156	(69)	165	(74)	175	(79)	On
105	4650	(32100)	129	(54)	138	(59)	148	(64)	158	(70)	167	(75)	177	(81)	Off
110	4650	(32100)	130	(54)	139	(59)	149	(65)	159	(71)	168	(76)	178	(81)	On
120	4650	(32100)	132	(56)	141	(61)	151	(66)	161	(72)	170	(77)	180	(82)	Off
125	4650	(32100)	133	(56)	142	(61)	152	(67)	162	(72)	171	(77)	181	(83)	On
135	4650	(32100)	134	(57)	144	(62)	154	(68)	164	(73)	173	(78)	183	(84)	Off
140	4650	(32100)	134	(57)	145	(63)	155	(68)	165	(74)	174	(79)	184	(84)	On
150	4650	(32100)	134	(57)	146	(63)	157	(69)	167	(75)	176	(80)	186	(86)	Off
155	4650	(32100)	134	(57)	146	(63)	158	(70)	168	(76)	177	(81)	187	(86)	On
165	4650	(32100)	134	(57	146	(63)	158	(70)	170	(77)	179	(82)	189	(87)	Off
170	4650	(32100)	134	(57	146	(63)	158	(70)	170	(77)	180	(82)	190	(88)	On
180	4650	(32100)	134	(57	146	(63)	158	(70)	170	(77)	182	(83)	192	(89)	Off
185	4650	(32100)	134	(57	146	(63)	158	(70)	170	(77)	182	(83)	193	(89)	On
195	4650	(32100)	134	(57)	146	(63)	158	(70)	170	(77)	182	(83)	194	(90)	Off
200	4650	(32100)	134	(57)	146	(63)	158	(70)	170	(77)	182	(83)	194	(90)	On

Segment 1:												
Ramp (Deg/min)	2.50	(1.39)	3.14	(1.74)	3.86	(2.14)	4.57	(2.54)	5.21	(2.89)	5.93	(3.29)
Ramp Time	14 Minutes											
Temp. Dwell	21 Minutes											
Pressure Rate (per min)	170 psi (1171 kPa) for 14 minutes, then 70 psi (486 kPa) for 21 minutes											
Segment 2:												
Ramp (Deg/min)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	95	Minutes	110	Minutes	120	Minutes	130	Minutes	145	Minutes	155	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.42								
	Depth	8,000 ft	(2440 m)								Mud density: 10.8 lb/gal (1.29 kg/L)				
0	1000	(6900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	1185	(8200)	83	(28)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	On
2	1370	(9400)	85	(29)	87	(31)	88	(31)	89	(32)	91	(33)	92	(33)	On
3	1555	(10700)	88	(31)	90	(32)	92	(33)	94	(34)	96	(36)	98	(37)	On
4	1740	(12000)	91	(33)	93	(34)	96	(36)	99	(37)	101	(38)	104	(40)	On
5	1925	(13300)	93	(34)	97	(36)	100	(38)	103	(39)	107	(42)	111	(44)	On
6	2110	(14500)	96	(36)	100	(38)	104	(40)	108	(42)	112	(44)	117	(47)	On
7	2295	(15800)	98	(37)	103	(39)	108	(42)	113	(45)	118	(48)	123	(51)	On
8	2480	(17100)	101	(38)	107	(42)	112	(44)	117	(47)	123	(51)	129	(54)	On
9	2665	(18400)	104	(40)	110	(43)	116	(47)	122	(50)	128	(53)	135	(57)	On
10	2850	(19700)	106	(41)	113	(45)	120	(49)	127	(53)	134	(57)	141	(61)	On
11	3035	(20900)	109	(43)	116	(47)	124	(51)	132	(56)	139	(59)	147	(64)	On
12	3220	(22200)	112	(44)	120	(49)	128	(53)	136	(58)	144	(62)	153	(67)	On
13	3405	(23500)	114	(46)	123	(51)	132	(56)	141	(61)	150	(66)	159	(71)	On
14	3590	(24800)	117	(47)	126	(52)	136	(58)	146	(63)	155	(68)	165	(74)	On
15	3775	(26000)	119	(48)	130	(54)	140	(60)	150	(66)	161	(72)	172	(78)	On
16	3960	(27300)	122	(50)	133	(56)	144	(62)	155	(68)	166	(74)	178	(81)	On
17	4145	(28600)	125	(52)	136	(58)	148	(64)	160	(71)	171	(77)	184	(84)	On
18	4330	(29900)	127	(53)	140	(60)	152	(67)	164	(73)	177	(81)	190	(88)	On
19	4515	(31100)	130	(54)	143	(62)	156	(69)	169	(760	182	(83)	196	(91)	On
20	4600	(31700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
21	4685	(32300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
22	4770	(32900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
23	4855	(33500)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
24	4940	(34100)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
25	5025	(34600)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
26	5110	(35200)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
27	5195	(35800)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
28	5280	(36400)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
29	5365	(37000)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
30	5450	(37600)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
31	5535	(38200)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
32	5620	(38700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
33	5705	(39300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
34	5790	(39900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
35	5875	(40500)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
36	5960	(41100)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
37	6045	(41700)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
38	6130	(42300)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
39	6215	(42900)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	On
40	6300	(43400)	130	(54)	143	(62)	156	(69)	169	(76)	182	(83)	196	(91)	Off
50	6300	(43400)	132	(56)	145	(63)	158	(70)	171	(77)	184	(84)	198	(92)	On
55	6300	(43400)	133	(56)	146	(63)	159	(71)	172	(78)	185	(85)	199	(93)	Off
65	6300	(43400)	135	(57)	148	(64)	161	(72)	174	(79)	187	(86)	201	(94)	On
70	6300	(43400)	136	(58)	149	(65)	162	(72)	175	(79)	188	(87)	202	(94)	Off
80	6300	(43400)	138	(59)	151	(66)	164	(73)	177	(81)	190	(88)	204	(96)	On
85	6300	(43400)	139	(59)	152	(67)	165	(74)	178	(81)	191	(88)	205	(96)	Off
95	6300	(43400)	141	(61)	154	(68)	167	(75)	180	(82)	193	(89)	207	(97)	On
100	6300	(43400)	142	(61)	155	(68)	168	(76)	181	(83)	194	(90)	208	(98)	Off
110	6300	(43400)	144	(62)	157	(69)	170	(77)	183	(84)	196	(91)	210	(99)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.42 (Continued)		
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
115	6300	(43400)	145	(63)	158	(70)	171	(77)	184	(84)	197	(92)	211	(99)	Off
125	6300	(43400)	147	(64)	160	(71)	173	(78)	186	(86)	199	(93)	213	(101)	On
130	6300	(43400)	148	(64)	161	(72)	174	(79)	187	(86)	200	(93)	214	(101)	Off
140	6300	(43400)	150	(66)	163	(73)	176	(80)	189	(87)	202	(94)	216	(102)	On
145	6300	(43400)	151	(66)	164	(73)	177	(81)	190	(88)	203	(95)	217	(103)	Off
155	6300	(43400)	152	(67)	166	(74)	179	(82)	192	(89)	205	(96)	219	(104)	On
160	6300	(43400)	152	(67)	167	(75)	180	(82)	193	(89)	206	(97)	220	(104)	Off
170	6300	(43400)	152	(67)	168	(76)	182	(83)	195	(91)	208	(98)	222	(106)	On
175	6300	(43400)	152	(67)	168	(76)	183	(84)	196	(91)	209	(98)	223	(106)	Off
185	6300	(43400)	152	(67)	168	(76)	184	(84)	198	(92)	211	(99)	225	(107)	On
190	6300	(43400)	152	(67)	168	(76)	184	(84)	199	(93)	212	(100)	226	(108)	Off
200	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	214	(101)	228	(109)	On
205	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	215	(102)	229	(109)	Off
215	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	216	(102)	231	(111)	On
220	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	216	(102)	232	(111)	Off
230	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	216	(102)	232	(111)	Off
235	6300	(43400)	152	(67)	168	(76)	184	(84)	200	(93)	216	(102)	232	(111)	On
Segment 1:															
Ramp (Deg/min)			2.63	(1.46)	3.32	(1.84)	4.00	(2.22)	4.68	(2.60)	5.37	(2.98)	6.11	(3.39)	
Ramp Time			19 Minutes												
Temp. Dwell			21 Minutes												
Pressure Rate (per min)			185 psi (1274 kPa) for 19 minutes, then 85 psi (586 kPa) for 21 minutes												
Segment 2:															
Ramp (Deg/min)			0.2	0.11	0.20	0.11	0.20	0.11	0.20	0.11	0.20	0.11	0.20	0.11	
Ramp Time			110	Minutes	125	Minutes	140	Minutes	155	Minutes	170	Minutes	180	Minutes	

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.43								
	Depth	10,000 ft	(3050 m)								Mud density: 11.5 lb/gal (1.38 kg/L)				
0	1300	(9000)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	1500	(10300)	83	(28)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)	On
2	1700	(11700)	86	(30)	87	(31)	88	(31)	90	(32)	91	(33)	92	(33)	On
3	1900	(13100)	88	(31)	90	(32)	92	(33)	95	(35)	97	(36)	99	(37)	On
4	2100	(14500)	91	(33)	94	(34)	97	(36)	99	(37)	102	(39)	105	(41)	On
5	2300	(15900)	94	(34)	97	(36)	101	(38)	104	(40)	108	(42)	111	(44)	On
6	2500	(17200)	97	(36)	101	(38)	105	(41)	109	(43)	113	(45)	117	(47)	On
7	2700	(18600)	99	(37)	104	(40)	109	(43)	114	(46)	119	(48)	123	(51)	On
8	2900	(20000)	102	(39)	108	(42)	113	(45)	119	(48)	124	(51)	130	(54)	On
9	3100	(21400)	105	(41)	111	(44)	117	(47)	124	(51)	130	(54)	136	(58)	On
10	3300	(22800)	108	(42)	115	(46)	121	(49)	128	(53)	135	(57)	142	(61)	On
11	3500	(24100)	110	(43)	118	(48)	125	(52)	133	(56)	141	(61)	148	(64)	On
12	3700	(25500)	113	(45)	122	(50)	130	(54)	138	(59)	147	(64)	155	(68)	On
13	3900	(26900)	116	(47)	125	(52)	134	(57)	143	(62)	152	(67)	161	(72)	On
14	4100	(28300)	119	(48)	128	(53)	138	(59)	148	(64)	158	(70)	167	(75)	On
15	4300	(29600)	121	(49)	132	(56)	142	(61)	153	(67)	163	(73)	173	(78)	On
16	4500	(31000)	124	(51)	135	(57)	146	(63)	157	(69)	169	(76)	179	(82)	On
17	4700	(32400)	127	(53)	139	(59)	150	(66)	162	(72)	174	(79)	186	(86)	On
18	4900	(33800)	130	(54)	142	(61)	154	(68)	167	(75)	180	(82)	192	(89)	On
19	5100	(35200)	132	(56)	146	(63)	158	(70)	172	(78)	185	(85)	198	(92)	On
20	5300	(36500)	135	(57)	149	(65)	163	(73)	177	(81)	191	(88)	204	(96)	On
21	5500	(37900)	138	(59)	153	(67)	167	(75)	182	(83)	196	(91)	210	(99)	On
22	5700	(39300)	141	(61)	156	(69)	171	(77)	186	(86)	202	(94)	217	(103)	On
23	5900	(40700)	143	(62)	160	(71)	175	(79)	191	(88)	207	(97)	223	(106)	On
24	6100	(42100)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
25	6195	(42700)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
26	6290	(43400)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
27	6385	(44000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
28	6480	(44700)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
29	6575	(45300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
30	6670	(46000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
31	6765	(46600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
32	6860	(47300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
33	6955	(48000)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
34	7050	(48600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
35	7145	(49300)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
36	7240	(49900)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
37	7335	(50600)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
38	7430	(51200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
39	7525	(51900)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
40	7620	(52500)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
41	7715	(53200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
42	7810	(53800)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
43	7905	(54500)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
44	8000	(55200)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	On
45	8095	(55800)	146	(63)	163	(73)	179	(82)	196	(91)	213	(101)	229	(109)	Off
55	8095	(55800)	148	(64)	165	(74)	181	(83)	198	(92)	215	(102)	231	(111)	On
60	8095	(55800)	149	(65)	166	(74)	182	(83)	199	(93)	216	(102)	232	(111)	Off
70	8095	(55800)	151	(66)	168	(76)	184	(84)	201	(94)	218	(103)	234	(112)	On
75	8095	(55800)	152	(67)	169	(76)	185	(85)	202	(94)	219	(104)	235	(113)	Off

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.43 (Continued)		
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
85	8095	(55800)	154	(68)	171	(77)	187	(86)	204	(96)	221	(105)	237	(114)	On
90	8095	(55800)	155	(68)	172	(78)	188	(87)	205	(96)	222	(106)	238	(114)	Off
100	8095	(55800)	157	(69)	174	(79)	190	(88)	207	(97)	224	(107)	240	(116)	On
105	8095	(55800)	158	(70)	175	(79)	191	(88)	208	(98)	225	(107)	241	(116)	Off
115	8095	(55800)	160	(71)	177	(81)	193	(89)	210	(99)	227	(108)	243	(117)	On
120	8095	(55800)	161	(72)	178	(81)	194	(90)	211	(99)	228	(109)	244	(118)	Off
130	8095	(55800)	163	(73)	180	(82)	196	(91)	213	(101)	230	(110)	246	(119)	On
135	8095	(55800)	164	(73)	181	(83)	197	(92)	214	(101)	231	(111)	247	(119)	Off
145	8095	(55800)	166	(74)	183	(84)	199	(93)	216	(102)	233	(112)	249	(121)	On
150	8095	(55800)	167	(75)	184	(84)	200	(93)	217	(103)	234	(112)	250	(121)	Off
160	8095	(55800)	169	(76)	186	(86)	202	(94)	219	(104)	236	(113)	252	(122)	On
165	8095	(55800)	170	(77)	187	(86)	203	(95)	220	(104)	237	(114)	253	(123)	Off
175	8095	(55800)	170	(77)	189	(87)	205	(96)	222	(106)	239	(115)	255	(124)	On
180	8095	(55800)	170	(77)	190	(88)	206	(97)	223	(106)	240	(116)	256	(124)	Off
190	8095	(55800)	170	(77)	190	(88)	208	(98)	225	(107)	242	(117)	258	(126)	On
195	8095	(55800)	170	(77)	190	(88)	209	(98)	226	(108)	243	(117)	259	(126)	Off
205	8095	(55800)	170	(77)	190	(88)	210	(99)	228	(109)	245	(118)	261	(127)	On
210	8095	(55800)	170	(77)	190	(88)	210	(99)	229	(109)	246	(119)	262	(128)	Off
220	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	248	(120)	264	(129)	On
225	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	249	(121)	265	(129)	Off
235	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	250	(121)	267	(131)	On
240	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	250	(121)	268	(131)	Off
250	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	250	(121)	270	(132)	On
255	8095	(55800)	170	(77)	190	(88)	210	(99)	230	(110)	250	(121)	270	(132)	Off
Segment 1:															
Ramp (Deg/min)			2.75	(1.53)	3.46	(1.92)	4.13	(2.29)	4.83	(2.68)	5.54	(3.08)	6.21	(3.45)	
Ramp Time			24 Minutes												
Temp. Dwell			21 Minutes												
Pressure Rate (per min)			200 psi (1379 kPa) for 24 minutes, then 95 psi (652 kPa) for 21 minutes												
Segment 2:															
Deg/min			0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	
Ramp Time			120	Minutes	135	Minutes	155	Minutes	170	Minutes	185	Minutes	205	Minutes	

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.44								
	Depth	12,000 ft	(3660 m)								Mud density: 12.4 lb/gal (1.49 kg/L)				
0	1500	(10300)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	1720	(11900)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	86	(30)	On
2	1940	(13400)	86	(30)	87	(31)	88	(31)	90	(32)	91	(33)	93	(34)	On
3	2160	(14900)	88	(31)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	On
4	2380	(16400)	91	(33)	94	(34)	97	(36)	100	(38)	103	(39)	105	(41)	On
5	2600	(17900)	94	(34)	98	(37)	101	(38)	105	(41)	108	(42)	112	(44)	On
6	2820	(19400)	97	(36)	101	(38)	105	(41)	110	(43)	114	(46)	118	(48)	On
7	3040	(21000)	100	(38)	105	(41)	110	(43)	115	(46)	120	(49)	124	(51)	On
8	3260	(22500)	103	(39)	108	(42)	114	(46)	119	(48)	125	(52)	131	(55)	On
9	3480	(24000)	105	(41)	112	(44)	118	(48)	124	(51)	131	(55)	137	(58)	On
10	3700	(25500)	108	(42)	116	(47)	122	(50)	129	(54)	137	(58)	143	(62)	On
11	3920	(27000)	111	(44)	119	(48)	127	(53)	134	(57)	142	(61)	150	(66)	On
12	4140	(28500)	114	(46)	123	(51)	131	(55)	139	(59)	148	(64)	156	(69)	On
13	4360	(30100)	117	(47)	126	(52)	135	(57)	144	(62)	154	(68)	162	(72)	On
14	4580	(31600)	120	(49)	130	(54)	139	(59)	149	(65)	159	(71)	169	(76)	On
15	4800	(33100)	122	(50)	133	(56)	144	(62)	154	(68)	165	(74)	175	(79)	On
16	5020	(34600)	125	(52)	137	(58)	148	(64)	159	(71)	170	(77)	182	(83)	On
17	5240	(36100)	128	(53)	140	(60)	152	(67)	164	(73)	176	(80)	188	(87)	On
18	5460	(37600)	131	(55)	144	(62)	156	(69)	169	(76)	182	(83)	194	(90)	On
19	5680	(39200)	134	(57)	147	(64)	161	(72)	174	(79)	187	(86)	201	(94)	On
20	5900	(40700)	137	(58)	151	(66)	165	(74)	179	(82)	193	(89)	207	(97)	On
21	6120	(42200)	139	(59)	155	(68)	169	(76)	184	(84)	199	(93)	213	(101)	On
22	6340	(43700)	142	(61)	158	(70)	173	(78)	188	(87)	204	(96)	220	(104)	On
23	6560	(45200)	145	(63)	162	(72)	178	(81)	193	(89)	210	(99)	226	(108)	On
24	6780	(46700)	148	(64)	165	(74)	182	(83)	198	(92)	216	(102)	232	(111)	On
25	7000	(48300)	151	(66)	169	(76)	186	(86)	203	(95)	221	(105)	239	(115)	On
26	7220	(49800)	154	(68)	172	(78)	190	(88)	208	(98)	227	(108)	245	(118)	On
27	7440	(51300)	156	(69)	176	(80)	195	(91)	213	(101)	233	(112)	251	(122)	On
28	7660	(52800)	159	(71)	179	(82)	199	(93)	218	(103)	238	(114)	258	(126)	On
29	7880	(54300)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
30	7985	(55100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
31	8090	(55800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
32	8195	(56500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
33	8300	(57200)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
34	8405	(58000)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
35	8510	(58700)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
36	8615	(59400)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
37	8720	(60100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
38	8825	(60800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
39	8930	(61600)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
40	9035	(62300)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
41	9140	(63000)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
42	9245	(63700)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
43	9350	(64500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
44	9455	(65200)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
45	9560	(65900)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
46	9665	(66600)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
47	9770	(67400)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
48	9875	(68100)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
49	9980	(68800)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	On
50	10085	(69500)	162	(72)	183	(84)	203	(95)	223	(106)	244	(118)	264	(129)	Off
60	10085	(69500)	164	(73)	185	(85)	205	(96)	225	(107)	246	(119)	266	(130)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

Temperature Gradient, °F/100 ft depth (°C/100 m depth)
Temperature, °F (°C)
Schedule 9.44 (Continued)

1	2		3		4		5		6		7		8		9
Time, Min	Pressure psi	Pressure (kPa)	0.9 °F	(1.6) (°C)	1.1 °F	(2.0) (°C)	1.3 °F	(2.4) (°C)	1.5 °F	(2.7) (°C)	1.7 °F	(3.1) (°C)	1.9 °F	(3.5) (°C)	Stirring
65	10085	(69500)	165	(74)	186	(86)	206	(97)	226	(108)	247	(119)	267	(131)	Off
75	10085	(69500)	167	(75)	188	(87)	208	(98)	228	(109)	249	(121)	269	(132)	On
80	10085	(69500)	168	(76)	189	(87)	209	(98)	229	(109)	250	(121)	270	(132)	Off
90	10085	(69500)	170	(77)	191	(88)	211	(99)	231	(111)	252	(122)	272	(133)	On
95	10085	(69500)	171	(77)	192	(89)	212	(100)	232	(111)	253	(123)	273	(134)	Off
105	10085	(69500)	173	(78)	194	(90)	214	(101)	234	(112)	255	(124)	275	(135)	On
110	10085	(69500)	174	(79)	195	(91)	215	(102)	235	(113)	256	(124)	276	(136)	Off
120	10085	(69500)	176	(80)	197	(92)	217	(103)	237	(114)	258	(126)	278	(137)	On
125	10085	(69500)	177	(81)	198	(92)	218	(103)	238	(114)	259	(126)	279	(137)	Off
135	10085	(69500)	179	(82)	200	(93)	220	(104)	240	(116)	261	(127)	281	(138)	On
140	10085	(69500)	180	(82)	201	(94)	221	(105)	241	(116)	262	(128)	282	(139)	Off
150	10085	(69500)	182	(83)	203	(95)	223	(106)	243	(117)	264	(129)	284	(140)	On
155	10085	(69500)	183	(84)	204	(96)	224	(107)	244	(118)	265	(129)	285	(141)	Off
165	10085	(69500)	185	(85)	206	(97)	226	(108)	246	(119)	267	(131)	287	(142)	On
170	10085	(69500)	186	(86)	207	(97)	227	(108)	247	(119)	268	(131)	288	(142)	Off
180	10085	(69500)	188	(87)	209	(98)	229	(109)	249	(121)	270	(132)	290	(143)	On
185	10085	(69500)	188	(87)	210	(99)	230	(110)	250	(121)	271	(133)	291	(144)	Off
195	10085	(69500)	188	(87)	212	(100)	232	(111)	252	(122)	273	(134)	293	(145)	On
200	10085	(69500)	188	(87)	212	(100)	233	(112)	253	(123)	274	(134)	294	(146)	Off
210	10085	(69500)	188	(87)	212	(100)	235	(113)	255	(124)	276	(136)	296	(147)	On
215	10085	(69500)	188	(87)	212	(100)	236	(113)	256	(124)	277	(136)	297	(147)	Off
225	10085	(69500)	188	(87)	212	(100)	236	(113)	258	(126)	279	(137)	299	(148)	On
230	10085	(69500)	188	(87)	212	(100)	236	(113)	259	(126)	280	(138)	300	(149)	Off
240	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	282	(139)	302	(150)	On
245	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	283	(139)	303	(151)	Off
255	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	284	(140)	305	(152)	On
260	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	284	(140)	306	(152)	Off
270	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	284	(140)	308	(153)	On
275	10085	(69500)	188	(87)	212	(100)	236	(113)	260	(127)	284	(140)	308	(153)	Off

Segment 1:												
Ramp (Deg/min)	2.83	(1.57)	3.55	(1.97)	4.24	(2.36)	4.93	(2.74)	5.66	(3.14)	6.34	(3.52)
Ramp Time	29 Minutes											
Temp. Dwell	21 Minutes											
Pressure Rate (per min)	220 psi (1517 kPa) for 29 minutes, then 105 (724 kPa) psi for 21 minutes											
Segment 2:												
Deg/min	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	130	Minutes	145	Minutes	165	Minutes	185	Minutes	200	Minutes	220	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.45								
	Depth	14,000 ft	(4270 m)								Mud density: 13.3 lb/gal (1.59 kg/L)				
0	1800	(12400)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	2035	(14000)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	86	(30)	On
2	2270	(15700)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	93	(34)	On
3	2505	(17300)	89	(32)	91	(33)	93	(34)	95	(35)	97	(36)	99	(37)	On
4	2740	(18900)	92	(33)	95	(35)	97	(36)	100	(38)	103	(39)	106	(41)	On
5	2975	(20500)	95	(35)	98	(37)	102	(39)	105	(41)	109	(43)	112	(44)	On
6	3210	(22100)	97	(36)	102	(39)	106	(41)	110	(43)	115	(46)	119	(48)	On
7	3445	(23800)	100	(38)	106	(41)	110	(43)	115	(46)	120	(49)	125	(52)	On
8	3680	(25400)	103	(39)	109	(43)	115	(46)	120	(49)	126	(52)	132	(56)	On
9	3915	(27000)	106	(41)	113	(45)	119	(48)	126	(52)	132	(56)	138	(59)	On
10	4150	(28600)	109	(43)	116	(47)	124	(51)	131	(55)	138	(59)	145	(63)	On
11	4385	(30200)	112	(44)	120	(49)	128	(53)	136	(58)	143	(62)	151	(66)	On
12	4620	(31900)	115	(46)	124	(51)	132	(56)	141	(61)	149	(65)	158	(70)	On
13	4855	(33500)	118	(48)	127	(53)	137	(58)	146	(63)	155	(68)	164	(73)	On
14	5090	(35100)	121	(49)	131	(55)	141	(61)	151	(66)	161	(72)	171	(77)	On
15	5325	(36700)	124	(51)	135	(57)	145	(63)	156	(69)	166	(74)	177	(81)	On
16	5560	(38300)	127	(53)	138	(59)	150	(66)	161	(72)	172	(78)	184	(84)	On
17	5795	(40000)	130	(54)	142	(61)	154	(68)	166	(74)	178	(81)	190	(88)	On
18	6030	(41600)	132	(56)	146	(63)	158	(70)	171	(77)	184	(84)	196	(91)	On
19	6265	(43200)	135	(57)	149	(65)	163	(73)	176	(80)	190	(88)	203	(95)	On
20	6500	(44800)	138	(59)	153	(67)	167	(75)	181	(83)	195	(91)	209	(98)	On
21	6735	(46400)	141	(61)	157	(69)	171	(77)	186	(86)	201	(94)	216	(102)	On
22	6970	(48100)	144	(62)	160	(71)	176	(80)	191	(88)	207	(97)	222	(106)	On
23	7205	(49700)	147	(64)	164	(73)	180	(82)	196	(91)	213	(101)	229	(109)	On
24	7440	(51300)	150	(66)	168	(76)	184	(84)	201	(94)	218	(103)	235	(113)	On
25	7675	(52900)	153	(67)	171	(77)	189	(87)	206	(97)	224	(107)	242	(117)	On
26	7910	(54500)	156	(69)	175	(79)	193	(89)	212	(100)	230	(110)	248	(120)	On
27	8145	(56200)	159	(71)	178	(81)	198	(92)	217	(103)	236	(113)	255	(124)	On
28	8380	(57800)	162	(72)	182	(83)	202	(94)	222	(106)	241	(116)	261	(127)	On
29	8615	(59400)	164	(73)	186	(86)	206	(97)	227	(108)	247	(119)	268	(131)	On
30	8850	(61000)	167	(75)	189	(87)	211	(99)	232	(111)	253	(123)	274	(134)	On
31	9085	(62600)	170	(77)	193	(89)	215	(102)	237	(114)	259	(126)	281	(138)	On
32	9320	(64300)	173	(78)	197	(92)	219	(104)	242	(117)	264	(129)	287	(142)	On
33	9555	(65900)	176	(80)	200	(93)	224	(107)	247	(119)	270	(132)	294	(146)	On
34	9790	(67500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
35	9895	(68200)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
36	10000	(69000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
37	10105	(69700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
38	10210	(70400)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
39	10315	(71100)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
40	10420	(71800)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
41	10525	(72600)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
42	10630	(73300)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
43	10735	(74000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
44	10840	(74700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
45	10945	(75500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
46	11050	(76200)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
47	11155	(76900)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
48	11260	(77600)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
49	11365	(78400)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8	9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.45 (Continued)	
	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Time, Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
50	11470	(79100)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
51	11575	(79800)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
52	11680	(80500)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
53	11785	(81300)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
54	11890	(82000)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
55	11995	(82700)	179	(82)	204	(96)	228	(109)	252	(122)	276	(136)	300	(149)	Off
65	11995	(82700)	181	(83)	206	(97)	230	(110)	254	(123)	278	(137)	302	(150)	On
70	11995	(82700)	182	(83)	207	(97)	231	(111)	255	(124)	279	(137)	303	(151)	Off
80	11995	(82700)	184	(84)	209	(98)	233	(112)	257	(125)	281	(138)	305	(152)	On
85	11995	(82700)	185	(85)	210	(99)	234	(112)	258	(126)	282	(139)	306	(152)	Off
95	11995	(82700)	187	(86)	212	(100)	236	(113)	260	(127)	284	(140)	308	(153)	On
100	11995	(82700)	188	(87)	213	(101)	237	(114)	261	(127)	285	(141)	309	(154)	Off
110	11995	(82700)	190	(88)	215	(102)	239	(115)	263	(128)	287	(142)	311	(155)	On
115	11995	(82700)	191	(88)	216	(102)	240	(116)	264	(129)	288	(142)	312	(156)	Off
125	11995	(82700)	193	(89)	218	(103)	242	(117)	266	(130)	290	(143)	314	(157)	On
130	11995	(82700)	194	(90)	219	(104)	243	(117)	267	(131)	291	(144)	315	(157)	Off
140	11995	(82700)	196	(91)	221	(105)	245	(118)	269	(132)	293	(145)	317	(158)	On
145	11995	(82700)	197	(92)	222	(106)	246	(119)	270	(132)	294	(146)	318	(159)	Off
155	11995	(82700)	199	(93)	224	(107)	248	(120)	272	(133)	296	(147)	320	(160)	On
160	11995	(82700)	200	(93)	225	(107)	249	(121)	273	(134)	297	(147)	321	(161)	Off
170	11995	(82700)	202	(94)	227	(108)	251	(122)	275	(135)	299	(148)	323	(162)	On
175	11995	(82700)	203	(95)	228	(109)	252	(122)	276	(136)	300	(149)	324	(162)	Off
185	11995	(82700)	205	(96)	230	(110)	254	(123)	278	(137)	302	(150)	326	(163)	On
190	11995	(82700)	206	(97)	231	(111)	255	(124)	279	(137)	303	(151)	327	(164)	Off
200	11995	(82700)	206	(97)	233	(112)	257	(125)	281	(138)	305	(152)	329	(165)	On
205	11995	(82700)	206	(97)	234	(112)	258	(126)	282	(139)	306	(152)	330	(166)	Off
215	11995	(82700)	206	(97)	234	(112)	260	(127)	284	(140)	308	(153)	332	(167)	On
220	11995	(82700)	206	(97)	234	(112)	261	(127)	285	(141)	309	(154)	333	(167)	Off
230	11995	(82700)	206	(97)	234	(112)	262	(128)	287	(142)	311	(155)	335	(168)	On
235	11995	(82700)	206	(97)	234	(112)	262	(128)	288	(142)	312	(156)	336	(169)	Off
245	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	314	(157)	338	(170)	On
250	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	315	(157)	339	(171)	Off
260	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	317	(158)	341	(172)	On
265	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	342	(172)	Off
275	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	344	(173)	On
280	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	345	(174)	Off
290	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	346	(174)	On
295	11995	(82700)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	346	(174)	Off
Segment 1:															
Ramp (Deg/min)			2.91	(1.62)	3.65	(2.03)	4.35	(2.42)	5.06	(2.81)	5.76	(3.20)	6.47	(3.59)	
Ramp Time			34 Minutes												
Temp. Dwell			21 Minutes												
Pressure Rate (per min)			235 psi (1621 kPa) for 34 minutes, then 105 psi (724 kPa) for 21 minutes												
Segment 2:															
Deg/min			0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	
Ramp Time			135	Minutes	150	Minutes	170	Minutes	190	Minutes	210	Minutes	230	Minutes	

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

Temperature Gradient, °F/100 ft depth (°C/100 m depth)
Temperature, °F (°C)

Schedule 9.46

Depth 16,000 ft (4880 m) Mud density: 14.4 lb/gal (1.73 kg/L)

1	2		3		4		5		6		7		8		9
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
0	2000	(13800)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	2255	(15500)	83	(28)	84	(29)	84	(29)	85	(29)	86	(30)	87	(31)	On
2	2510	(17300)	86	(30)	87	(31)	89	(32)	90	(32)	92	(33)	93	(34)	On
3	2765	(19100)	89	(32)	91	(33)	93	(34)	95	(35)	98	(37)	100	(38)	On
4	3020	(20800)	92	(33)	95	(35)	98	(37)	101	(38)	103	(39)	106	(41)	On
5	3275	(22600)	95	(35)	99	(37)	102	(39)	106	(41)	109	(43)	113	(45)	On
6	3530	(24300)	98	(37)	102	(39)	107	(42)	111	(44)	115	(46)	120	(49)	On
7	3785	(26100)	101	(38)	106	(41)	111	(44)	116	(47)	121	(49)	126	(52)	On
8	4040	(27900)	104	(40)	110	(43)	115	(46)	121	(49)	127	(53)	133	(56)	On
9	4295	(29600)	107	(42)	113	(45)	120	(49)	126	(52)	133	(56)	140	(60)	On
10	4550	(31400)	110	(43)	117	(47)	124	(51)	132	(56)	139	(59)	146	(63)	On
11	4805	(33100)	113	(45)	121	(49)	129	(54)	137	(58)	145	(63)	153	(67)	On
12	5060	(34900)	116	(47)	125	(52)	133	(56)	142	(61)	150	(66)	159	(71)	On
13	5315	(36600)	119	(48)	128	(53)	138	(59)	147	(64)	156	(69)	166	(74)	On
14	5570	(38400)	122	(50)	132	(56)	142	(61)	152	(67)	162	(72)	173	(78)	On
15	5825	(40200)	125	(52)	136	(58)	147	(64)	157	(69)	168	(76)	179	(82)	On
16	6080	(41900)	128	(53)	139	(59)	151	(66)	162	(72)	174	(79)	186	(86)	On
17	6335	(43700)	131	(55)	143	(62)	155	(68)	168	(76)	180	(82)	192	(89)	On
18	6590	(45400)	134	(57)	147	(64)	160	(71)	173	(78)	186	(86)	199	(93)	On
19	6845	(47200)	137	(58)	151	(66)	164	(73)	178	(81)	192	(89)	206	(97)	On
20	7100	(49000)	140	(60)	154	(68)	169	(76)	183	(84)	197	(92)	212	(100)	On
21	7355	(50700)	143	(62)	158	(70)	173	(78)	188	(87)	203	(95)	219	(104)	On
22	7610	(52500)	146	(63)	162	(72)	178	(81)	193	(89)	209	(98)	226	(108)	On
23	7865	(54200)	149	(65)	166	(74)	182	(83)	199	(93)	215	(102)	232	(111)	On
24	8120	(56000)	152	(67)	169	(76)	186	(86)	204	(96)	221	(105)	239	(115)	On
25	8375	(57700)	155	(68)	173	(78)	191	(88)	209	(98)	227	(108)	245	(118)	On
26	8630	(59500)	158	(70)	177	(81)	195	(91)	214	(101)	233	(112)	252	(122)	On
27	8885	(61300)	161	(72)	180	(82)	200	(93)	219	(104)	239	(115)	259	(126)	On
28	9140	(63000)	164	(73)	184	(84)	204	(96)	224	(107)	244	(118)	265	(129)	On
29	9395	(64800)	167	(75)	188	(87)	209	(98)	229	(109)	250	(121)	272	(133)	On
30	9650	(66500)	170	(77)	192	(89)	213	(101)	235	(113)	256	(124)	278	(137)	On
31	9905	(68300)	173	(78)	195	(91)	218	(103)	240	(116)	262	(128)	285	(141)	On
32	10160	(70100)	176	(80)	199	(93)	222	(106)	245	(118)	268	(131)	292	(144)	On
33	10415	(71800)	179	(82)	203	(95)	226	(108)	250	(121)	274	(134)	298	(148)	On
34	10670	(73600)	182	(83)	206	(97)	231	(111)	255	(124)	280	(138)	305	(152)	On
35	10925	(75300)	185	(85)	210	(99)	235	(113)	260	(127)	286	(141)	312	(156)	On
36	11180	(77100)	188	(87)	214	(101)	240	(116)	266	(130)	291	(144)	318	(159)	On
37	11435	(78800)	191	(88)	218	(103)	244	(118)	271	(133)	297	(147)	325	(163)	On
38	11690	(80600)	194	(90)	221	(105)	249	(121)	276	(136)	303	(151)	331	(166)	On
39	11945	(82400)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
40	12085	(83300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
41	12225	(84300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
42	12365	(85300)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
43	12505	(86200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
44	12645	(87200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
45	12785	(88200)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
46	12925	(89100)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
47	13065	(90100)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
48	13205	(91000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
49	13345	(92000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.46 (Continued)		
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
50	13485	(93000)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
51	13625	(93900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
52	13765	(94900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
53	13905	(95900)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
54	14045	(96800)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	On
55	14185	(97800)	197	(92)	225	(107)	253	(123)	281	(138)	309	(154)	338	(170)	Off
65	14185	(97800)	199	(93)	227	(108)	255	(124)	283	(139)	311	(155)	340	(171)	On
70	14185	(97800)	200	(93)	228	(109)	256	(124)	284	(140)	312	(156)	341	(172)	Off
80	14185	(97800)	202	(94)	230	(110)	258	(126)	286	(141)	314	(157)	343	(173)	On
85	14185	(97800)	203	(95)	231	(111)	259	(126)	287	(142)	315	(157)	344	(173)	Off
95	14185	(97800)	205	(96)	233	(112)	261	(127)	289	(143)	317	(158)	346	(174)	On
100	14185	(97800)	206	(97)	234	(112)	262	(128)	290	(143)	318	(159)	347	(175)	Off
110	14185	(97800)	208	(98)	236	(113)	264	(129)	292	(144)	320	(160)	349	(176)	On
115	14185	(97800)	209	(98)	237	(114)	265	(129)	293	(145)	321	(161)	350	(177)	Off
125	14185	(97800)	211	(99)	239	(115)	267	(131)	295	(146)	323	(162)	352	(178)	On
130	14185	(97800)	212	(100)	240	(116)	268	(131)	296	(147)	324	(162)	353	(178)	Off
140	14185	(97800)	214	(101)	242	(117)	270	(132)	298	(148)	326	(163)	355	(179)	On
145	14185	(97800)	215	(102)	243	(117)	271	(133)	299	(148)	327	(164)	356	(180)	Off
155	14185	(97800)	217	(103)	245	(118)	273	(134)	301	(149)	329	(165)	358	(181)	On
160	14185	(97800)	218	(103)	246	(119)	274	(134)	302	(150)	330	(166)	359	(182)	Off
170	14185	(97800)	220	(104)	248	(120)	276	(136)	304	(151)	332	(167)	361	(183)	On
175	14185	(97800)	221	(105)	249	(121)	277	(136)	305	(152)	333	(167)	362	(183)	Off
185	14185	(97800)	223	(106)	251	(122)	279	(137)	307	(153)	335	(168)	364	(184)	On
190	14185	(97800)	224	(107)	252	(122)	280	(138)	308	(153)	336	(169)	365	(185)	Off
200	14185	(97800)	224	(107)	254	(123)	282	(139)	310	(154)	338	(170)	367	(186)	On
205	14185	(97800)	224	(107)	255	(124)	283	(139)	311	(155)	339	(171)	368	(187)	Off
215	14185	(97800)	224	(107)	256	(124)	285	(141)	313	(156)	341	(172)	370	(188)	On
220	14185	(97800)	224	(107)	256	(124)	286	(141)	314	(157)	342	(172)	371	(188)	Off
230	14185	(97800)	224	(107)	256	(124)	288	(142)	316	(158)	344	(173)	373	(189)	On
235	14185	(97800)	224	(107)	256	(124)	288	(142)	317	(158)	345	(174)	374	(190)	Off
245	14185	(97800)	224	(107)	256	(124)	288	(142)	319	(159)	347	(175)	376	(191)	On
250	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	348	(176)	377	(192)	Off
260	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	350	(177)	379	(193)	On
265	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	351	(177)	380	(193)	Off
275	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	352	(178)	382	(194)	On
280	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	352	(178)	383	(195)	Off
290	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	352	(178)	384	(196)	On
295	14185	(97800)	224	(107)	256	(124)	288	(142)	320	(160)	352	(178)	384	(196)	Off

Segment 1:												
Ramp (Deg/min)	3.00	(1.67)	3.72	(2.07)	4.44	(2.47)	5.15	(2.86)	5.87	(3.26)	6.62	(3.68)
Ramp Time	39 Minutes											
Temp. Dwell	16 Minutes											
Pressure Rate (per min)	255 psi (1759 kPa) for 39 minutes, then 140 psi (963 kPa) for 16 minutes											
Segment 2:												
Deg/min	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	135	Minutes	155	Minutes	175	Minutes	195	Minutes	215	Minutes	230	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.47								
	Depth	18,000 ft	(5490 m)								Mud density: 15.6 lb/gal (1.87 kg/L)				
0	2200	(15200)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	2475	(17100)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	87	(31)	On
2	2750	(19000)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	93	(34)	On
3	3025	(20900)	89	(32)	91	(33)	94	(34)	96	(36)	98	(37)	100	(38)	On
4	3300	(22800)	92	(33)	95	(35)	98	(37)	101	(38)	104	(40)	107	(42)	On
5	3575	(24600)	95	(35)	99	(37)	103	(39)	106	(41)	110	(43)	114	(46)	On
6	3850	(26500)	98	(37)	103	(39)	107	(42)	112	(44)	116	(47)	120	(49)	On
7	4125	(28400)	101	(38)	107	(42)	112	(44)	117	(47)	122	(50)	127	(53)	On
8	4400	(30300)	105	(41)	111	(44)	116	(47)	122	(50)	128	(53)	134	(57)	On
9	4675	(32200)	108	(42)	114	(46)	121	(49)	127	(53)	134	(57)	141	(61)	On
10	4950	(34100)	111	(44)	118	(48)	125	(52)	133	(56)	140	(60)	147	(64)	On
11	5225	(36000)	114	(46)	122	(50)	130	(54)	138	(59)	146	(63)	154	(68)	On
12	5500	(37900)	117	(47)	126	(52)	135	(57)	143	(62)	152	(67)	161	(72)	On
13	5775	(39800)	120	(49)	130	(54)	139	(59)	149	(65)	158	(70)	167	(75)	On
14	6050	(41700)	123	(51)	133	(56)	144	(62)	154	(68)	164	(73)	174	(79)	On
15	6325	(43600)	126	(52)	137	(58)	148	(64)	159	(71)	170	(77)	181	(83)	On
16	6600	(45500)	129	(54)	141	(61)	153	(67)	164	(73)	176	(80)	188	(87)	On
17	6875	(47400)	132	(56)	145	(63)	157	(69)	170	(77)	182	(83)	194	(90)	On
18	7150	(49300)	135	(57)	149	(65)	162	(72)	175	(79)	188	(87)	201	(94)	On
19	7425	(51200)	138	(59)	153	(67)	166	(74)	180	(82)	194	(90)	208	(98)	On
20	7700	(53100)	141	(61)	156	(69)	171	(77)	185	(85)	200	(93)	215	(102)	On
21	7975	(55000)	144	(62)	160	(71)	175	(79)	191	(88)	206	(97)	221	(105)	On
22	8250	(56900)	148	(64)	164	(73)	180	(82)	196	(91)	212	(100)	228	(109)	On
23	8525	(58800)	151	(66)	168	(76)	185	(85)	201	(94)	218	(103)	235	(113)	On
24	8800	(60700)	154	(68)	172	(78)	189	(87)	207	(97)	224	(107)	241	(116)	On
25	9075	(62600)	157	(69)	175	(79)	194	(90)	212	(100)	230	(110)	248	(120)	On
26	9350	(64500)	160	(71)	179	(82)	198	(92)	217	(103)	236	(113)	255	(124)	On
27	9625	(66400)	163	(73)	183	(84)	203	(95)	222	(106)	242	(117)	262	(128)	On
28	9900	(68300)	166	(74)	187	(86)	207	(97)	228	(109)	248	(120)	268	(131)	On
29	10175	(70200)	169	(76)	191	(88)	212	(100)	233	(112)	254	(123)	275	(135)	On
30	10450	(72100)	172	(78)	195	(91)	216	(102)	238	(114)	260	(127)	282	(139)	On
31	10725	(73900)	175	(79)	198	(92)	221	(105)	243	(117)	266	(130)	289	(143)	On
32	11000	(75800)	178	(81)	202	(94)	225	(107)	249	(121)	272	(133)	295	(146)	On
33	11275	(77700)	181	(83)	206	(97)	230	(110)	254	(123)	278	(137)	302	(150)	On
34	11550	(79600)	184	(84)	210	(99)	235	(113)	259	(126)	284	(140)	309	(154)	On
35	11825	(81500)	187	(86)	214	(101)	239	(115)	265	(129)	290	(143)	315	(157)	On
36	12100	(83400)	190	(88)	217	(103)	244	(118)	270	(132)	296	(147)	322	(161)	On
37	12375	(85300)	194	(90)	221	(105)	248	(120)	275	(135)	302	(150)	329	(165)	On
38	12650	(87200)	197	(92)	225	(107)	253	(123)	280	(138)	308	(153)	336	(169)	On
39	12925	(89100)	200	(93)	229	(109)	257	(125)	286	(141)	314	(157)	342	(172)	On
40	13200	(91000)	203	(95)	233	(112)	262	(128)	291	(144)	320	(160)	349	(176)	On
41	13475	(92900)	206	(97)	237	(114)	266	(130)	296	(147)	326	(163)	356	(180)	On
42	13750	(94800)	209	(98)	240	(116)	271	(133)	301	(149)	332	(167)	363	(184)	On
43	14025	(96700)	212	(100)	244	(118)	275	(135)	307	(153)	338	(170)	369	(187)	On
44	14300	(98600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
45	14435	(99500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
46	14570	(100500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
47	14705	(101400)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
48	14840	(102300)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
49	14975	(103300)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

Temperature Gradient, °F/100 ft depth (°C/100 m depth)

Temperature, °F (°C)

Schedule 9.47 (Continued)

1	2		3		4		5		6		7		8		9
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
50	15110	(104200)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
51	15245	(105100)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
52	15380	(106000)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
53	15515	(107000)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
54	15650	(107900)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
55	15785	(108800)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
56	15920	(109800)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
57	16055	(110700)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
58	16190	(111600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
59	16325	(112600)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	On
60	16460	(113500)	215	(102)	248	(120)	280	(138)	312	(156)	344	(173)	376	(191)	Off
70	16460	(113500)	217	(103)	250	(121)	282	(139)	314	(157)	346	(174)	378	(192)	On
75	16460	(113500)	218	(103)	251	(122)	283	(139)	315	(157)	347	(175)	379	(193)	Off
85	16460	(113500)	220	(104)	253	(123)	285	(141)	317	(158)	349	(176)	381	(194)	On
90	16460	(113500)	221	(105)	254	(123)	286	(141)	318	(159)	350	(177)	382	(194)	Off
100	16460	(113500)	223	(106)	256	(124)	288	(142)	320	(160)	352	(178)	384	(196)	On
105	16460	(113500)	224	(107)	257	(125)	289	(143)	321	(161)	353	(178)	385	(196)	Off
115	16460	(113500)	226	(108)	259	(126)	291	(144)	323	(162)	355	(179)	387	(197)	On
120	16460	(113500)	227	(108)	260	(127)	292	(144)	324	(162)	356	(180)	388	(198)	Off
130	16460	(113500)	229	(109)	262	(128)	294	(146)	326	(163)	358	(181)	390	(199)	On
135	16460	(113500)	230	(110)	263	(128)	295	(146)	327	(164)	359	(182)	391	(199)	Off
145	16460	(113500)	232	(111)	265	(129)	297	(147)	329	(165)	361	(183)	393	(201)	On
150	16460	(113500)	233	(112)	266	(130)	298	(148)	330	(166)	362	(183)	394	(201)	Off
160	16460	(113500)	235	(113)	268	(131)	300	(149)	332	(167)	364	(184)	396	(202)	On
165	16460	(113500)	236	(113)	269	(132)	301	(149)	333	(167)	365	(185)	397	(203)	Off
175	16460	(113500)	238	(114)	271	(133)	303	(151)	335	(168)	367	(186)	399	(204)	On
180	16460	(113500)	239	(115)	272	(133)	304	(151)	336	(169)	368	(187)	400	(204)	Off
190	16460	(113500)	241	(116)	274	(134)	306	(152)	338	(170)	370	(188)	402	(206)	On
195	16460	(113500)	242	(117)	275	(135)	307	(153)	339	(171)	371	(188)	403	(206)	Off
205	16460	(113500)	242	(117)	277	(136)	309	(154)	341	(172)	373	(189)	405	(207)	On
210	16460	(113500)	242	(117)	278	(137)	310	(154)	342	(172)	374	(190)	406	(208)	Off
220	16460	(113500)	242	(117)	278	(137)	312	(156)	344	(173)	376	(191)	408	(209)	On
225	16460	(113500)	242	(117)	278	(137)	313	(156)	345	(174)	377	(192)	409	(209)	Off
235	16460	(113500)	242	(117)	278	(137)	314	(157)	347	(175)	379	(193)	411	(211)	On
240	16460	(113500)	242	(117)	278	(137)	314	(157)	348	(176)	380	(193)	412	(211)	Off
250	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	382	(194)	414	(212)	On
255	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	383	(195)	415	(213)	Off
265	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	385	(196)	417	(214)	On
270	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	418	(214)	Off
280	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	420	(216)	On
285	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	421	(216)	Off
295	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	422	(217)	On
300	16460	(113500)	242	(117)	278	(137)	314	(157)	350	(177)	386	(197)	422	(217)	Off

Segment 1:												
Ramp (Deg/min)	3.07	(1.71)	3.82	(2.12)	4.55	(2.53)	5.27	(2.93)	6.00	(3.33)	6.73	(3.74)
Ramp Time	44 Minutes											
Temp. Dwell	16 Minutes											
Pressure Rate (per min)	275 psi (1895 kPa) for 44 minutes, then 135 psi (931 kPa) for 16 minutes											
Segment 2:												
Deg/min	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	135	Minutes	150	Minutes	170	Minutes	190	Minutes	210	Minutes	235	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
			Schedule 9.48												
	Depth	20,000 ft	(6095 m)								Mud density: 16.9 lb/gal (2.03 kg/L)				
0	2400	(16500)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	2695	(18600)	83	(28)	84	(29)	85	(29)	85	(29)	86	(30)	87	(31)	On
2	2990	(20600)	86	(30)	88	(31)	89	(32)	91	(33)	92	(33)	94	(34)	On
3	3285	(22700)	89	(32)	92	(33)	94	(34)	96	(36)	98	(37)	101	(38)	On
4	3580	(24700)	93	(34)	96	(36)	99	(37)	102	(39)	104	(40)	108	(42)	On
5	3875	(26700)	96	(36)	99	(37)	103	(39)	107	(42)	111	(44)	114	(46)	On
6	4170	(28800)	99	(37)	103	(39)	108	(42)	112	(44)	117	(47)	121	(49)	On
7	4465	(30800)	102	(39)	107	(42)	112	(44)	118	(48)	123	(51)	128	(53)	On
8	4760	(32800)	105	(41)	111	(44)	117	(47)	123	(51)	129	(54)	135	(57)	On
9	5055	(34900)	108	(42)	115	(46)	122	(50)	128	(53)	135	(57)	142	(61)	On
10	5350	(36900)	111	(44)	119	(48)	126	(52)	134	(57)	141	(61)	149	(65)	On
11	5645	(38900)	115	(46)	123	(51)	131	(55)	139	(59)	147	(64)	156	(69)	On
12	5940	(41000)	118	(48)	127	(53)	136	(58)	145	(63)	153	(67)	163	(73)	On
13	6235	(43000)	121	(49)	131	(55)	140	(60)	150	(66)	160	(71)	169	(76)	On
14	6530	(45000)	124	(51)	135	(57)	145	(63)	155	(68)	166	(74)	176	(80)	On
15	6825	(47100)	127	(53)	138	(59)	149	(65)	161	(72)	172	(78)	183	(84)	On
16	7120	(49100)	130	(54)	142	(61)	154	(68)	166	(74)	178	(81)	190	(88)	On
17	7415	(51100)	133	(56)	146	(63)	159	(71)	172	(78)	184	(84)	197	(92)	On
18	7710	(53200)	137	(58)	150	(66)	163	(73)	177	(81)	190	(88)	204	(96)	On
19	8005	(55200)	140	(60)	154	(68)	168	(76)	182	(83)	196	(91)	211	(99)	On
20	8300	(57200)	143	(62)	158	(70)	173	(78)	188	(87)	202	(94)	218	(103)	On
21	8595	(59300)	146	(63)	162	(72)	177	(81)	193	(89)	209	(98)	224	(107)	On
22	8890	(61300)	149	(65)	166	(74)	182	(83)	199	(93)	215	(102)	231	(111)	On
23	9185	(63300)	152	(67)	170	(77)	187	(86)	204	(96)	221	(105)	238	(114)	On
24	9480	(65400)	155	(68)	174	(79)	191	(88)	209	(98)	227	(108)	245	(118)	On
25	9775	(67400)	159	(71)	177	(81)	196	(91)	215	(102)	233	(112)	252	(122)	On
26	10070	(69400)	162	(72)	181	(83)	200	(93)	220	(104)	239	(115)	259	(126)	On
27	10365	(71500)	165	(74)	185	(85)	205	(96)	225	(107)	245	(118)	266	(130)	On
28	10660	(73500)	168	(76)	189	(87)	210	(99)	231	(111)	251	(122)	273	(134)	On
29	10955	(75500)	171	(77)	193	(89)	214	(101)	236	(113)	258	(126)	279	(137)	On
30	11250	(77600)	174	(79)	197	(92)	219	(104)	242	(117)	264	(129)	286	(141)	On
31	11545	(79600)	177	(81)	201	(94)	224	(107)	247	(119)	270	(132)	293	(145)	On
32	11840	(81600)	181	(83)	205	(96)	228	(109)	252	(122)	276	(136)	300	(149)	On
33	12135	(83700)	184	(84)	209	(98)	233	(112)	258	(126)	282	(139)	307	(153)	On
34	12430	(85700)	187	(86)	213	(101)	238	(114)	263	(128)	288	(142)	314	(157)	On
35	12725	(87700)	190	(88)	216	(102)	242	(117)	269	(132)	294	(146)	321	(161)	On
36	13020	(89800)	193	(89)	220	(104)	247	(119)	274	(134)	300	(149)	328	(164)	On
37	13315	(91800)	196	(91)	224	(107)	251	(122)	279	(137)	307	(153)	334	(168)	On
38	13610	(93800)	199	(93)	228	(109)	256	(124)	285	(141)	313	(156)	341	(172)	On
39	13905	(95900)	203	(95)	232	(111)	261	(127)	290	(143)	319	(159)	348	(176)	On
40	14200	(97900)	206	(97)	236	(113)	265	(129)	296	(147)	325	(163)	355	(179)	On
41	14495	(99900)	209	(98)	240	(116)	270	(132)	301	(149)	331	(166)	362	(183)	On
42	14790	(102000)	212	(100)	244	(118)	275	(135)	306	(152)	337	(169)	369	(187)	On
43	15085	(104000)	215	(102)	248	(120)	279	(137)	312	(156)	343	(173)	376	(191)	On
44	15380	(106000)	218	(103)	252	(122)	284	(140)	317	(158)	349	(176)	383	(195)	On
45	15675	(108100)	221	(105)	255	(124)	288	(142)	322	(161)	356	(180)	389	(198)	On
46	15970	(110100)	225	(107)	259	(126)	293	(145)	328	(164)	362	(183)	396	(202)	On
47	16265	(112100)	228	(109)	263	(128)	298	(148)	333	(167)	368	(187)	403	(206)	On
48	16560	(114200)	231	(111)	267	(131)	302	(150)	339	(171)	374	(190)	410	(210)	On
49	16855	(116200)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
50	17030	(117400)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

Temperature Gradient, °F/100 ft depth (°C/100 m depth)
Temperature, °F (°C)

Schedule 9.48 (Continued)

1	2		3		4		5		6		7		8		9
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
51	17205	(118600)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
52	17380	(119800)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
53	17555	(121000)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
54	17730	(122200)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
55	17905	(123500)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
56	18080	(124700)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
57	18255	(125900)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
58	18430	(127100)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
59	18605	(128300)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	On
60	18780	(129500)	234	(112)	271	(133)	307	(153)	344	(173)	380	(193)	417	(214)	Off
70	18780	(129500)	236	(113)	273	(134)	309	(154)	346	(174)	382	(194)	419	(215)	On
75	18780	(129500)	237	(114)	274	(134)	310	(154)	347	(175)	383	(195)	420	(216)	Off
85	18780	(129500)	239	(115)	276	(136)	312	(156)	349	(176)	385	(196)	422	(217)	On
90	18780	(129500)	240	(116)	277	(136)	313	(156)	350	(177)	386	(197)	423	(217)	Off
100	18780	(129500)	242	(117)	279	(137)	315	(157)	352	(178)	388	(198)	425	(218)	On
105	18780	(129500)	243	(117)	280	(138)	316	(158)	353	(178)	389	(198)	426	(219)	Off
115	18780	(129500)	245	(118)	282	(139)	318	(159)	354	(179)	391	(199)	428	(220)	On
120	18780	(129500)	246	(119)	283	(139)	319	(159)	356	(180)	392	(200)	429	(221)	Off
130	18780	(129500)	248	(120)	285	(141)	321	(161)	357	(181)	394	(201)	431	(222)	On
135	18780	(129500)	249	(121)	286	(141)	322	(161)	359	(182)	395	(202)	432	(222)	Off
145	18780	(129500)	251	(122)	288	(142)	324	(162)	360	(183)	397	(203)	434	(223)	On
150	18780	(129500)	252	(122)	289	(143)	325	(163)	362	(183)	398	(203)	435	(224)	Off
160	18780	(129500)	254	(123)	291	(144)	327	(164)	364	(184)	400	(204)	437	(225)	On
165	18780	(129500)	255	(124)	292	(144)	328	(164)	365	(185)	401	(205)	438	(226)	Off
175	18780	(129500)	257	(125)	294	(146)	330	(166)	367	(186)	403	(206)	440	(227)	On
180	18780	(129500)	258	(126)	295	(146)	331	(166)	368	(187)	404	(207)	441	(227)	Off
190	18780	(129500)	260	(127)	297	(147)	333	(167)	370	(188)	406	(208)	443	(228)	On
195	18780	(129500)	260	(127)	298	(148)	334	(168)	371	(188)	407	(208)	444	(229)	Off
205	18780	(129500)	260	(127)	300	(149)	336	(169)	373	(189)	409	(209)	446	(230)	On
210	18780	(129500)	260	(127)	300	(149)	337	(169)	374	(190)	410	(210)	447	(231)	Off
220	18780	(129500)	260	(127)	300	(149)	339	(171)	376	(191)	412	(211)	449	(232)	On
225	18780	(129500)	260	(127)	300	(149)	340	(171)	377	(192)	413	(212)	450	(232)	Off
235	18780	(129500)	260	(127)	300	(149)	340	(171)	379	(193)	415	(213)	452	(233)	On
240	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	416	(213)	453	(234)	Off
250	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	418	(214)	455	(235)	On
255	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	419	(215)	456	(236)	Off
265	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	458	(237)	On
270	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	459	(237)	Off
280	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	460	(238)	On
285	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	460	(238)	Off
295	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	460	(238)	On
300	18780	(129500)	260	(127)	300	(149)	340	(171)	380	(193)	420	(216)	460	(238)	Off

Segment 1:												
Ramp (Deg/min)	3.14	(1.74)	3.90	(2.17)	4.63	(2.57)	5.39	(2.99)	6.12	(3.40)	6.88	(3.82)
Ramp Time	49 Minutes											
Temp. Dwell	11 Minutes											
Pressure Rate (per min)	295 psi (2035 kPa) for 49 minutes, then 175 psi (1209 kPa) for 11 minutes											
Segment 2:												
Deg/min	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	130	Minutes	145	Minutes	165	Minutes	180	Minutes	200	Minutes	215	Minutes

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)												
Time,	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
Min	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
							Schedule 9.49								
	Depth	22,000 ft	(6705 m)								Mud density: 18.2 lb/gal (2.18 kg/L)				
0	2600	(17900)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	80	(27)	On
1	2910	(20100)	83	(28)	84	(29)	85	(29)	86	(30)	86	(30)	87	(31)	On
2	3220	(22200)	86	(30)	88	(31)	89	(32)	91	(33)	93	(34)	94	(34)	On
3	3530	(24300)	90	(32)	92	(33)	94	(34)	97	(36)	99	(37)	101	(38)	On
4	3840	(26500)	93	(34)	96	(36)	99	(37)	102	(39)	105	(41)	108	(42)	On
5	4150	(28600)	96	(36)	100	(38)	104	(40)	108	(42)	111	(44)	115	(46)	On
6	4460	(30800)	99	(37)	104	(40)	108	(42)	113	(45)	118	(48)	122	(50)	On
7	4770	(32900)	103	(39)	108	(42)	113	(45)	119	(48)	124	(51)	129	(54)	On
8	5080	(35000)	106	(41)	112	(44)	118	(48)	124	(51)	130	(54)	136	(58)	On
9	5390	(37200)	109	(43)	116	(47)	123	(51)	130	(54)	136	(58)	143	(62)	On
10	5700	(39300)	112	(44)	120	(49)	127	(53)	135	(57)	143	(62)	150	(66)	On
11	6010	(41400)	115	(46)	124	(51)	132	(56)	141	(61)	149	(65)	157	(69)	On
12	6320	(43600)	119	(48)	128	(53)	137	(58)	146	(63)	155	(68)	164	(73)	On
13	6630	(45700)	122	(50)	132	(56)	142	(61)	152	(67)	161	(72)	171	(77)	On
14	6940	(47900)	125	(52)	136	(58)	146	(63)	157	(69)	168	(76)	178	(81)	On
15	7250	(50000)	128	(53)	140	(60)	151	(66)	163	(73)	174	(79)	185	(85)	On
16	7560	(52100)	132	(56)	144	(62)	156	(69)	168	(76)	180	(82)	192	(89)	On
17	7870	(54300)	135	(57)	148	(64)	161	(72)	174	(79)	186	(86)	199	(93)	On
18	8180	(56400)	138	(59)	152	(67)	165	(74)	179	(82)	193	(89)	206	(97)	On
19	8490	(58500)	141	(61)	156	(69)	170	(77)	185	(85)	199	(93)	213	(101)	On
20	8800	(60700)	144	(62)	160	(71)	175	(79)	190	(88)	205	(96)	220	(104)	On
21	9110	(62800)	148	(64)	164	(73)	180	(82)	196	(91)	211	(99)	227	(108)	On
22	9420	(65000)	151	(66)	168	(76)	184	(84)	201	(94)	218	(103)	234	(112)	On
23	9730	(67100)	154	(68)	172	(78)	189	(87)	207	(97)	224	(107)	241	(116)	On
24	10040	(69200)	157	(69)	176	(80)	194	(90)	212	(100)	230	(110)	248	(120)	On
25	10350	(71400)	161	(72)	180	(82)	199	(93)	218	(103)	236	(113)	255	(124)	On
26	10660	(73500)	164	(73)	184	(84)	203	(95)	223	(106)	243	(117)	262	(128)	On
27	10970	(75600)	167	(75)	188	(87)	208	(98)	229	(109)	249	(121)	270	(132)	On
28	11280	(77800)	170	(77)	191	(88)	213	(101)	234	(112)	255	(124)	277	(136)	On
29	11590	(79900)	173	(78)	195	(91)	217	(103)	240	(116)	262	(128)	284	(140)	On
30	11900	(82100)	177	(81)	199	(93)	222	(106)	245	(118)	268	(131)	291	(144)	On
31	12210	(84200)	180	(82)	203	(95)	227	(108)	251	(122)	274	(134)	298	(148)	On
32	12520	(86300)	183	(84)	207	(97)	232	(111)	256	(124)	280	(138)	305	(152)	On
33	12830	(88500)	186	(86)	211	(99)	236	(113)	262	(128)	287	(142)	312	(156)	On
34	13140	(90600)	190	(88)	215	(102)	241	(116)	267	(131)	293	(145)	319	(159)	On
35	13450	(92700)	193	(89)	219	(104)	246	(119)	273	(134)	299	(148)	326	(163)	On
36	13760	(94900)	196	(91)	223	(106)	251	(122)	278	(137)	305	(152)	333	(167)	On
37	14070	(97000)	199	(93)	227	(108)	255	(124)	284	(140)	312	(156)	340	(171)	On
38	14380	(99200)	202	(94)	231	(111)	260	(127)	289	(143)	318	(159)	347	(175)	On
39	14690	(101300)	206	(97)	235	(113)	265	(129)	295	(146)	324	(162)	354	(179)	On
40	15000	(103400)	209	(98)	239	(115)	270	(132)	300	(149)	330	(166)	361	(183)	On
41	15310	(105600)	212	(100)	243	(117)	274	(134)	306	(152)	337	(169)	368	(187)	On
42	15620	(107700)	215	(102)	247	(119)	279	(137)	311	(155)	343	(173)	375	(191)	On
43	15930	(109800)	219	(104)	251	(122)	284	(140)	317	(158)	349	(176)	382	(194)	On
44	16240	(112000)	222	(106)	255	(124)	289	(143)	322	(161)	355	(179)	389	(198)	On
45	16550	(114100)	225	(107)	259	(126)	293	(145)	328	(164)	362	(183)	396	(202)	On
46	16860	(116200)	228	(109)	263	(128)	298	(148)	333	(167)	368	(187)	403	(206)	On
47	17170	(118400)	231	(111)	267	(131)	303	(151)	339	(171)	374	(190)	410	(210)	On
48	17480	(120500)	235	(113)	271	(133)	308	(153)	344	(173)	380	(193)	417	(214)	On
49	17790	(122700)	238	(114)	275	(135)	312	(156)	350	(177)	387	(197)	424	(218)	On
50	18100	(124800)	241	(116)	279	(137)	317	(158)	355	(179)	393	(201)	431	(222)	On

Table 7—Hesitation Squeeze Well-Simulation Tests (Continued)

1	2		3		4		5		6		7		8		9
			Temperature Gradient, °F/100 ft depth (°C/100 m depth) Temperature, °F (°C)										Schedule 9.49 (Continued)		
Time, Min	Pressure		0.9	(1.6)	1.1	(2.0)	1.3	(2.4)	1.5	(2.7)	1.7	(3.1)	1.9	(3.5)	
	psi	(kPa)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	°F	(°C)	Stirring
51	18410	(126900)	244	(118)	283	(139)	322	(161)	361	(183)	399	(204)	438	(226)	On
52	18720	(129100)	248	(120)	287	(142)	327	(164)	366	(186)	405	(207)	445	(229)	On
53	19030	(131200)	251	(122)	291	(144)	331	(166)	372	(189)	412	(211)	452	(233)	On
54	19340	(133300)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
55	19515	(134600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
56	19690	(135800)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
57	19865	(137000)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
58	20040	(138200)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
59	20215	(139400)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
60	20390	(140600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
61	20565	(141800)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
62	20740	(143000)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
63	20915	(144200)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
64	21090	(145400)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	On
65	21265	(146600)	254	(123)	295	(146)	336	(169)	377	(192)	418	(214)	459	(237)	Off
75	21265	(146600)	256	(124)	297	(147)	338	(170)	379	(193)	420	(216)	461	(238)	On
80	21265	(146600)	257	(125)	298	(148)	339	(171)	380	(193)	421	(216)	462	(239)	Off
90	21265	(146600)	259	(126)	300	(149)	341	(172)	382	(194)	423	(217)	464	(240)	On
95	21265	(146600)	260	(127)	301	(149)	342	(172)	383	(195)	424	(218)	465	(241)	Off
105	21265	(146600)	262	(128)	303	(151)	344	(173)	385	(196)	426	(219)	467	(242)	On
110	21265	(146600)	263	(128)	304	(151)	345	(174)	386	(197)	427	(219)	468	(242)	Off
120	21265	(146600)	265	(129)	306	(152)	347	(175)	388	(198)	429	(221)	470	(243)	On
125	21265	(146600)	266	(130)	307	(153)	348	(176)	389	(198)	430	(221)	471	(244)	Off
135	21265	(146600)	268	(131)	309	(154)	350	(177)	391	(199)	432	(222)	473	(245)	On
140	21265	(146600)	269	(132)	310	(154)	351	(177)	392	(200)	433	(223)	474	(246)	Off
150	21265	(146600)	271	(133)	312	(156)	353	(178)	394	(201)	435	(224)	476	(247)	On
155	21265	(146600)	272	(133)	313	(156)	354	(179)	395	(202)	436	(224)	477	(247)	Off
165	21265	(146600)	274	(134)	315	(157)	356	(180)	397	(203)	438	(226)	479	(248)	On
170	21265	(146600)	275	(135)	316	(158)	357	(181)	398	(203)	439	(226)	480	(249)	Off
180	21265	(146600)	277	(136)	318	(159)	359	(182)	400	(204)	441	(227)	482	(250)	On
185	21265	(146600)	278	(137)	319	(159)	360	(182)	401	(205)	442	(228)	483	(251)	Off
195	21265	(146600)	278	(137)	321	(161)	362	(183)	403	(206)	444	(229)	485	(252)	On
200	21265	(146600)	278	(137)	322	(161)	363	(184)	404	(207)	445	(229)	486	(252)	Off
210	21265	(146600)	278	(137)	322	(161)	365	(185)	406	(208)	447	(231)	488	(253)	On
215	21265	(146600)	278	(137)	322	(161)	366	(186)	407	(208)	448	(231)	489	(254)	Off
225	21265	(146600)	278	(137)	322	(161)	366	(186)	409	(209)	450	(232)	491	(255)	On
230	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	451	(233)	492	(256)	Off
240	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	453	(234)	494	(257)	On
245	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	495	(257)	Off
255	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	497	(258)	On
260	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	498	(259)	Off
270	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	498	(259)	On
275	21265	(146600)	278	(137)	322	(161)	366	(186)	410	(210)	454	(234)	498	(259)	Off

Segment 1:												
Ramp Deg/min	3.22	(1.79)	3.98	(2.21)	4.74	(2.63)	5.50	(3.06)	6.26	(3.48)	7.02	(3.90)
Ramp Time	54 Minutes											
Temp. Dwell	11 Minutes											
Pressure Rate (per min)	310 psi (2137 kPa) for 54 minutes, then 175 psi (1209 kPa) for 11 minutes											
Segment 2:												
Deg/min	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)	0.20	(0.11)
Ramp Time	120	Minutes	135	Minutes	150	Minutes	165	Minutes	180	Minutes	195	Minutes

10 Static Fluid Loss Test

10.1 GENERAL

This section provides several procedures for running static fluid loss tests. For tests at *temperatures less than 194°F (90°C)*, testing may be performed using a static fluid loss cell after slurry conditioning in an atmospheric or pressurized consistometer or by using a stirred fluid loss cell. For tests at *temperatures greater than 193°F (89.4°C)*, testing may be performed using a static fluid loss cell following conditioning in a pressurized consistometer or by using a stirred fluid loss cell. Regardless of whether the slurry is conditioned on a consistometer or in a stirred fluid loss cell, the fluid loss value is determined under static conditions.

10.2 APPARATUS

10.2.1 High temperature, high pressure fluid loss cell or stirred fluid loss cell fitted with a 325 mesh screen [3.5 in^2 (22.6 cm^2) filtration area] backed by a 60 mesh screen. The end caps must have radial grooves if a screen with perforated metal back is used. The radial grooves provide a flow path for the cement filtrate.

Note: Do not exceed equipment manufacturer's recommendations for maximum temperatures, pressures, and volumes.

10.2.2 The temperature of the cement slurry is to be measured using a Type J thermocouple (ASTM classification, special) mounted in the wall of the cell or immersed in the slurry. The location of the thermocouple should be noted on the report form. A thermocouple mounted in the heating jacket measures the temperature of the jacket. This temperature is usually higher than the temperature inside the fluid loss cell. Thermocouples and displays on consistometers and fluid loss cells should be calibrated according to Appendix D, API Recommended Practice 10B.

Note: Metal thermometers are not acceptable because of their relatively poor accuracy. Glass thermometers are not used because they do not have dimensions that allow them to be fitted in the heating jacket or the test cell.

10.2.3 Pressure gauges should have a scale such that pressure can be read to ±50 psi (±345 kPa). Gauges should be calibrated annually.

10.3 SAFETY

These procedures require the handling of hot, pressurized equipment and materials that are hazardous and can cause injury. *Only trained personnel should run these tests.*

10.4 MIXING PROCEDURE

The slurry should be mixed according to Section 5.

10.5 CONDITIONING PROCEDURES

All slurry conditioning should start at 80, ±2°F (26.7, ±1.1°C), or at a temperature appropriate for the well conditions, and be heated according to the appropriate schedule.

10.6 PROCEDURES FOR TESTING AT TEMPERATURES LESS THAN 194°F (90°C)

10.6.1 Atmospheric Pressure Conditioning

10.6.1.1 Within one minute after mixing, place the slurry into the container of the atmospheric pressure consistometer.

10.6.1.2 Heat the slurry to PBHCT or PSqT according to the thickening time schedule that most closely simulates actual field conditions. (See optional Step 10.6.4, "Extra Conditioning at Test Temperature.")

Note: It is preferred that the slurry and not the bath should be heated according to the appropriate schedule.

If the atmospheric consistometer is not equipped to measure slurry temperature, the bath should be heated according to the appropriate schedule.

10.6.1.3 After conditioning, remove the paddle and stir the slurry briskly with a spatula to ensure a uniform slurry.

10.6.1.4 Fill the fluid loss cell as specified in 10.8.

10.6.2 Pressurized Conditioning

Any consistometer referenced in Section 9 may be used. The following procedure applies to the most commonly used equipment.

10.6.2.1 Place the slurry in the container of the pressurized consistometer according to the procedure in 9.4, API Recommended Practice 10B.

10.6.2.2 Apply pressure and heat according to the thickening time schedule which most closely simulates actual field conditions. (See optional Step 10.6.4, "Extra Conditioning at Test Temperature.")

10.6.2.3 At the end of the schedule, turn off the heaters and release the pressure [about 200 psi/sec (1380 kPa/sec)].

10.6.2.4 Remove the slurry cup from the consistometer, keeping the cup upright so that the oil does not mix with the slurry.

10.6.2.5 Remove the top locking ring, diaphragm cover, drive bar, and collar from the shaft.

10.6.2.6 Syringe and blot the oil from the top of the diaphragm.

10.6.2.7 Remove the diaphragm and the support ring.

10.6.2.8 Syringe and blot any remaining oil from the top of the slurry. If the contamination is severe, discard the slurry and begin the test again.

10.6.2.9 Remove the paddle and stir the slurry briskly with a spatula to ensure a uniform slurry.

10.6.2.10 Fill the fluid loss cell as specified in 10.6.

10.6.3 Stirred Fluid Loss Cell Conditioning

10.6.3.1 Prepare the stirred fluid loss cell according to manufacturer's instructions.

10.6.3.2 After mixing according to Section 5, pour the slurry into a clean, dry, stirred fluid loss cell, according to manufacturer instructions.

10.6.3.3 Complete assembly of the fluid loss cell (screen, O-rings, end cap, etc.).

10.6.3.4 Apply 500, ±50 psig (3,450, ±345 kPag) to the cell. Do not close the pressurizing valve.

10.6.3.5 While agitating with the paddle, heat the slurry according to the thickening time schedule which most closely simulates actual field conditions.

10.6.3.6 Once the slurry has reached the specified temperature (and been conditioned for an optional additional period as described in 10.6.4), if required, close the test valve and invert the pressure vessel, reconnect the nitrogen to the top valve and repressure the nitrogen supply line (if disconnected), and open the top valve slowly.

10.6.3.7 Apply 1000, ±50 psi (6985, ±345 kPa) differential pressure to the test cell.

10.6.3.8 Open the test valve below the screen to begin the test as specified in 10.9.

10.6.4 Extra Conditioning at Test Temperature (Optional)

Following the same procedure as described in 10.6.1.2, 10.6.2.2 or 10.6.3.6 above, then hold the slurry at the specified temperature and pressure for 30, ±$^1/_2$ minutes or other desired conditioning period before proceeding to the next step. Document the conditioning period used.

10.7 PROCEDURES FOR TESTING AT TEMPERATURES GREATER THAN 193°F (89.4°C)

10.7.1 Conditioning Using Pressurized Consistometer

Any consistometer referenced in Section 9 may be used. The following procedure applies to the most commonly used equipment.

10.7.1.1 Place the slurry in the container of the pressurized consistometer and begin a thickening time test according to the procedure in 9.4, API Recommended Practice 10B.

10.7.1.2 Apply pressure and heat according to the thickening time schedule which most closely simulates actual field conditions.

10.7.1.3 At the end of the schedule, turn off the heaters and cool as quickly as practical.

10.7.1.4 After the slurry has been cooled to approximately 190°F (87.8°C), release the pressure slowly [about 200 psi/sec (1380 kPa/sec)].

10.7.1.5 Remove the slurry cup from the consistometer, keeping the container upright so that oil does not mix with the slurry.

10.7.1.6 Remove the top locking ring, diaphragm cover, drive bar and collar from the shaft.

10.7.1.7 Syringe and blot the oil from the top of the diaphragm.

10.7.1.8 Remove the diaphragm and the support ring.

10.7.1.9 Syringe and blot any remaining oil from the top of the slurry. If the contamination is severe, discard the slurry and begin the test again.

10.7.1.10 Remove the paddle and stir the slurry briskly with a spatula to ensure a uniform slurry.

10.7.1.11 Fill the fluid loss cell as specified in 10.6. *There is a hazard due to thermal expansion if this device is overfilled.* See Table 8, "Vapor Pressure and Volume Expansion of Water at Temperatures between 212°F (100°C) and 600°F (316°C)."

10.7.2 Conditioning Using Stirred Fluid Loss Cell

10.7.2.1 Prepare the stirred fluid loss cell according to manufacturer's instructions.

10.7.2.2 Pour the slurry into a clean, dry, fluid loss cell following the manufacturer's instructions. *There is a hazard due to thermal expansion if this device is overfilled.* See Table, "Vapor Pressure and Volume Expansion of Water at Temperatures Between 212°F (100°C) and 600°F (316°C)."

10.7.2.3 Complete assembly of the stirred fluid loss cell (screen, O-rings, end cap, etc.) according to manufacturer's instructions.

10.7.2.4 Apply and maintain 500, ±50 psig (3450, ±345 kPag) (or sufficient pressure to prevent the fluid from boiling at the maximum test temperature—see Table 8) to the cell. Do not close the pressurizing valve.

Table 8—Vapor Pressure and Volume Expansion of Water at Temperatures between 212°F (100°C) and 600°F (316°C)

Temperature		Water Vapor Pressure		Coefficient of Volume Expansion for Water at Saturation Pressure
°F	C	psi	kPa	
212	100	14.7	100	1.04
250	121	30	210	1.06
300	149	67	460	1.09
350	177	135	930	1.12
400	204	247	1,700	1.16
450*	232	422	2,910	1.21
500	260	680	4,960	1.27
550	288	1,044	7,200	1.36
600	316	1,541	10,620	1.47

*Do not exceed equipment manufacturer's recommendations for maximum temperatures, pressures, and volumes.

10.7.2.5 While agitating with the paddle, heat the slurry according to the thickening time schedule which most closely simulates actual field conditions. Monitor pressures closely to prevent over-pressurizing the cell.

10.7.2.6 Once the slurry has reached the specified temperature (and been conditioned for an optional period as described in 10.6.4), stop stirring, close the pressurizing valve, invert the pressure vessel, reconnect the nitrogen and repressure the nitrogen supply line (if disconnected) and open the top valve slowly.

10.7.2.7 Connect the back-pressure receiver or condenser to the test valve below the screen. If a back-pressure receiver is used, apply sufficient pressure to the back-pressure receiver to prevent the cement filtrate from boiling at the test temperature (see Table 8).

10.7.2.8 Apply 1000, ±50 psig (6895, ±345 kPag) differential pressure to the pressure vessel.

10.7.2.9 Open the test valve below the screen and begin the test as specified in 10.7.

10.8 FILLING THE STATIC FLUID LOSS CELL

10.8.1 Prepare the fluid loss cell (it must be ready to be filled when the slurry conditioning period has been completed). It must be clean and dry.

10.8.2 Preheat the fluid loss cell to the test temperature of 194, ±5°F (90, ±3°C) for tests at 194°F (90°C) or greater.

10.8.3 With the test pressure supply valve closed, pour the slurry into the fluid loss cell to 1, ±1/4 inch (2.5, ±0.6 cm) below the shoulder on which the screen rests in the 5 inch (12.7 cm) cell or 2, ±1/4 inch (5.1, ±0.6 cm) in the 10 inch (25.4 cm) cell. *There is a hazard due to thermal expansion if the cell is overfilled.* See Table 8, "Vapor Pressure and Volume Expansion of Water at Temperatures Between 212°F (100°C) and 600°F (316°C)."

10.8.4 Place the screen and O-rings in the cell and secure the end cap in the cell. Apply 500, ±50 psig (3450, ±345 kPag). Do not close the test valve.

10.9 HEATING (NON-STIRRED CELL)

10.9.1 For tests at temperatures less than 194°F (90°C), the test should be started as quickly as possible, but no more than six minutes may elapse from the time of completion of conditioning to the start of the test (opening the bottom valve, 10.7.1). Completion of conditioning is the end of the heat-up schedule (plus optional extra conditioning).

10.9.2 For tests at temperatures greater than 194°F (89.4°C) heat the fluid loss cell to the test temperature as fast as the heating jacket will heat. No more than six minutes should elapse from the time of completion of conditioning to the start of heating. Completion of the conditioning is the end of the heat-up schedule (plus optional extra conditioning) and cooling. Record the time to temperature.

Note: In order for the slurry to reach the test temperature, it may be necessary to set the controller temperature higher than the desired test temperature.

10.10 EQUIPMENT SETUP

10.10.1 Close the fluid loss cell top valve, bleed the pressure from the supply line and disconnect the nitrogen line.

10.10.2 Invert the cell so that the screen is on the bottom.

10.10.3 Attach the back pressure receiver (or condenser) to the outlet stem. If a back-pressure receiver is used, apply sufficient pressure to the back-pressure receiver to prevent the cement filtrate from boiling at the test temperature (see Table 8).

10.10.4 Connect the nitrogen line and apply a differential pressure of 1000, ±50 psig (6895, ±345 kPag). Open the top fluid loss cell valve to apply and maintain 1000, ±50 psig (6895, ±345 kPag) differential pressure to the cell.

10.11 FLUID LOSS TEST

10.11.1 Open the bottom valve (which starts the test). The test should be started within 30 seconds of inverting the cell. The temperature will be maintained at the specified temperature for the duration of the test.

10.11.2 Collect the filtrate and record the volume to ±1 mL at 30 seconds and 1, 2, 5, 7.5, 10, 15, 25, and 30 minutes. Alternatively, the filtrate may be continuously weighed and recorded. The fluid loss reporting form (see Figure 8) may be used for recording data and other pertinent information about the test. If weighed, the filtrate specific gravity must be measured and reported at 80°F (26.7°C) and the recorded filtrate volumes corrected for specific gravity. When a condenser is used, the filtrate volume in condenser should be accounted for.

10.11.3 If nitrogen blows though at less than 30 minutes, record the volume and time at which the blowout occurs. Close all valves to the cell and turn off the heater.

10.11.4 Calculate the API Fluid Loss. For tests that run the entire 30 minutes without "blowing out," measure the collected filtrate volume, double the value and report it as the fluid loss value. For tests that "blow out" in less than the 30 minute test interval, use Equation 11 to calculate the API Fluid Loss.

$$\text{Calculated API Fluid Loss} = 2\ Q_t \frac{5.477}{\sqrt{t}} \qquad (11)$$

Q_t is the volume (mL) of filtrate collected at the time t (min) of the blowout.

10.11.5 When reporting the fluid loss of cement slurries, those for which the fluid loss was measured for a full 30 minutes will be reported as "API Fluid Loss" while those for which the fluid "blew out" in less than 30 minutes will be reported as "Calculated API Fluid Loss."

10.12 TEST COMPLETION AND CLEAN UP

10.12.1 Cool the cell to a safe handling temperature and release the pressure.

CAUTION: It is not uncommon for pressure to become trapped inside the cell, even if the valve stems are open or removed.

10.12.2 Ensuring that all the pressure is released, disassemble the cell and inspect the screen to check for holes or damage. If there is damage to the O-ring seals or screen, discard the test results and rerun the test.

10.12.3 Carefully clean the screen to remove cement or fluid loss additive residue.

10.12.4 Clean and dry the fluid loss cell in preparation for the next test. Pay particular attention to the O-rings in the cell and on the valve stems.

Notes:
1. Slurries with significant sedimentation give erroneous values for fluid loss.
2. Fluid loss tests which do not run a full 30 minutes have a potential error which becomes greater as the length of the test becomes shorter.
3. Fluid loss tests that run the full 30 minutes typically show 5 percent variability. Tests that run less than 5 minutes may have a variability of more than 30 percent.

11 Permeability Tests

11.1 SCOPE

This procedure should be used to determine the relative permeability of a set cement sample to liquids or gases. Test results can be used to enhance the design of cement slurry formulations; however, they may not provide an accurate indication of the actual permeability of a set cement under subterranean wellbore conditions.

11.2 APPARATUS

A cement (or core) permeameter must be capable of: a) confining a set cement sample in a sample holder assembly, b) displacing gas or liquid through the sample under pressure, and c) measuring or recording the pressure and rate of flow through the sample. There are a variety of permeameters available which can be used to perform this test. The equipment designs may be somewhat different, but their component parts and basic operating functions are similar. A cement permeameter should consist of the following:

11.2.1 Sample Holder Assembly

There are several types of sample holder assemblies which can be used to confine a set cement sample depending on the type of permeameter used for this test. Some recommended types of holder assemblies are listed below:

11.2.1.1 Molded Sample Holder

A mold of brass or stainless steel should have a height of 1.000 in (25.40 mm), an inside diameter tapered from 1.102 in (27.99 mm) at the bottom to 1.154 in (29.31 mm) at the top, an outside diameter of 2.00 in (50.80 mm), and a 0.206 in (5.23 mm) by 45 degree beveled top and bottom edge. The cement sample will be cured in this mold, then placed in the sample holder assembly of the cement permeameter (see Figure 9). The molded cement sample is sealed in the holder assembly.

Heat-Up Schedule: _____ minutes to ______°F (°C) Test Temperature (______ °F (°C)/min)

Conditioning Method	[ ] Atmospheric	[ ] Pressurized (_____ psi, kPa)
	[ ] Stirred Fluid Loss Cell	
	[ ] Optional Extra Conditioning _________ minutes	
Static Cell Length	[ ] 5 inches (12.7 cm)	[ ] 10 inches (25.4 cm)
Cell Type (Ends)	[ ] Double	[ ] Single
Screen Type	[ ] 325 mesh x 60 mesh	
	[ ] 325 mesh x 60 mesh with perforated metal back	

Time (min)	Filtrate ([ ] mL or [ ] g)	Time (min)	Filtrate ([ ] mL or [ ] g)
$1/2$	____________	10	____________
1	____________	15	____________
2	____________	25	____________
5	____________	30	____________
$7^1/_2$	____________		

If filtrate weighed, specific gravity: ___________ at 80°F (26.7°C)

API Fluid Loss	=	__________ mL/30 min		
Blowout	=	__________ mL (or g) at ________ min/sec		
Calculated API Fluid Loss	=	__________ mL/30 min		
Filter Cake Conditions	=	Thickness[a] ________ Consistency[b] ________		
Time From End of Conditioning to to Test Start	=	___________ minutes		
Temperature	=	Start of Test	_________ °F (°C)	
		End of Test	_________ °F (°C)	
Location of Thermocouple	=	[ ] Cell Wall,	[ ] In Slurry	
Date of Calibration of Sensors	=		Consistometer	Fluid Loss Cell
		Pressure Gauge	_________	_________
		Thermocouple	_________	_________

[a]Thickness: of cake only; do not include remaining slurry if gelled.
[b]Consistency: hard, firm, mushy, gelled, etc.

Figure 8—Fluid Loss Results Reporting Form

11.2.1.2 Cored Sample Holder

The cement slurry may be cured in a 2 in (5.08 mm) x 2 in (5.08 mm) compressive strength mold (or other suitable mold), then a cylindrical sample may be prepared by coring the set cement with a 1 in (25.4 mm) ID diamond core drill. Water or air should be used to lubricate the drill bit while coring the 1 in (25.4 mm) OD cement sample. The cement sample is then cut to 1 in (25.4 mm) length using a diamond core saw so that the ends of the sample are parallel and as perpendicular to the sides of the sample as possible.

The ends of the cored cement sample are then cleaned of any residue and the sample is placed inside a rubber core holder (Ruska, Hassler, Tapered, etc.). (See Figure 10.) The rubber core holder and cement sample are then placed inside the core holder assembly and secured and confined in the permeameter such that no pressurized gas or liquid can bypass the cement sample during testing.

11.2.2 Pressure Medium

Pressure should be applied by compressed air, nitrogen, or any other safe and adequate means of maintaining constant gas pressure. For gas permeability, the gas is transmitted under pressure directly through the cement sample.

For liquid permeability, the gas pressure is placed on a liquid filled accumulator system (rubber bladder, tank, sealed piston reservoir, cylinder, etc.) which, in turn, displaces a liquid out of the accumulator through the cement sample. Constant gas pressure will ensure a constant liquid flow rate into the cement sample. Alternate fluid delivery systems such as constant rate pumps may be used.

11.2.3 Measuring or Recording Device

The flow rate to gas may be measured using a "ball" type flow meter (Brooks, Gilmont, etc.) or an electronic mass flow meter. The flow rate to liquid may be measured using a flow meter (rotameter), electronic mass flow meter, or other appropriate means. Flow rate should be measured in mL per second.

Note: When using the electronic mass flow meter with liquid, the liquid should be collected inside a closed, sealed reservoir on the downstream side of the specimen which, in turn, will displace air out of the reservoir through the mass flow meter.

11.3 SAMPLE PREPARATION

Prior to curing, the cement slurry and curing mold should be prepared as follows.

11.3.1 Slurry

11.3.1.1 Molded Sample

The cement slurry, prepared in accordance with Section 5, is poured into a clean, ungreased, cement permeameter mold which has been placed on a flat plate and sealed around the exterior with a thin film of grease. The cement slurry should be puddled 27 times with a stirring rod and leveled with a spatula or straightedge. A top plate is carefully placed on the mold so as not to trap air bubbles in the sample. The molded sample is then cured according to the curing procedure outlined in Section 7.

11.3.1.2 Cored Sample

The cement slurry is prepared in accordance with Section 5. The slurry is then transferred into prepared compressive strength molds and cured according to the procedure outlined in Section 7.

11.3.2 Set Cement

11.3.2.1 Molded Sample

After the cement slurry has cured under the desired test conditions, the mold containing the sample is taken from the curing chamber or water bath. The cover plates are removed and the sample is cooled under water to room temperature. The sample should be cleaned by scraping under a stream of water to remove any residue prior to testing. A soft wire brush, emery cloth or knife blade may be used for removing residue.

11.3.2.2 Cored Sample

After the cement slurry has cured under the desired test conditions, the mold containing the sample is taken from the curing chamber or water bath. The cover plates are removed and the set cement is cooled under water to room temperature and removed from the mold. The set cement is then cored according to the procedure outlined in 11.2.1.2.

11.4 LIQUID PERMEABILITY (CEMENT PERMEAMETER—FIGURE 9)

Prior to testing, saturate the sample with water. The sample should remain immersed in water until the time of testing. The mold is sealed in the sample holder assembly with its larger face downward. Tightening the assembly assures an O-ring seal at the top and bottom of the cement sample. To prevent collection of any air in the water and under the sample, the following procedure is recommended.

11.4.1 With mercury in the system as shown (Figure 9), valve A closed, valves B, C, and D opened, connect an aspirator bottle containing recently boiled, deaerated and filtered (0.15 micron ceramic filter) water to valve C. Fill the water chamber until water overflows through valve D.

11.4.2 With valves B, C, and D closed and valve A opened, adjust the air regulator to obtain the desired pressure drop across the cement sample by observing pressure gauge G [generally 20 to 200 psi (100 to 1400 kPa)].

11.4.3 Connect aspirator bottle to valve E.

11.4.4 With the aspirator bottle 12 in to 24 in (305 mm to 610 mm) higher than valve E, open valves D and E slightly to allow a small flow of water past the mold containing the set cement as the holder cap is screwed into place.

11.4.5 Close valve E and fully open valve D.

11.4.6 Connect an aspirator bottle to valve F, open valve F slightly, and allow water to flow over top of the sample and up the stem of the pipette to obtain a reference starting point.

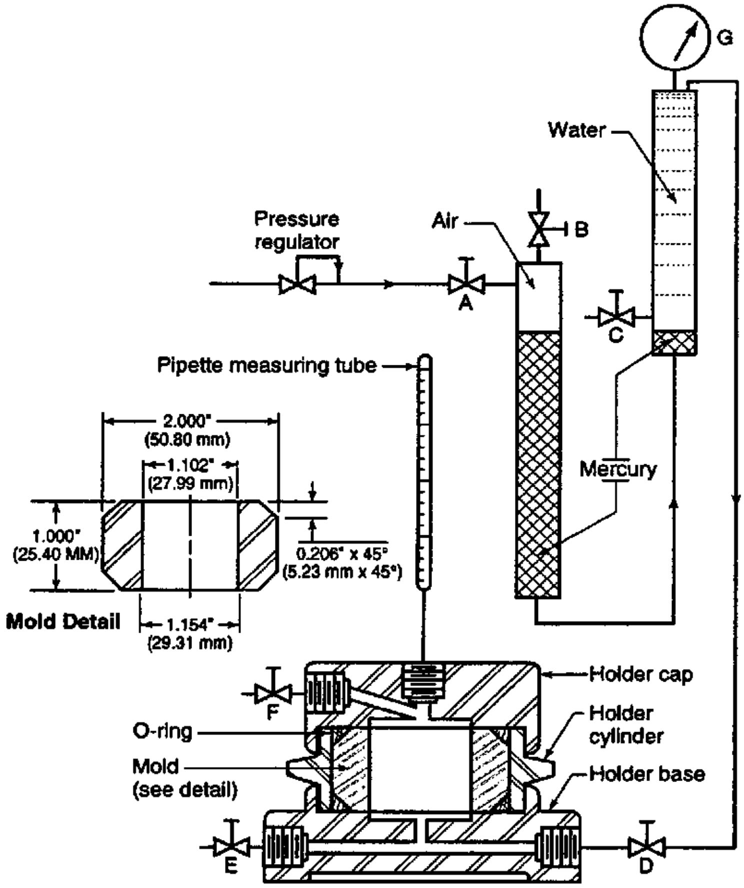
11.4.7 Flow water through the sample for a minimum of 15 minutes or until about 1 mL has been forced through the sample into the measuring tube. During this period the flow rate and differential pressure should be measured at least twice.

11.5 LIQUID PERMEABILITY ALTERNATE PROCEDURE (CORE PERMEAMETER—FIGURE 10)

Prior to testing, saturate the sample with water. The sample should remain immersed in water until the time of testing. A cored cement sample is placed in a rubber core holder and, in turn, in a (Ruska, Hassler, Tapered, etc.) core holder assembly (Figure 10). The cement sample is then sealed in the permeameter by means of mechanical or gas confining pressure applied to the core holder assembly.

11.5.1 Fill the liquid accumulator in the core permeameter with deaerated, filtered (0.15 micron ceramic filter) deionized water.

11.5.2 With the air regulator backed off, and all valves closed on the permeameter, apply gas pressure (300 to 500 psi) to the permeameter.



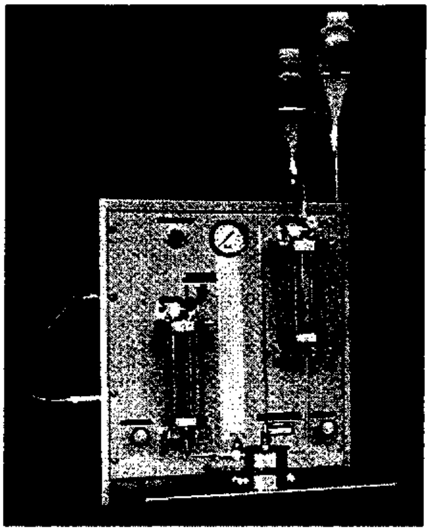
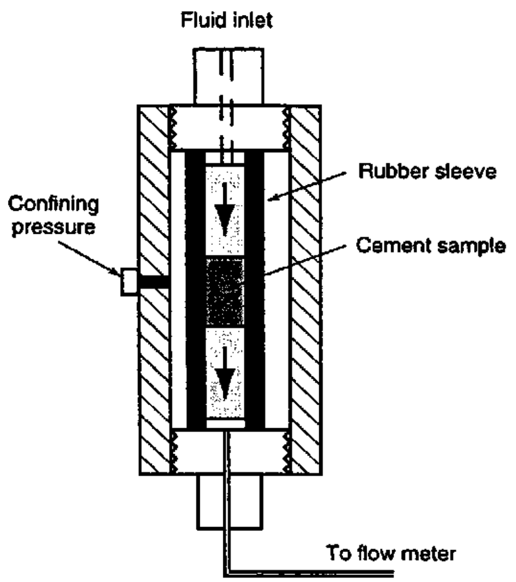
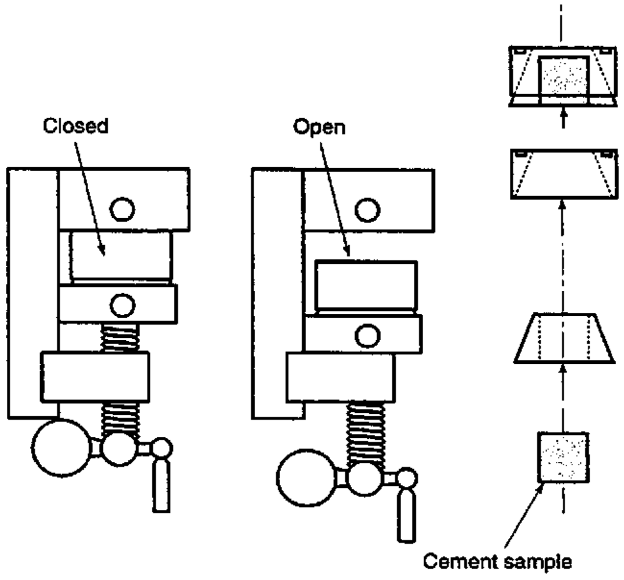


Figure 9—Cement Permeameter



Hassler Sleeve Assembly
Hydraulic Seal



Tapered Sleeve Assembly
Mechanical Seal

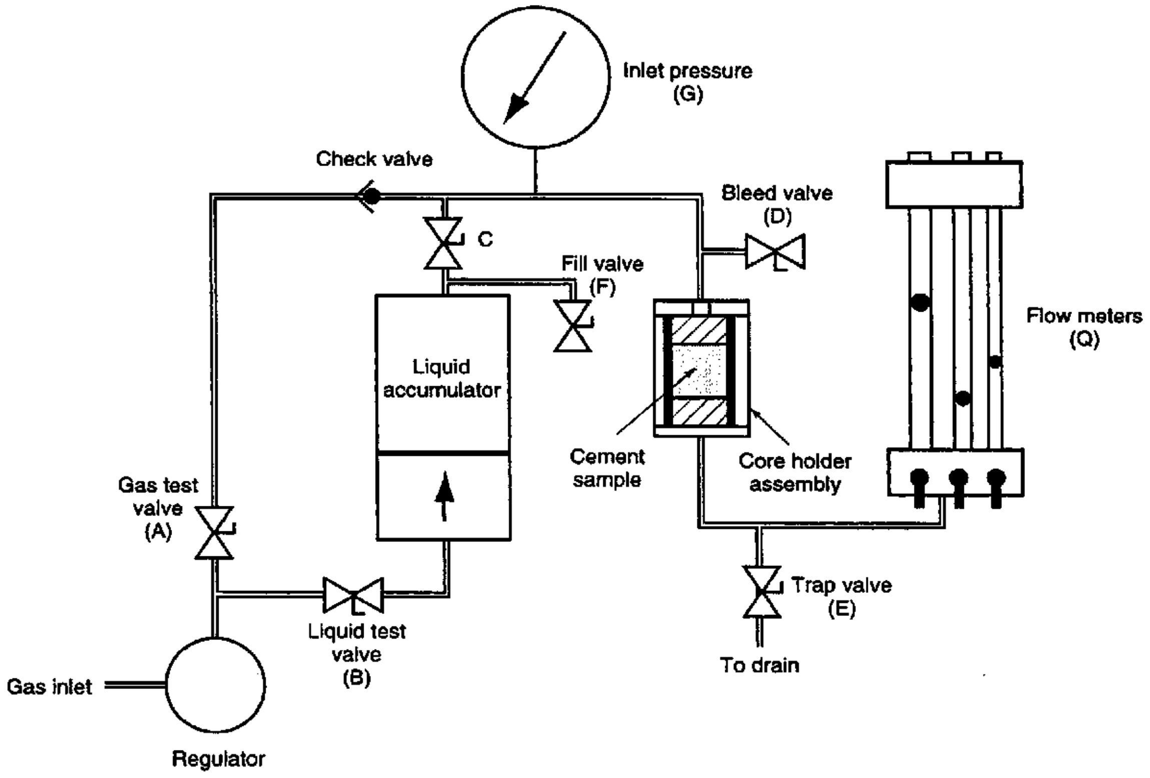


Figure 10—Liquid/Gas Core Permeameter

11.5.3 Leaving valves A (gas test valve) and F closed, open valves B, C, and D to the liquid side of the permeameter, and trap valve E.

11.5.4 Slowly increase pressure with the regulator, as observed on gauge G, until a steady stream of liquid begins to flow out of valve D above the core holder assembly.

11.5.5 Close valve D to divert flow through the cement sample. Increase pressure indicated on gauge G to between 20 and 200 psi (100 and 1,400 kPa) or until flow is observed on the downstream side of the cement sample at valve E. Close valve E to divert the flow through the flow meter assembly.

Note: The slowest measurable flow rate should be used to measure permeability. High differential pressures and large flow rates may provide erroneous measurements.

11.5.6 When the flow rate has stabilized, record the inlet pressure as indicated on gauge G (P_1) and flow rate (Q) in mL/sec. When completed, relieve pressure on the regulator and slowly open valves D and E to relieve any pressure in the system. Remove the cement sample.

Note: In either case, "unsteady state" permeability is observed as an increase or decrease in differential pressure and flow rate across the core sample at constant drive pressure. "Stable state" permeability occurs when the differential pressure and flow rate remain steady at constant drive pressure. Only steady state measurements are valid.

11.6 CALCULATING LIQUID PERMEABILITY

Liquid permeability of the set cement should be calculated using Darcy's Law as expressed in Equation 12 (millidarcies) or Equation 13 (square micrometers). The curing temperature, curing pressure, and curing time should also be reported with the permeability measurement.

$$K = 14{,}700\,\frac{Q \times \mu \times L}{A \times \Delta P} \qquad (12)$$

Where:

K = permeability (md).
Q = flow rate (mL/sec).
μ = liquid viscosity (cps).
L = sample length (cm).
A = cross sectional area (cm²) = $\pi \cdot r^2$ (where radius measured in cm).
P_i = inlet pressure (psi).
P_o = outlet pressure (psi).
ΔP = $P_i - P_o$.

or:

$$K = 10^5\,\frac{Q \times \mu \times L}{A \times \Delta P} \qquad (13)$$

Where:

K = permeability (μm²).
Q = flow rate (mL/sec).
μ = liquid viscosity (Pa·s).
L = Sample length (cm).
A = cross sectional area (cm²) = $\pi \cdot r^2$ (where radius measured in cm).
P_i = inlet pressure (kPa).
P_o = outlet pressure (kPa).
ΔP = $P_i - P_o$.

11.7 GAS PERMEABILITY (CORE PERMEAMETER—FIGURE 10)

Prior to testing, the sample should be dried to a constant weight in a drying oven or desiccator. This procedure may be used to determine the permeability of the cement sample to gas. This test can be used to quickly screen cement samples to enhance the design of extremely low permeability formulations.

11.7.1 The sample is prepared and loaded into the core permeameter as outlined in 11.5.

11.7.2 With the air regulator backed off, and all valves closed on the permeameter, apply gas pressure (300 to 500 psig) to the permeameter.

11.7.3 Leaving valves B and C (liquid test valves) closed, open valves A and D to the gas side of the permeameter.

11.7.4 Slowly increase pressure with the regulator until the lines have been purged of all liquid and gas is slowly bleeding out of valve D above the core holder assembly.

11.7.5 Close valve D to divert the gas flow through the cement sample. Increase the pressure indicated on gauge G until a flow rate is observed at the flow meter assembly. Be sure valve E is closed. Once the flow rate has stabilized, record the inlet pressure on gauge G (P_1) and flow rate (Q, mL/sec).

11.7.6 Once the readings are taken, relieve the pressure at the regulator, open bleed valves D and E to make sure no pressure is trapped in the permeameter and remove the cement sample.

11.8 CALCULATING GAS PERMEABILITY

Gas permeability of the set cement should be calculated using Darcy's Law as expressed in Equation 14 (millidarcies). The curing temperature, curing pressure, and curing time should also be reported with the permeability measurement.

$$K(\text{md}) = \frac{2000 \times \mu \times Q_b \times P_b \times L}{A(P_i^2 - P_o^2)} \qquad (14)$$

Where:

K = permeability to gas (md).
μ = viscosity of gas (cps).

Q_b = flow rate to gas (mL/sec).
P_b = adjusted barometric pressure (atm).
L = cement sample length (cm).
A = cross sectional area (cm^2) ($A=\pi \cdot r^2$).
P_i = inlet pressure in atmospheres.
(psi/14.7 = atmospheres).
P_o = outlet pressure in atmospheres (usually 1 atm).

12 Determination of Rheological Properties and Gel Strength Using a Rotational Viscometer

12.1 SCOPE

The scope of this procedure is to characterize the rheological behavior of cement slurries. Determination of rheological properties of cement slurries may be sensitive to the procedure being used. Therefore, a comparison of rheological properties of cement slurries obtained using different procedures is not recommended. A standardized procedure has been developed to generate reproducible results for the oil industry.

12.2 PROCEDURE

This procedure was developed after a careful analysis of many parameters which affect the rheological behavior of cement slurries. The large majority of data was accumulated using nondispersed slurries; however, data from some dispersed slurries were also evaluated. The results of the analysis showed that highly dispersed slurries will generally yield data of less quality with this procedure, because of possible settling while running the test.

12.3 UNITS

Whenever necessary, the relevant mathematical equations are presented both in oilfield units—their labels ends with an "a"—and in SI units—their labels ends with a "b." In the text itself an oilfield unit is most of the time followed by the corresponding SI unit in parenthesis.

12.4 APPARATUS

An apparatus conforming to the following description should be used to determine the rheological properties of cement slurries:

12.4.1 A Rotational Viscometer

With this type of viscometer, the sample is confined between two concentric cylinders of radii R_1 and R_2 ($R_2 > R_1$), one of which, the rotor, is rotating at a constant rotational velocity Ω. The rotation of the rotor in the presence of the sample produces a torque that is usually measured at the wall of the inner cylinder, but is also prevalent on the outer cylinder wall. The cylinder radii should be such that the sample is homogeneous and the shear-stress is as uniform as possible across the gap. These conditions are assumed to be satisfied if:

$$\left(\frac{R_1}{R_2}\right) > 0.9 \qquad (15)$$

and:

$$R_2 - R_1 > 10 \times \Phi \qquad (16)$$

Where:
Φ = diameter of the largest sample particle.

The nominal shear-rate, γ, and the shear-stress, τ, are calculated at the inner cylinder wall by the following expressions:

$$\gamma = \frac{\pi}{15}\frac{R_2^2 \times \Omega}{R_2^2 - R_1^2} \qquad (17a)$$

$$\gamma = \frac{4 \times R_2^2 \times \Omega}{R_2^2 - R_1^2} \qquad (17b)$$

Where γ is in 1/s and Ω, the viscometer rotational speed, is in rpm (r/s), and:

$$\tau = 1.44\frac{T}{2\pi R_1^2} \qquad (18a)$$

$$\tau = \frac{T}{2\pi R_1^2} \qquad (18b)$$

Where τ is in lbf/100ft² (Pa); T, the torque per unit length, is in lbf (N); and R_1, R_2 are in inches (m). The following assumptions were used in the derivation of Equations 17 and 18:

a. The slurry is homogeneous and the shear-stress is uniform in the gap.
b. The flow regime in the annular gap is laminar.
c. Slip at the wall is negligible.
d. The fluid exhibits essentially time independent behavior.

The rotational viscometer should be capable of measuring shear-stress at shear-rates in the range from near zero to at least as high as 511 reciprocal seconds (1/s). Typically used instruments provide a minimum of five readings in that range. Instruments providing less than five readings in that shear-rate range are not recommended.

12.4.2 Description and Specifications of a Typical Rotational Viscometer

This viscometer is a direct-indicating instrument powered by a motor with or without a speed reduction gear box. The outer cylinder or sleeve is driven at a constant rotational velocity for each rpm (r/s) setting. The rotation of the sleeve on the cement slurry produces a torque on the inner cylinder which is also transmitted to the bob. A torsion spring restrains the movement of the bob and a dial attached to the torsion spring indicates the displacement of the bob. Specifications are as follows:

a. Sleeve:
   1. Inside Diameter: 1.450 in (36.83 mm).
   2. Total length may vary slightly with manufacturer.
   3. Scribed line 2.30 in (58.4 mm) above bottom.
   4. Two rows of $^1/_8$ in (3.18 mm) holes, spaced 120 degrees (2.09 radians) apart, around rotor sleeve and centered $^1/_8$ and $^3/_8$ inch below the scribed line.

b. Bob:
   1. Diameter: 1.358 in (34.49 mm).
   2. Cylinder Length: 1.496 in (38.00 mm).
   3. Bob is closed with a flat base and tapered top with a cone semi-angle of 60 degrees.

When using this instrument, nominal shear-rate and shear-stress can be calculated from the instruments raw data by using the expressions:

$$\gamma = 1.705 \times \Omega \quad (19a)$$

$$\gamma = 32.55 \times \Omega \quad (19b)$$

and:

$$\tau\,(\text{lbf}/100\ \text{ft}^2) = 1.065 \times F \times \theta \quad (20a)$$

$$\tau\,(\text{Pa}) = 0.5099 \times F \times \theta \quad (20b)$$

Where:

Ω = the viscometer speed in rpm (r/s).
γ = the nominal shear-rate in 1/s.
θ = the viscometer reading in instrument degrees.
F = the instrument's torsion spring factor.
τ = the shear-stress in lbf/100 ft^2 (Pa).

12.4.3 Interval Counter

Use a stopwatch or electric timer.

12.4.4 Temperature Measurement

Use a thermometer or thermocouple capable of measuring temperature within ±1°F (±0.5°C).

12.5 CALIBRATION

Calibration procedures for a given viscometer should be followed as suggested by the manufacturer to assure the repeatability of the measurements.

Proper operation of a direct-indicating viscometer depends, among other things, upon maintenance of the correct spring tension. Procedures for testing spring tension by a simple dead weight method or by measuring Newtonian fluids of known viscosity at specific temperatures are available from manufacturers. Rotational speeds should be checked with a tachometer. In addition, it is important to make sure that when empty, the instrument reads zero when rotating at any speed.

Although typically used instruments are generally provided with a torsion spring having a spring factor of 1 as standard, other torsion springs are available for measuring fluids having lower or higher viscosity. Each time the torsion spring is changed, the instrument must be recalibrated. When the instrument is equipped with a torsion spring having a spring factor other than 1, the dial readings obtained should be multiplied by the appropriate factor *F*.

The bob-sleeve assembly should be checked for centralization before using the instrument. This should be done by turning on the instrument and placing a small mirror underneath the bob-sleeve assembly. Severe non-centralization must be corrected.

12.6 PROCEDURE FOR THE DETERMINATION OF RHEOLOGICAL PROPERTIES

This procedure is recommended when using atmospheric or pressurized viscometers [for measurements above 189°F (87°C)]. For safety reasons, atmospheric viscometers must not be used at temperatures above 189°F (87°C). Deviations from this procedure for pressurized viscometers should only be made as required due to equipment characteristics. The instrument (bob, sleeve and cup) should be cleaned and dried before each test.

12.6.1 The cement slurry should be prepared in accordance with Section 6, API Specification 10A with the following exceptions:

12.6.1.1 The mix water should be carefully weighed in the clean, dry blender jar to avoid water loss.

12.6.1.2 The blades of the blender should be checked for wear and replaced as recommended in 7.4. If water leakage occurs around the bearings, the entire blender blade assembly should be replaced.

12.6.1.3 When needed, antifoam agent should be added to the mix water before adding the solids to the water to minimize foaming.

12.6.2 The prepared cement slurry should be poured immediately into the slurry cup of an atmospheric or a pressurized consistometer for preconditioning. The slurry cup should be initially at ambient temperature, as this may avoid the possibility of thermally shocking temperature sensitive additives. The slurry may then be heated to the desired test temperature up to 189°F (87°C) in the atmospheric consistometer, or to the desired elevated temperature and pressure in a pressurized consistometer, and to the appropriate thickening time test schedule for the cementing application.

With slurries that are not affected by thermal shock, the slurry cup may be pre-heated [±5°F (±2°C)] at the test temperature or any other initial temperature selected by the operator, before pouring the slurry into the slurry cup.

12.6.3 The cement slurry should then be stirred for a period of 20 minutes after the desired preconditioning temperature (and pressure) have been reached. If preconditioning is done in a pressurized consistometer, the slurry should then be cooled down as fast as possible to 189°F (87°C) or the test temperature if less than 189°F (87°C), before releasing the pressure from the consistometer. The pressurized consistometer can then be safely opened.

Any oil which may have invaded the pressurized consistometer cup during the pre-conditioning period should be blotted from the top of the slurry.

After the oil is blotted, the slurry paddle should be removed and the slurry should be stirred vigorously with a spatula for five seconds to re-disperse all the solids which may have settled at the bottom of the cup.

12.6.4 The cement slurry should immediately be poured into the viscometer cup up to the fill line. The viscometer's cup, bob, and sleeve should be maintained at the test temperature within ±5°F (±2°C) for the duration of the test, by using a heated cup assembly large enough to allow good temperature control (as indicated in 12.6, the maximum test temperature must not exceed 189°F (87°C) with an atmospheric viscometer). During steps 12.6.3 and 12.6.4, every effort should be made to prevent the slurry from remaining static for any period of time.

12.6.5 With the sleeve turning at the lowest rpm, the preheated cup should be raised until the liquid level is at the inscribed line on the sleeve. This operation will minimize slurry gellation and insure uniform distribution of the slurry.

12.6.6 The temperature of the slurry in the viscometer cup should be recorded before taking the first reading. The initial instrument dial reading should be taken 10 seconds after continuous rotation at the lowest speed. All the remaining readings should be taken first in ascending order, and then in descending order, after continuous rotation of 10 seconds at each speed. Shifting to the next speed should be done immediately after taking each reading.

Note: Repeatability of data taken at shear-rates at and below 10.2 1/s is often poor. At the discretion of the operator, readings at and below 10.2 1/s may be omitted from the test, except when measuring gel strength (see 12.7).

The recommended highest reading should be taken at a shear-rate (equivalent speed) of about 511 1/s. Exposing cement slurries to shear-rates above 511 1/s has been reported to generate inconsistent results. If desired, after ramping up and down and after measuring the gel strength (see 12.7), readings at shear-rates greater than 511 1/s may be taken. After taking all the readings, the temperature of the slurry in the viscometer cup should again be recorded.

12.6.7 The ratio of the ramp-up to ramp-down readings should be calculated at each speed. This ratio can be used to help qualify certain slurry properties.

a. When the ratio at all the speeds is approximately 1, this is an indication that the slurry is a non-settling, time independent fluid at the average test temperature.
b. Ratio values mostly higher than 1 may suggest settling of the slurry at the average test temperature. In addition, if some ramp down readings at the same RPM are lower than 5 instrument degrees (obtained with the viscometer in 12.4.2 with a spring factor of 1), this may be a further indication of the possibility of settling.
c. Ratio values mostly lower than 1 may suggest gelling of the slurry.

When significant differences in the readings indicate that the cement slurry is not stable, i.e. prone to extreme settling of excessive gellation, adjustments in the slurry composition should be considered.

12.6.8 The slurry rheological measurements should be reported as the average of the readings [(ramp-up + ramp-down)/2], at the average of the temperatures recorded in Step 12.6.6. An example is shown in Table 9.

Table 9—Example of a Rheological Properties Test

RPM	Ramp-up Readings	Ramp-down Readings	Reading Ratio	Average Readings
3	21	24	0.87	22.5
6	40	36	1.11	38
30	65	83	0.78	74
60	84	100	0.84	92
100	100	115	0.87	107.5
200	137	147	0.93	142
300	170			170

Initial slurry temperature = 150°F
Final slurry temperature = 146°F
Rheological properties reported at average temperature = 148°F

12.6.9 For improved reliability of the measurements, the entire procedure may be repeated several times using a freshly prepared sample of slurry each time. If the procedure is repeated several times, each instrument reading should then be reported as the average of all the acceptable measurements.

12.7 PROCEDURE FOR DETERMINATION OF GEL STRENGTH

The gel strength of a cement slurry may be measured immediately after determining the rheological properties of the slurry sample, or as an independent observation. If increasing slurry gellation is observed during the rheological measurements a brief reconditioning of the slurry in the viscometer for 1 minute at 300 RPM may disperse the gels and allow better measurement of the gel strength. For all independent tests, the slurry should be prepared, conditioned and loaded into the viscometer as outlined in 12.6.1 through 12.6.5.

12.7.1 Shut off the viscometer for 10 seconds and record the slurry temperature.

12.7.2 Set the viscometer at the speed equivalent to 5.1 1/s and start rotation. Record the maximum observed reading immediately after turning on the instrument. Use this reading to calculate the 10 second gel strength per Equation 20.

12.7.3 Shut off the viscometer for 10 minutes and record the slurry temperature. Repeat the measurements as in 12.7.2 to report the 10 minute gel strength.

12.7.4 After taking the readings, the temperature of the slurry in the viscometer cup should again be recorded.

12.7.5 The slurry gel strengths should be reported at the average of the recorded temperatures.

12.7.6 For improved reliability of the measurements, the entire procedure may be repeated several times using a freshly prepared sample of slurry each time. If the procedure is repeated several times, the gel strength values should then be reported as the average of all the acceptable measurements.

12.8 MODELING OF THE RHEOLOGICAL BEHAVIOR

To be able to characterize the flow behavior (friction pressures, flow regime, etc.) of the cement slurry in any geometry (pipe, annulus, etc.), a rheological model that best represents the data must be selected. To do this the raw data obtained (rotational velocities and torque readings) should be converted to shear-rate and shear-stress using Equations 17 and 18 (see 12.4.1). Simplified Equations 19 and 20 may be used when the viscometer in 12.4.2 is being used. A rheological model for the fluid can then be selected by a regression analysis or by plotting the shear-rate, shear-stress data.

The following assumptions were made to develop the equations that appear in this section:

a. The fluid is homogeneous.
b. Slip at the wall is negligible.
c. The fluid exhibits essentially time independent behavior.
d. The flow regime is laminar.

12.8.1 Rheological Models

Rheological models describe the relationship between shear-stress and shear-rate of a fluid. The most commonly used models to describe the rheological properties of cement slurries are the Bingham plastic and the Power Law models.

12.8.1.1 Bingham Plastic Model

When plotting shear-stress versus shear-rate on Cartesian (rectangular) coordinates, a cement slurry behaving as a Bingham plastic will result in a straight line with a positive shear-stress at zero shear-rate (Figure 11, Curve A). For this model, the shear-stress is related to the shear-rate by the relationship:

$$\tau = \tau_0 + \mu_p \times \gamma \quad (21)$$

In Equation 21, τ_0 is the positive shear-stress at zero shear-rate and is referred to as yield stress or yield point (often denoted as YP). Above the yield point, the shear-stress of the fluid is proportional to the shear-rate and the proportionality constant μ_p is referred to as the plastic viscosity (often denoted as PV). If in Equation 21 the yield point is equal to zero, the equation then becomes the relationship for the simplest of all rheological models, the Newtonian fluid model (Figure 11, Curve B). The units in Equation 21 are SI units i.e., 1/s for the shear-rate, Pa for the shear-stress and for the yield point, and Pa•s for the plastic viscosity.

12.8.1.2 Power Law Model

When plotting shear-stress versus shear-rate on Cartesian (rectangular) coordinates, this model will produce a curve with zero shear-stress at zero shear-rate (Figure 11, Curve C). When plotting shear-stress versus shear-rate on log-log paper, a cement slurry behaving as a Power Law fluid will result in a straight line (Figure 12, Curves B and C). For this model, the shear-stress is related to the shear-rate by the relationship:

$$\tau = k \times \gamma^n \quad (22)$$

In Equation 22 n is referred to as the Power Law exponent or flow behavior index (Ostwald-de index) and k is a constant, referred to as the consistency index. For shear thinning fluids (pseudo-plastic) n is a positive number between zero and 1 (Figure 11, Curve C). Cement slurries normally exhibit pseudo-plastic behavior. For shear thickening fluids (dilatant) n is a positive number greater than one (Figure 11, Curve D). Cement slurries normally do not exhibit dilating behavior. If in Equation 22 n is equal to 1, the equation then conforms to the Newtonian fluid model (Figure 11, Curve B). The units in Equation 22 are SI units i.e., 1/s for the shear-rate, Pa for the shear-stress, and Pa•s^n for the consistency index.

12.8.2 Selecting a Rheological Model

The shear-stress, shear-rate data of the cement slurry should be analyzed according to Equations 21 and 22 to make a decision about which model best fits the data. This can best be done by performing a regression analysis on the data. The model with the best regression coefficient should be selected as the model describing the data.

12.8.2.1 Bingham Plastic Model

A regression analysis should be performed using Equation 21 to determine the slope A and the intercept B. If shear-stresses τ are expressed in lbf/100 ft² and shear-rates γ are expressed in 1/s, the Bingham plastic parameters in oilfield units can be derived from:

$$\mu_p\ (\text{cp}) = 478.8 \times A \qquad (23a)$$

and:

$$\tau_0\ (\text{lbf}/100\ \text{ft}^2) = B \qquad (24a)$$

If shear-stresses τ are expressed in Pa and shear-rates γ are expressed in 1/s, the Bingham plastic parameters in SI units can be derived from:

$$\mu_p\ (\text{Pa·s}) = A \qquad (23b)$$

and:

$$\tau_0\ (\text{Pa}) = B \qquad (24b)$$

A negative calculated yield point is an indication that 1) the cement slurry has tendencies to settle, or 2) the cement slurry may be gelling up while its rheological properties are being measured. If this happens, it is recommended that the slurry be re-mixed and its rheological properties re-measured. If the problem persists, the cement slurry could present problems downhole, and its use should be reconsidered.

12.8.2.2 Power Law Model

Here, the parameters are obtained using regression analysis on the logarithmic form of Equation 22:

$$\log(\tau) = \log(k) + n \times \log(\gamma) \qquad (25)$$

Regardless of the unit system, the flow behavior index can be derived directly from the slope C:

$$n = C \qquad (26)$$

If shear-stresses τ are expressed in lbf/100 ft² and shear-rates γ are expressed in 1/s, the consistency index in lbf·s^n/ft² can be derived from the intercept D using:

$$k\ (\text{lbf·s}^n/\text{ft}^2) = (0.01) \times 10^D \qquad (27a)$$

If shear-stresses τ are expressed in Pa and shear-rates γ are expressed in 1/s, the consistency index in Pa·s^n can be derived from the intercept D using:

$$k\ (\text{Pa·s}^n) = 10^D \qquad (27b)$$

12.8.3 The "Two Point" Method

If a regression analysis cannot be performed, a less accurate "two point" method may be used. With this method, two data points from the shear-stress, shear-rate raw data are selected to calculate the parameters of the models. A better way to select two data points to use with this method is to plot the shear-stress shear-rate data on Cartesian (rectangular) coordinates for the Bingham plastic model, and on log-log paper for the Power Law model. After that, the "best" straight line is drawn through the data points. Two data points are then chosen on the line, and used to calculate the parameters. From these two data points the parameters can be obtained as follows:

12.8.3.1 Bingham Plastic Model

$$\mu_p(\text{cp}) = 478.8 \times \frac{\tau_2 - \tau_1}{\gamma_2 - \gamma_1} \qquad (28a)$$

and:

$$\tau_0(\text{lbf}/100\ \text{ft}^2) = \tau_1 - \left(\gamma_1 \times \frac{\tau_2 - \tau_1}{\gamma_2 - \gamma_1}\right) \qquad (29a)$$

with shear-stresses in lbf/100 ft², or:

$$\mu_p(\text{Pa·s}) = \frac{\tau_2 - \tau_1}{\gamma_2 - \gamma_1} \qquad (28b)$$

and:

$$\tau_0(\text{Pa}) = \tau_2 - \left(\gamma_2 \times \frac{\tau_2 - \tau_1}{\gamma_2 - \gamma_1}\right) \qquad (29b)$$

with shear-stresses in Pa, and where the subscripts $_1$ and $_2$ refer to the two selected data points.

If the viscometer of 12.4.2 is being used, and if the cement slurry is truly behaving as a Bingham plastic fluid, the following simple expressions may be used:

$$\mu_p\ (\text{cp}) = 1.50 \times F \times (\theta_{300} - \theta_{100}) \qquad (30a)$$

$$\mu_p\ (\text{Pa·s}) = 0.00150 \times F \times (\theta_{300} - \theta_{100}) \qquad (30b)$$

or:

$$\mu_p\ (\text{cp}) = F \times (\theta_{600} - \theta_{300}) \qquad (31a)$$

$$\mu_p\ (\text{Pa·s}) = \frac{F}{1000} \times (\theta_{600} - \theta_{300}) \qquad (31b)$$

and:

$$\tau_0\ (\text{lbf}/100\ \text{ft}^2) = F \times \theta_{300} - \mu_p \qquad (32a)$$

$$\tau_0\ (\text{Pa}) = 0.4788 \times [(F \times \theta_{300}) - (1000 \times \mu_p)] \qquad (32a)$$

Where θ_{600}, θ_{300}, and θ_{100} are the instrument's reading at the denoted rpms. A better choice is to use data points selected at the denoted rpms, from the best straight line drawn through the raw data points on a Cartesian plot of rpm versus instrument readings.

12.8.3.2 Power Law Model

For the Power Law model, the parameters using the "two point" method can be obtained as follows:

$$n = \frac{\log(\tau_2/\tau_1)}{\log(\gamma_2/\gamma_1)} \qquad (33)$$

and:

$$k(\text{lbf}\cdot\text{s}^n/\text{ft}^2) = 0.01 \times \frac{\tau_1}{\gamma_1^n} = 0.01 \times \frac{\tau_2}{\gamma_2^n} \qquad (34a)$$

$$k(\text{Pa}\cdot\text{s}^n) = \frac{\tau_1}{\gamma_1^n} = \frac{\tau_2}{\gamma_2^n} \qquad (34b)$$

If the viscometer of 12.4.2 is being used, and if the cement slurry is truly behaving as a Power Law fluid, the following simple expressions may be used:

$$n = 3.322 \times \log(\theta_{600} / \theta_{300}) \qquad (35)$$

or:

$$n = 2.096 \times \log(\theta_{300} / \theta_{100}) \qquad (36)$$

and:

$$k(\text{lbf}\cdot\text{s}^n / \text{ft}^2) = (F \times \theta_{300}) \times (100 \times 511^n) \qquad (37a)$$

$$k(\text{Pa}\cdot\text{s}^n / \text{ft}^2) = (F \times \theta_{300}) \times \frac{511^n}{0.4788} \qquad (37b)$$

Where again the preferred way to obtain the instrument's readings for the last two equations is from the best straight line drawn through the raw data points on a log-log plot of rpm versus instrument readings.

12.9 EXAMPLES

Two examples are given below illustrating the selection of the best model for the given measured data:

a. Example 1—The following data were obtained using the procedure outlined in this document:

Velocity rpm	Reading $F = 1$	Shear-Rate 1/s	Shear-Stress lbf/100 ft²
3	4	5.11	4.26
6	7	10.2	7.45
30	27	51.1	28.7
60	51	102	54.3
100	78	170	83.1
200	143	340	152
300	200	511	213

Figures 13 and 14 show a comparison of the data plotted on Cartesian and on log-log coordinates. The figures suggest that a Power Law model may be used for the data. From a regression analysis, the correlation coefficient for the Power Law model was 1.000. For the Bingham plastic, 0.996. The rheological parameters for the Power Law model from the regression analysis were in this case:

n —	k lbf·s^n/ft²	k Pa·s^n
0.854	0.0103	0.494

a. Example 2.

Velocity rpm	Reading $F = 1$	Shear-Rate 1/s	Shear-Stress lbf/100 ft²
3	56	5.11	59.6
6	60	10.2	63.9
30	84	51.1	89.5
60	109	102	116
100	140	170	149
200	200	340	213
300	260	511	277

Figures 15 and 16 show that data best fits a Bingham plastic model. This was verified using regression analysis. The correlation coefficients were 0.992 for the Bingham plastic model and 0.937 for the Power Law model. The rheological parameters for the Bingham plastic model from the regression analysis were:

τ_0 lbf/100 ft²	τ_0 Pa	μ_p cp
62.0	29.7	204

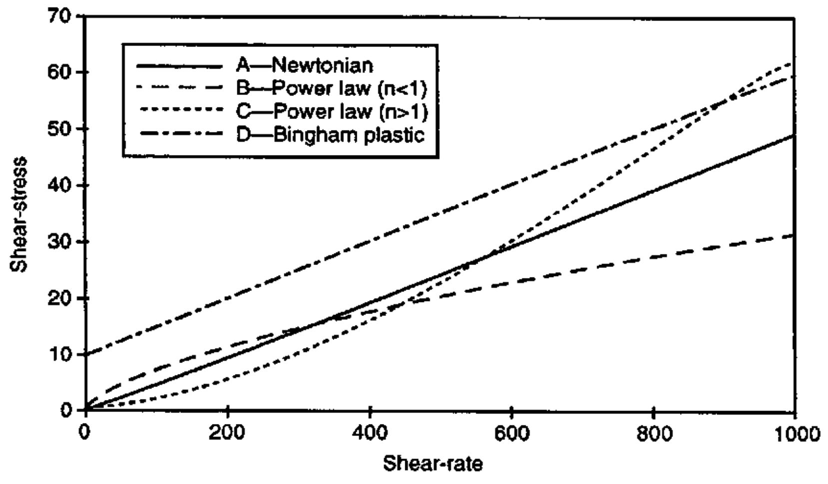


Figure 11—An Illustration of Shear-Stress Shear-Rate Behavior of Various Fluids on a Linear Plot

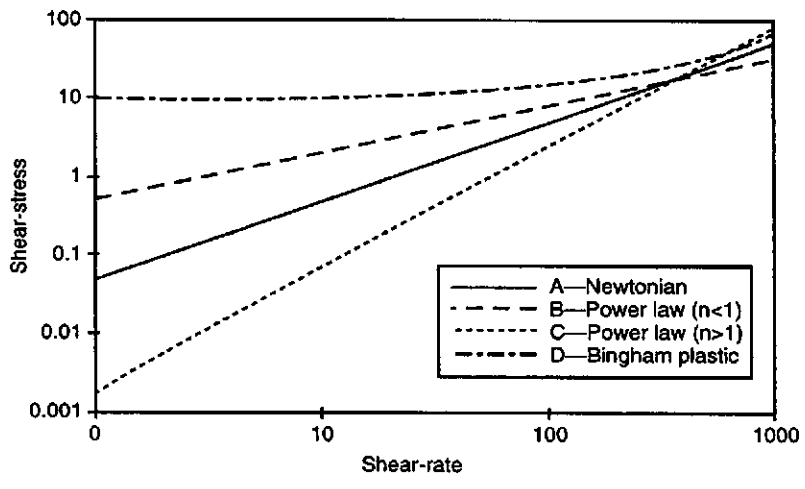


Figure 12—An Illustration of Shear-Stress Shear-Rate Behavior of Various Fluids on a Log-Log Plot

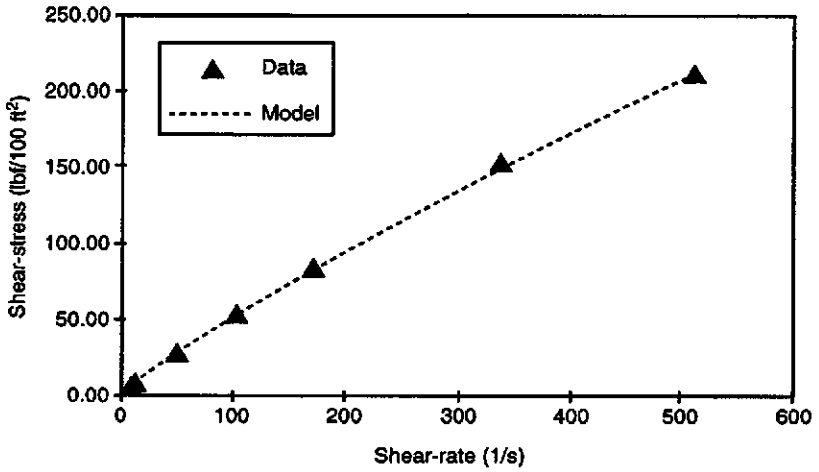


Figure 13—A Linear Plot of Shear-Stress vs. Shear-Rate for Example 1

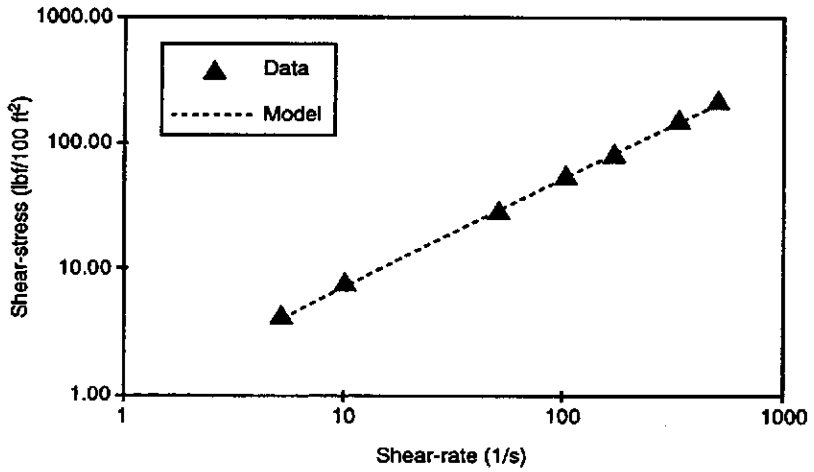


Figure 14—A Logarithmic Plot of Shear-Stress vs. Shear-Rate for Example 1

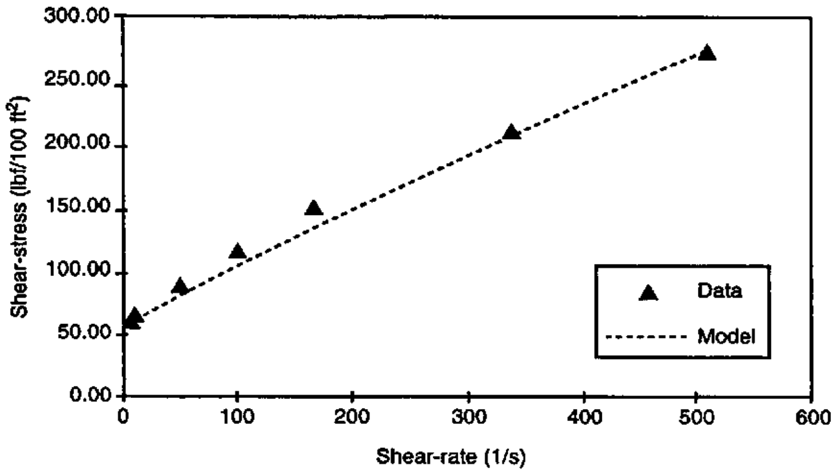


Figure 15—A Linear Plot of Shear-Stress vs. Shear-Rate for Example 2

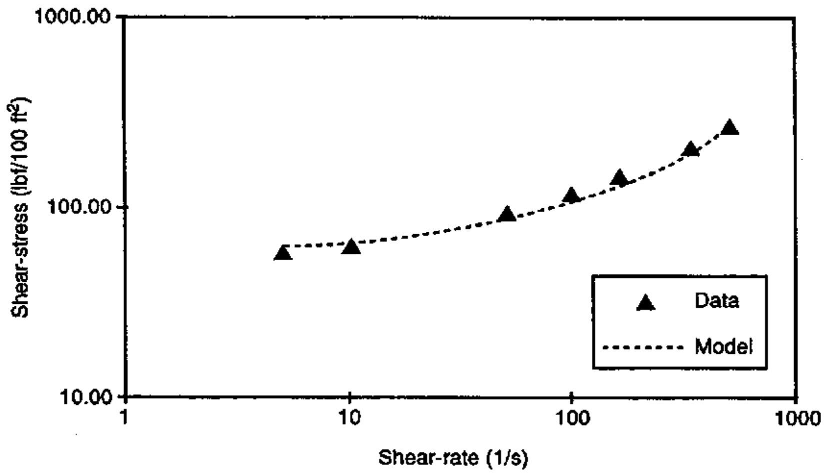


Figure 16—A Logarithmic Plot of Shear-Stress vs. Shear-Rate for Example 2

13 Procedure for Calculating Pressure Drop and Flow Regime for Cement Slurries in Pipes and Annuli

13.1 GENERAL

Selection of the rheological model which best fits the slurry rheology data is required to calculate the flow behavior of a cement slurry in any wellbore geometry. The procedure for rheological model selection is presented in 12.5.

13.1.1 Scope

The following equations can be used for calculating pressure drop and flow regime for cement slurries in casing and concentric annuli. Shear rates and shear stresses change as wellbore geometries and annular tolerances change with varying degrees of eccentricity. Also slurry behavior is altered with changing wellbore sizes, surfaces, annular tolerances, temperatures and velocities. Rheological properties may also be affected by solid or fluid contamination of the slurry downhole or by water loss to the surrounding formation which may increase the solids:liquid ratio. The equations given in this section outline a procedure to estimate pressure drop and flow regime in a concentric annulus by using the rheological data from a rotational viscometer. Due to the complexity of equations needed to address eccentric annuli they are not included in this procedure; however, good computer models are available for this purpose. References in which such models are discussed are included in this section.

13.1.2 Assumptions

Assumptions are as follows:

a. The fluid is assumed to be time independent, its rheology is supposed to be well described either by a Newtonian, a power law or Bingham plastic model.
b. The fluid is assumed to be homogeneous.
c. The fluid temperature is assumed to be homogeneous.
d. The flow is fully developed.
e. For annular flow, it is assumed that the geometry is concentric.

For annular flow, we give two sets of equations. One is the pipe approximation which applies to annuli with low diameter ratios—D_o/D_h (D_o and D_h being the inner and outer diameters of the annulus). The other is the narrow slot approximation which applies to annuli with a diameter ratio higher than typically 0.3. In fact the diameter ratio can be taken into account but it leads to equations which are more complicated.

13.1.3 Pertinent Equations

In the equations that follow in this document, the multiplier K is a unit conversion constant. It has appropriate subscripts, for example: v for velocity. The values of these constants for SI Metric and US oil field units are given in Table 10.

To simplify the flow equations presented below, the fluid mean velocity, V, will be used rather than the fluid volumetric flow rate Q. The relationship between these two parameters is as follows. Nomenclature describing each of the symbols is given in Table 11 and conversion factors are included in Table 12.

Pipe Flow	Annular Flow
$V = \frac{4QK_v}{\pi D_i^2}$ (38)	$V = \frac{4QK_v}{\pi(D_h^2 - D_o^2)}$ (39)
$Q = \frac{\pi D_i^2 V}{K_v 4}$ (40)	$Q = \frac{\pi(D_h^2 - D_o^2)V}{K_v 4}$ (41)

Where:

D_i = inner diameter of the pipe.
D_o = inner diameter of the annulus.
D_h = outer diameter of the annulus.

Friction pressure gradients, *DP/L*, will be calculated from the relationship between at least two dimensionless groups: the Reynolds number *Re*, and the friction factor *f*. The Reynolds number represents the ratio of the inertia forces to the viscous forces. The friction factor represents the ratio of the wall shear stresses to kinetic energy per unit volume.

Once the friction factor is known, the friction pressure gradient can be determined from:

Pipe Flow	Annular Flow
$\frac{\Delta P}{L} = \frac{2\rho V^2 f K_{\Delta P/L}}{D_i}$ (42)	$\frac{\Delta P}{L} = \frac{2\rho V^2 f K_{\Delta P/L}}{(D_h - D_o)}$ (43)

The following sections discuss how the friction factor is calculated for Newtonian, Power Law and Bingham plastic fluids.

13.2 NEWTONIAN FLUIDS

For a Newtonian fluid with a viscosity *m* and a density *r*, the Reynolds number, *Re*, is defined as:

Pipe Flow	Annular Flow
$Re = \frac{K_{Re}\rho V D_i}{\mu}$ (44)	$Re = \frac{K_{Re}\rho V(D_h - D_o)}{\mu}$ (45)

Therefore the fluid mean velocity for a given value of the Reynolds number can be calculated from:

Pipe Flow	Annular Flow
$V = \frac{\mu Re}{K_{Re}\rho D_i}$ (46)	$V = \frac{\mu Re}{K_{Re}\rho(D_h - D_o)}$ (47)

Depending on the value of the Reynolds number, the flow regime is classified as follows:

Flow Regime	Pipe Flow	Annular Flow
Laminar	$Re \le 2{,}100$	$Re \le 2{,}100$
Transitional	$2{,}100 < Re < 3{,}000$	$2{,}100 < Re < 3{,}000$
Turbulent	$Re \ge 3{,}000$	$Re \ge 3{,}000$

The critical fluid mean velocity for turbulent flow, V_c, is given by:

Pipe Flow	Annular Flow
$V_c = \frac{3{,}000 \times \mu}{K_{Re}\rho D_i}$ (48)	$V_c = \frac{3{,}000 \times \mu}{K_{Re}\rho(D_h - D_o)}$ (49)

In laminar flow the friction factor, f, can be calculated from the following equations:

Flow Regime	Pipe Flow	Annular Flow: Pipe	Annular Flow: Slot
Laminar	$f = \frac{16}{Re}$ (50)	$f = \frac{16}{Re}$ (51)	$f = \frac{24}{Re}$ (52)

In turbulent flow, whatever the flow geometry is, the friction factor can be calculated from the following equation:

$$\frac{1}{\sqrt{f}} = 4.0 \times \log(Re\sqrt{f}) - 0.4 \qquad (53)$$

In transitional flow, a log-log approximation is performed between $Re = 2{,}100$ and $Re = 3{,}000$.

13.3 POWER LAW FLUIDS

For a Power Law fluid with a Power Law index n, a consistency index k and a density r, the Reynolds number, Re_{PL}, is defined as:

Pipe Flow
$Re_{PL} = \frac{K_{Re\,PL}\rho V^{2-n} D_i^n}{8^{n-1}[(3n+1)/(4n)]^n k}$ (54)

Annular Flow: Pipe	Annular Flow: Slot
$Re_{PL} = \frac{K_{Re\,PL}\rho V^{2-n}(D_h - D_o)^n}{8^{n-1}[(3n+1)/(4n)]^n k}$ (55)	$Re_{PL} = \frac{K_{Re\,PL}\rho V^{2-n}(D_h - D_o)^n}{12^{n-1}[(2n+1)/(3n)]^n k}$ (56)

Therefore the fluid mean velocity for a given value of the Reynolds number can be calculated from:

Pipe Flow
$V = \left\{\frac{8^{n-1}[(3n+1)/(4n)]^n k Re_{PL}}{K_{Re\,PL}\rho D_i^n}\right\}^{[1/(2-n)]}$ (57)

Annular Flow: Pipe
$V = \left\{\frac{8^{n-1}[(3n+1)/(4n)]^n k Re_{PL}}{K_{Re\,PL}\rho (D_h - D_o)^n}\right\}^{[1/(2-n)]}$ (58)
Annular Flow: Slot
$V = \left\{\frac{12^{n-1}[(2n+1)/(3n)]^n k Re_{PL}}{K_{Re\,PL}\rho (D_h - D_o)^n}\right\}^{[1/(2-n)]}$ (59)

Depending on the value of the Reynolds number the flow regime will considered as:

Flow Regime	Pipe Flow	Annular Flow
Laminar	$Re_{PL} \le Re_{PL1}$	$Re_{PL} \le Re_{PL1}$
Transitional	$Re_{PL1} < Re_{PL} < Re_{PL2}$	$Re_{PL1} < Re_{PL} < Re_{PL2}$
Turbulent	$Re_{PL} \ge Re_{PL2}$	$Re_{PL} \ge Re_{PL2}$

with:

$$Re_{PL1} = 3{,}250 - 1{,}150 \times n \qquad (60)$$

$$Re_{PL2} = 4{,}150 - 1{,}150 \times n \qquad (61)$$

The critical fluid mean velocity for turbulent flow, V_c, is given by:

Pipe Flow
$V_c = \left\{\frac{K_{Re\,PL} 8^{n-1}[(3n+1)/(4n)]^n k Re_{PL2}}{\rho D_i^n}\right\}^{[1/(2-n)]}$ (62)

Annular Flow: Pipe
$V_c = \left\{\frac{K_{Re\,PL} 8^{n-1}[(3n+1)/(4n)]^n k Re_{PL2}}{\rho (D_h - D_o)^n}\right\}^{[1/(2-n)]}$ (63)
Annular Flow: Slot
$V_c = \left\{\frac{K_{Re\,PL} 12^{n-1}[(2n+1)/(3n)]^n k Re_{PL2}}{\rho (D_h - D_o)^n}\right\}^{[1/(2-n)]}$ (64)

In laminar flow the friction factor, f, can be calculated from the following equations:

Flow Regime	Pipe Flow	Annular Flow: Pipe	Annular Flow: Slot
Laminar	$f = \frac{16}{Re_{PL}}$ (65)	$f = \frac{16}{Re_{PL}}$ (66)	$f = \frac{24}{Re_{PL}}$ (67)

In turbulent flow, whatever the flow geometry is, the friction factor can be calculated from the following equation:

$$\frac{1}{\sqrt{f}} = \frac{4.0}{n^{0.75}} \times \log[Re_{PL} f^{(1-n/2)}] - \frac{0.4}{n^{1.2}} \quad (68)$$

In transitional flow, a log-log approximation is performed between $Re = Re_{PL1}$ and $Re = Re_{PL2}$.

13.4 BINGHAM PLASTIC FLUIDS

A Bingham plastic fluid is characterized by plastic viscosity and yield point. In the equations that follow, the plastic viscosity and yield point obtained from rotational viscometer data, $\mu_{p,R.V}$ and $\tau_{o,R.V.}$, are modified as follows.

$$\mu_p = K_{\mu p}\text{Exp}[0.98151\text{n}(\mu_{p,R.V.} K_{\mu p,R.V.}) - 0.03832] \quad (69)$$

$$\tau_o = K_{\tau o}[1.193\tau_{o,R.V.} K\tau_{o,R.V.} - 1.611] \quad (70)$$

In these equations R.V. refers to Rotational Viscometer.

For a Bingham plastic fluid, with a plastic viscosity m_p, a yield point τ_o, and a density r, the Bingham Reynolds number, Re_{BP}, is defined as:

Pipe Flow
$Re_{BP} = \frac{K_{Re_{BP}} V \rho D_i}{\mu_p}$ (71)

Pipe Flow	Annular Flow
$Re_{BP} = \frac{K_{Re_{BP}} V \rho (D_h - D_o)}{\mu_p}$ (72)	$Re_{BP} = \frac{K_{Re_{BP}} V \rho (D_h - D_o)}{1.5\mu_p}$ (73)

Therefore the fluid mean velocity for a given value of the Reynolds number can be calculated from:

Pipe Flow
$V = \frac{\mu_p Re_{BP}}{K_{Re_{BP}} \rho D_i}$ (74)

Pipe Flow	Annular Flow
$V = \frac{\mu_p Re_{BP}}{K_{Re_{BP}} \rho (D_h - D_o)}$ (75)	$V = \frac{1.5\mu_p Re_{BP}}{K_{Re_{BP}} \rho (D_h - D_o)}$ (76)

Depending on the value of the Reynolds number the flow regime will considered as:

Flow Regime	Pipe Flow	Annular Flow
Laminar	$Re_{BP} \le Re_{BP1}$	$Re_{BP} \le Re_{BP1}$
Transitional	$Re_{BP} > Re_{BP1} < Re_{BP2}$	$Re_{BP} > Re_{BP1} < Re_{BP2}$
Turbulent	$Re_{BP} \ge Re_{BP2}$	$Re_{BP} \ge Re_{BP2}$

Re_{BP1} and Re_{BP2} are estimated as follows:

Pipe Flow
$Re_{BP1} = Re_{BP2} - 866 \times (1 - \alpha_c)$ (77)

Pipe Flow	Annular Flow
$Re_{BP1} = Re_{BP2} - 866 \times (1 - \alpha_c)$ (78)	$Re_{BP1} = Re_{BP2} - 577 \times (1 - \alpha_c)$ (79)

and Re_{BP2} is calculated as shown below:

Pipe Flow
$Re_{BP2} = \frac{He(0.968774 - 1.362439 \times \alpha_c + 0.1600822 \times \alpha_c^4)}{8\alpha_c}$ (80)

Annular Flow: Pipe
$Re_{BP2} = \frac{He(0.968774 - 1.362439 \times \alpha_c + 0.1600822 \times \alpha_c^4)}{8\alpha_c}$ (81)
Annular Flow: Slot
$Re_{BP2} = \frac{He(0.968774 - 1.362439 \times \alpha_c + 0.1600822 \times \alpha_c^4)}{12\alpha_c}$ (82)

He is the Hedstrom number and is calculated from:

Pipe Flow
$He = \frac{K_{He} \tau_o \rho D_i^2}{\mu_p^2}$ (83)

Pipe Flow	Annular Flow
$He = \frac{K_{He} \tau_o \rho (D_h - D_o)^2}{\mu_p^2}$ (84)	$He = \frac{K_{He} \tau_o \rho (D_h - D_o)^2}{1.5^2 \mu_p^2}$ (85)

and α_c is calculated from:

$$\alpha_c = \frac{3}{4}\frac{\left(\frac{2He}{24500}+\frac{3}{4}\right)-\sqrt{\left(\frac{2He}{24500}+\frac{3}{4}\right)^2-4\left(\frac{He}{24500}\right)^2}}{2\left(\frac{He}{24500}\right)} \quad (86)$$

The critical fluid mean velocity for turbulent flow, V_c, is given by:

Pipe Flow
$V_c = \frac{\mu_p Re_{BP2}}{K_{Re_{BP}}\rho D_i}$ (87)

Pipe Flow	Annular Flow
$V_c = \frac{\mu_p Re_{BP2}}{K_{Re_{BP}}\rho(D_h - D_o)}$ (88)	$V_c = \frac{1.5\mu_p Re_{BP2}}{K_{Re_{BP}}\rho(D_h - D_o)}$ (89)

In laminar flow the friction factor, f, can be calculated from the following equations:

Flow Regime	Pipe Flow
Laminar	$f = 16\left[\frac{1}{Re_{BP}}+\frac{He}{6Re_{BP2}}\right]$ (90)

Flow Regime	Pipe Flow	Annular Flow
Laminar	$f = 16\left[\frac{1}{Re_{BP}}+\frac{He}{6Re_{BP2}}\right]$ (91)	$f = 16\left[\frac{1}{Re_{BP}}+\frac{(9/8)He}{6Re_{BP2}}\right]$ (92)

From fluid mechanics, the exact analytically derived friction factor correlation for a Bingham plastic fluid flowing through a *pipe* is:

$$f = 16\left[\frac{1}{Re_{BP}}+\frac{He}{6Re_{BP2}}-\frac{He^4}{3f^3Re^8_{BP}}\right] \quad (93)$$

Equation 90 is obtained from Equation 93 when the ratio $(\tau_o/\tau_w)^4$ can be neglected, where τ_o is the yield stress of the fluid and τ_w is the shear stress at the wall.

From fluid mechanics, the exact analytically derived friction factor correlation for a Bingham plastic fluid flowing through a *slot* is:

$$f = 24\left[\frac{1}{Re_{BP,h}}+\frac{He_h}{8Re^2_{BP,h}}-\frac{He^3_h}{6f^2Re^6_{BP,h}}\right] \quad (94)$$

If the ratio $(\tau_o/\tau_w)^4$ can be neglected, where τ_o is the yield stress of the fluid and τ_w is the shear stress at the wall, then Equation 92, friction factor correlation for a Bingham plastic fluid flowing through a *slot*, can be written as:

$$f = 24\left[\frac{1}{Re_{BP,h}}+\frac{He_h}{8Re^2_{BP,h}}\right] \quad (95)$$

Where the $Re_{BP,h}$ and He_h are defined as:

$$Re_{BP,h} = \frac{K_{Re_{BP}}V\rho(D_h - D_o)}{\mu_p} \quad (96)$$

and:

$$He_h = \frac{K_{He}\tau_o\rho(D_h - D_o)^2}{\mu^2_p} \quad (97)$$

In Equation 92, friction factor of a Bingham plastic fluid flowing through a *slot*, if the Reynolds and Hedstrom numbers are expressed in terms of hydraulic diameters then the equation can be written as:

$$f = 16\left[\frac{1.5}{Re_{BP,h}}+\frac{(9/8)He_h}{6Re^2_{BP,h}}\right] \quad (92a)$$

which can be simplified to:

$$f = 24\left[\frac{1}{Re_{BP,h}}+\frac{He_h}{8Re^2_{BP,h}}\right] \quad (92b)$$

which is same as Equation 95.

Hence Equations 90 to 92 recommended here for laminar flow of a Bingham plastic fluid can be obtained from analytically derived exact equations.

In turbulent flow, whatever the flow geometry is, the friction factor can be calculated from the following equation:

$$f = A(Re_{BP})^{-B} \quad (98)$$

The constants A and B are given below:

He	A	B
$\leq 0.75 \times 10^5$	0.20656	0.3780
$0.75 \times 10^5 < He \leq 1.575 \times 10^5$	0.26365	0.38931
$> 1.575 \times 10^5$	0.20521	0.35579

In transitional flow, a log-log approximation is performed between $Re = Re_{BP1}$ and $Re = Re_{BP2}$.

13.5 EXAMPLE OF CALCULATIONS

13.5.1 Newtonian Fluid

What is the critical flow rate for turbulent flow, in bbl/min, for a Newtonian fluid with a density of 8.4 lb/gal and a viscosity of 1.8 cp flowing in a 2.323 inch ID pipe? The critical velocity for turbulent flow is given by:

$$V_c = \frac{0.001}{[0.4536/(3.7852\times10^{-3})]\times0.0254}\times\frac{3{,}000\times1.8}{8.4\times2.323} = 0.0909\ \text{m·s}^{-1}$$

This gives a critical flow rate of:

$$Q_c = 0.0254^2\times\frac{\pi\times2.323^2}{4}\times0.0909 = 0.249\times10^{-3}\ \text{m}^3\text{·s}^{-1}$$

i.e.:

$$Q_c = \frac{60}{0.15898}\times0.249\times10^{-3} = 0.0938\ \text{bbl/min}$$

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min? Its velocity is:

$$V = \frac{0.15898/60}{0.0254^2}\times\frac{4\times6}{\pi\times2.323^2} = 5.81\ \text{m·s}^{-1}$$

So its Reynolds number is:

$$Re = \frac{[0.4536/(3.7852\times10^{-3})]\times0.0254}{0.001}\times\frac{8.4\times5.81\times2.323}{1.8} = 19{,}200$$

Since Re is larger than 3,000, the flow regime is turbulent and the value of the friction factor can be determined from:

$$f = 0.0790\times19{,}200^{-0.25} = 3.77\times10^{-3}$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{[0.4536\times(3.7852\times10^{-3})]}{0.0254}\times\frac{2\times8.4\times5.81^2\times3.77\times10^{-3}}{2.323} = 4{,}350\ \text{Pa·m}^{-1}$$

which gives a friction pressure of:

$$\Delta P = 0.14504\times10^{-3}\times4{,}350\times0.3048\times1{,}500 = 289\ \text{psi}$$

What is the critical flow rate for turbulent flow, in bbl/min, for a Newtonian fluid with a density of 8.4 lb/gal and a viscosity of 1.8 cp flowing in a 8⁵/₇ inch annulus? The critical velocity for turbulent flow is given by:

$$V_c = \frac{0.001}{[0.4536/(3.7852\times10^{-3})]\times0.0254}\times\frac{3{,}000\times1.8}{8.4\times(8.5-7.0)} = 0.141\ \text{m·s}^{-1}$$

This gives a critical flow rate of:

$$Q_c = 0.0254^2\times\frac{\pi\times(8.5^2-7.0^2)}{4}\times0.141 = 1.66\times10^{-3}\ \text{m}^3\text{·s}^{-1}$$

i.e.:

$$Q_c = \frac{60}{0.15898}\times1.66\times10^{-3} = 0.626\ \text{bbl/min}$$

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min? Its velocity is:

$$V = \frac{0.15898/60}{0.0254^2}\times\frac{4\times6}{\pi\times(8.5^2-7.0^2)} = 1.35\ \text{m·s}^{-1}$$

So its Reynolds number is:

$$Re = \frac{[0.4536/(3.7852\times10^{-3})]\times0.0254}{0.001}\times\frac{8.4\times1.35\times(8.5-7.0)}{1.8} = 28{,}800$$

Since Re is larger than 3,000, the flow regime is turbulent and the value of the friction factor can be determined from:

$$f = 0.0790\times28{,}800^{-0.25} = 6.07\times10^{-3}$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{[0.4536\times(3.7852\times10^{-3})]}{0.0254}\times\frac{2\times8.4\times1.35^2\times6.07\times10^{-3}}{(8.5-7.0)} = 584\ \text{Pa·m}^{-1}$$

which gives a friction pressure of:

$$\Delta P = 0.14504\times10^{-3}\times584\times0.3048\times1{,}500 = 38.7\ \text{psi}$$

13.5.2 Power Law Fluid

What is the critical flow rate for turbulent flow, in bbl/min, for a Power Law with a density of 13.0 lb/gal, a Power Law index of 0.5 and a consistency index of 0.007 lbf·s^n/ft² flowing in a 2.323 inch ID pipe? The critical velocity for turbulent flow is given by:

$$V_c = \left\{\frac{47.88}{[0.4536/(3.7852\times10^{-3})]\times0.0254^{0.5}}\times\frac{8^{-0.5}\times(2.5/2.0)^{0.5}\times0.007\times3.575}{13.0\times2.323^{0.5}}\right\}^{[1/(2-0.5)]}$$

$$V_c = 1.16\ \text{m·s}^{-1}$$

This gives a critical flow rate of:

$$Q_c = 0.0254^2\times\frac{\pi\times2.323^2}{4}\times1.16 = 3.18\times10^{-3}\ \text{m}^3\text{·s}^{-1}$$

i.e.:

$$Q_c = \frac{60}{0.15898}\times3.18\times10^{-3} = 1.20\ \text{bbl/min}$$

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min? Its velocity is:

$$V = \frac{0.15898/60}{0.0254^2} \times \frac{4 \times 6}{\pi \times 2.323^2} = 5.81 \ \text{m} \cdot \text{s}^{-1}$$

So its Reynolds number is:

$$Re = \frac{[0.4536/(3.7852 \times 10^{-3})] \times 0.0254^{0.5}}{47.88} \times \frac{13.0 \times 5.81^{1.5} \times 2.323^{0.5}}{8^{-0.5} \times (2.5/2.0)^{0.5} \times 0.007} = 40{,}000$$

Since Re is larger than 3,575 the flow regime is turbulent, and the value of the friction factor can be determined from:

$$f = 0.0730 \times 40{,}000^{-0.293} = 3.25 \times 10^{-3}$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{[0.4536 \times (3.7852 \times 10^{-3})]}{0.0254} \times \frac{2 \times 13.0 \times 5.81^2 \times 3.25 \times 10^{-3}}{2.323} = 5{,}810 \ \text{Pa} \cdot \text{m}^{-1}$$

which gives a friction pressure of:

$$\Delta P = 0.14504 \times 10^{-3} \times 5{,}810 \times 0.3048 \times 1{,}500 \ = \ 385 \text{ psi}$$

What is the critical flow rate for turbulent flow, in bbl/min, for a Power Law with a density of 13.0 lb/gal, a Power Law index of 0.5 and a consistency index of 0.007 lbf·s^n/ft^2 flowing in a $8^5/_7$ inch annulus? The critical velocity for turbulent flow is given by:

$$V_c = \left\{ \frac{47.88}{[0.4536/(3.7852 \times 10^{-3})] \times 0.0254^{0.5}} \times \frac{8^{-0.5} \times (2.5/2.0)^{0.5} \times 0.007 \times 3{,}575}{13.0 \times (8.5 - 7.0)^{0.5}} \right\}^{[1/(2-0.5)]}$$

$$V_c = 1.34 \ \text{m} \cdot \text{s}^{-1}$$

for the pipe approximation, and:

$$V_c = \left\{ \frac{47.88}{[0.4536/(3.7852 \times 10^{-3})] \times 0.0254^{0.5}} \times \frac{12^{-0.5} \times (2.5/1.5)^{0.5} \times 0.007 \times 3{,}575}{13.0 \times (8.5 - 7.0)^{0.5}} \right\}^{[1/(2-0.5)]}$$

$$V_c = 1.20 \ \text{m} \cdot \text{s}^{-1}$$

for the slot approximation. This gives a critical flow rate of:

$$Q_c = 0.0254^2 \times \frac{\pi \times (8.5^2 - 7.0^2)}{4} \times 1.34 = 0.0158 \ \text{m}^3 \cdot \text{s}^{-1}$$

i.e.:

$$Q_c = \frac{60}{0.15898} \times 0.0158 \ = \ 5.97 \text{ bbl/min}$$

for the pipe approximation and:

$$Q_c = \frac{60}{0.15898} \times 0.0141 \ = \ 5.33 \text{ bbl/min}$$

for the slot approximation.

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min? Its velocity is:

$$V = \frac{0.15898/60}{0.0254^2} \times \frac{4 \times 6}{\pi \times (8.5^2 - 7.0^2)} = 1.35 \ \text{m} \cdot \text{s}^{-1}$$

So its Reynolds number is:

$$Re = \frac{[0.4536/(3.7852 \times 10^{-3})] \times 0.0254^{0.5}}{47.88} \times \frac{13.0 \times 1.35^{1.5} \times (8.5 - 7.0)^{0.5}}{8^{-0.5} \times (2.5/2.0)^{0.5} \times 0.007} = 3{,}600$$

for the pipe approximation, and:

$$Re = \frac{[0.4536/(3.7852 \times 10^{-3})] \times 0.0254^{0.5}}{47.88} \times \frac{13.0 \times 1.35^{1.5} \times (8.5 - 7.0)^{0.5}}{12^{-0.5} \times (2.0/1.5)^{0.5} \times 0.007} = 4{,}270$$

for the slot approximation. Since Re is larger than 3,575, the flow regime is turbulent and the value of the friction factor can be determined from:

$$f = 0.0730 \times 3{,}600^{-0.293} = 6.60 \times 10^{-3}$$

for the pipe approximation, and:

$$f = 0.0730 \times 4{,}270^{-0.293} = 6.28 \times 10^{-3}$$

for the slot approximation. So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{[0.4536 \times (3.7852 \times 10^{-3})]}{0.0254} \times \frac{2 \times 13.0 \times 1.35^2 \times 6.60 \times 10^{-3}}{(8.5 - 7.0)} = 983 \ \text{Pa} \cdot \text{m}^{-1}$$

which gives a friction pressure of:

$$\Delta P = 0.14504 \times 10^{-3} \times 983 \times 0.3048 \times 1{,}500 \ = \ 65.2 \text{ psi}$$

for the pipe approximation, and:

$$\Delta P = 0.14504 \times 10^{-3} \times 935 \times 0.3048 \times 1{,}500 \ = \ 62.0 \text{ psi}$$

for the slot approximation.

13.5.3 Bingham Plastic Fluid

13.5.3.1 Example 1 is as follows:

What is the critical flow rate for turbulent flow, in bbl/min, for a Bingham plastic fluid with a density of 13.0 lb/gal, rotational viscometer PV of 6 cp and rotational viscometer YP of 8 lbf/100 ft^2, flowing in a 2.323 inch ID pipe?

The rotational viscometer PV and YP are modified as:

$$\mu_p = \text{Exp}[0.98151n(6) - 0.03832] = 5.5862$$

$$\tau_o = [1.1938 - 1.611] = 7.933$$

The Hedstrom number is:

$$He = \frac{37{,}010 \times 7.933 \times 13 \times 2.323^2}{5.5862} = 660{,}042$$

Once He is calculated, α_c and Re_{BP2} are estimated as:

$$\alpha_c = \frac{3}{4}\frac{\left(\frac{2 \times 660{,}042}{24{,}500} + \frac{3}{4}\right) - \sqrt{\left(\frac{2 \times 660{,}042}{24{,}500} + \frac{3}{4}\right)^2 - 4\left(\frac{660{,}042}{24{,}500}\right)^2}}{2\left(\frac{660{,}042}{24{,}500}\right)} = 0.6349$$

$$Re_{BP2} = \frac{660{,}042 \times (0.968774 - 1.362439 \times 0.6349 + 0.1600822 \times 0.6349^4)}{8 \times 0.6349}$$

$$= 16{,}870$$

The critical velocity is:

$$V_c = \frac{5.5862 \times 16{,}870}{927.6 \times 13 \times 2.323} = 3.36 \text{ ft/sec}$$

and the critical flowrate is:

$$Q_c = \frac{\pi \times 2.323^2 \times 3.36}{13.4828 \times 4} = 1.06 \text{ bbl/min}$$

13.5.3.2 Example 2 is as follows:

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min?

Its velocity is:

$$V = \frac{4 \times 6 \times 13.4828}{\pi \times 2.323^2} = 19.08 \text{ ft/sec}$$

So the Bingham Reynolds number is:

$$Re_{BP} = \frac{927.6 \times 19.08 \times 13 \times 2.323}{5.5862} = 95{,}677$$

Since Re is greater than Re_{BP2}, 16,870, the flow regime is turbulent, and since He is greater than 1.5×10^5 the value of the friction factor is determined from:

$$f = 0.20521(95{,}677)^{-0.35579} = 0.003468$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{2 \times 13 \times 19.08^2 \times 0.003468 \times 0.01936}{2.323} = 0.2736 \text{ psi/ft}$$

which gives a friction pressure of:

$$\Delta P = 0.2736 \times 1{,}500 = 410 \text{ psi}$$

13.5.3.3 Example 3 is as follows:

What is the critical flow rate for turbulent flow, in bbl/min, for a Bingham plastic fluid with a density of 13.0 lb/gal, a rotational viscometer PV of 6 and a rotational viscometer YP of 8, flowing in a 8.5 x 7 inch annulus?

The ratio, $D_d/D_h = 7/8.5 = 0.82$

This is greater than 0.3, hence slot approximation should be used. However, the example will be worked out for both pipe and slot model.

The critical velocity for turbulent flow is estimated as follows:

Hedstrom number is estimated as:

Annular Flow: Pipe
$He = \frac{37{,}010 \times 7.93 \times 13 \times (8.5-7)^2}{5.5862^2} = 275{,}204$
Annular Flow: Slot
$He = \frac{37{,}010 \times 7.93 \times 13 \times (8.5-7)^2}{1.5^2 \times 5.5862^2} = 122{,}313$

The α_c is estimated as:

Annular Flow: Pipe
$\alpha_c = \frac{3}{4}\frac{\left(\frac{2 \times 275{,}204}{24{,}500} + \frac{3}{4}\right) - \sqrt{\left(\frac{2 \times 275{,}204}{24{,}500} + \frac{3}{4}\right)^2 - 4\left(\frac{275{,}204}{24{,}500}\right)^2}}{2\left(\frac{275{,}204}{24{,}500}\right)} = 0.5796$
Annular Flow: Slot
$\alpha_c = \frac{3}{4}\frac{\left(\frac{2 \times 122{,}313}{24{,}500} + \frac{3}{4}\right) - \sqrt{\left(\frac{2 \times 122{,}313}{24{,}500} + \frac{3}{4}\right)^2 - 4\left(\frac{122{,}313}{24{,}500}\right)^2}}{2\left(\frac{122{,}313}{24{,}500}\right)} = 0.5102$

The critical Bingham Reynolds number, Re_{BP2}, is estimated as:

Annular Flow: Pipe
$Re_{BP2} = \frac{275{,}204 \times (0.968774 - 1.362439 \times 0.5796 + 0.1600822 \times 0.5796^4)}{8 \times 0.5796}$ $= 11{,}699$
Annular Flow: Slot
$Re_{BP2} = \frac{122{,}313 \times (0.968774 - 1.362439 \times 0.5102 + 0.1600822 \times 0.5102^4)}{120.5102}$ $= 5{,}682$

The critical fluid mean velocity for turbulent flow, V_c, is given by:

Annular Flow: Pipe
$V_c = \dfrac{5.5862 \times 11{,}699}{927.6 \times 13 \times (8.5-7)} = 3.61$ ft/sec
Annular Flow: Slot
$V_c = \dfrac{1.5 \times 5.5862 \times 5{,}682}{927.6 \times 13 \times (8.5-7)} = 1.75$ ft/sec

The critical flowrates are estimated as:

Annular Flow: Pipe
$Q_c = \dfrac{\pi \times (8.5^2 - 7^2) \times 3.61}{13.4828 \times 4} = 4.9$ bbl/min
Annular Flow: Slot
$Q_c = \dfrac{\pi \times (8.5^2 - 7^2) \times 1.75}{13.4828 \times 4} = 2.38$ bbl/min

13.5.3.4 Example 4 is as follows:

What is the friction pressure in psi over 1,500 ft for the same fluid flowing at 6 bbl/min?

Its velocity is:

$$V = \frac{4 \times 6 \times 13.4828}{\pi \times (8.5^2 - 7^2)} = 4.43 \text{ ft/sec}$$

So its Reynolds number is:

Annular Flow: Pipe
$Re_{BP} = \dfrac{927.6 \times 4.4284 \times 13 \times (8.5-7)}{5.5862} = 14{,}339$
Annular Flow: Slot
$Re_{BP} = \dfrac{927.6 \times 4.4284 \times 13 \times (8.5-7)}{1.5 \times 5.5862} = 9{,}559$

Since Re_{BP} is greater than Re_{BP2} in both pipe and slot model, the flow regime is turbulent.

For the pipe flow model the Hedstrom number, *He*, is greater than 1.5 x 10^5. So friction factor, *f*, is given by:

$$f = 0.20521(14{,}339)^{-0.35579} = 0.006813$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{2 \times 13 \times 4.4284^2 \times 0.006813 \times 0.01936}{(8.5-7)} = 0.0448 \text{ psi/ft}$$

which gives a friction pressure of:

$$\Delta P = 0.0448 \times 1{,}500 = 67.25 \text{ psi}$$

For the slot flow model the Hedstrom number, *He*, is such that 0.75 x 10^5 < *He* < 1.575 x 10^5. So friction factor, *f*, is given by:

$$f = 0.263651(9{,}559)^{-0.38931} = 0.007437$$

So the friction pressure gradient is given by:

$$\frac{\Delta P}{L} = \frac{2 \times 13 \times 4.4284^2 \times 0.007437 \times 0.01936}{2.323} = 0.0489 \text{ psi/ft}$$

which gives a friction pressure of:

$$\Delta P = 0.0489 \times 1{,}500 = 73.41 \text{ psi}$$

Table 10—Value of Constant *K*

Constant	Equation	U.S. Oil Field Unit	SI Metric Unit
K_v	38, 39, 40, 41	13.4828	1
$K_{\Delta P/L}$	42, 43	0.01936	1
K_{Re}	44, 45, 46, 47, 48, 49	927.6	1
K_{RePL}	54, 55, 56, 57, 58, 59, 62, 63, 64	$\frac{0.2325}{12}$	1
$K_{\mu p,R.V.}$	69	1	1,000
$K_{\tau o,R.V.}$	70	1	2.0885
$K_{\mu p}$	69	1	0.001
$K_{\tau o}$	70	1	0.4788
K_{ReBP}	71, 72, 73, 74, 75, 76, 87, 88, 89, 96	927.6	1
K_{He}	83, 84, 85, 97	37,010	1

Table 11—Nomenclature

Parameter	Definition	U.S. Oil Field Unit	SI Unit
D_i	Inner diameter of a pipe	in	m
D_o, D_h	Inner and outer diameters of an annulus	in	m
f	Friction factor	—	—
g_c	Gravitational constant	$lb \cdot ft \cdot lbf^{-1} \cdot sec^{-2}$	—
k	Consistency index of a Power Law fluid	$lbf \cdot sec^{n} \cdot ft^{-2}$	$Pa \cdot s^{n}$
L	Length of a pipe or of an annulus	ft	m
n	Power Law index of a Power Law fluid	—	—
Re	Reynolds number of a Newtonian fluid	—	—
Re_i	Critical values of Re	—	—
Re_{PL}	Reynolds number of a Power Law fluid	—	—
Re_{PLi}	Critical values of Re_{PL}	—	—
Re_{BP}	Reynolds number of a Bingham plastic fluid	—	—
Re_{BPi}	Critical values of Re_{BP}	—	—
Q	Volumetric flow rate	$bbl \cdot min^{-1}$	$m^3 \cdot s^{-1}$
Q_c	Critical value of Q	$bbl \cdot min^{-1}$	$m^3 \cdot s^{-1}$
V	Fluid mean velocity	$ft \cdot sec^{-1}$	$m \cdot s^{-1}$
V_c	Critical value of V	$ft \cdot sec^{-1}$	$m \cdot s^{-1}$
DP	Friction pressure	psi	Pa
m	Viscosity of a Newtonian fluid	cp	$Pa \cdot s$
m_p	Plastic viscosity of a Bingham plastic fluid	cp	$Pa \cdot s$
r	Fluid density	$lb \cdot gal^{-1}$	$kg \cdot m^{-3}$
t_y	Yield stress of a Bingham plastic fluid	$lbf \cdot (100ft^2)^{-1}$	Pa

Table 12—Conversion Factors

Unit	to be multiplied by	to get value in SI unit
bar	100,000	Pa
bbl	0.15898	m^3
bbl/min	0.15898/60	$m^3 \cdot s^{-1}$
cp	0.001	$Pa \cdot s$
ft	0.3048	m
gal/min	$(3.7852 \times 10^{-3})/60$	$m^3 \cdot s^{-1}$
in	0.0254	m
l	0.001	m^3
l/min	0.001/60	$m^3 \cdot s^{-1}$
lb/gal	$0.4536/(3.7852 \times 10^{-3})$	$kg \cdot m^{-3}$
lb/ft^3	$0.4536/0.3048^3$	$kg \cdot m^{-3}$
$lbf/100ft^2$	0.4788	Pa
$lbf \cdot s^n/ft^2$	47.88	$Pa \cdot s^n$
psi	0.14504×10^{-3}	Pa

14 Arctic Cementing Test Procedure

14.1 SCOPE

This procedure is intended for the testing of cement slurries that are to be placed in areas known to contain permafrost. The conditioning temperature for the test equipment, materials to be tested, and the test temperatures should be controlled to ±2°F (±1°C).

14.2 PREPARATION OF CEMENT SLURRY

Test samples should be prepared according to Section 5 procedures, except that the cement blend and mixing equipment should be pre-conditioned at 20°F (–7°C). Mix water should be pre-chilled to 34°F (1°C), and the slurry temperature should be recorded immediately after mixing; ~40°F (4°C) is typical. Each of the above temperatures should be measured and reported on all tests.

14.3 FLUID FRACTION

The fluid fraction should be expressed as percent by weight of basic dry blend (not including any additives needed for placement).

14.4 THICKENING TIME

Thickening time test should be performed in a consistometer at 40°F (4°C) at atmospheric pressure.

14.5 COMPRESSIVE STRENGTH

Specimens should be cured at 20°F (–7°C) and 40°F (4°C) for the desired testing period, i.e., 1-3-7 days.

The molds should be pre-conditioned by cooling to the temperature of the curing bath, 20°F (–7°C) or 40°F (4°C).

Selected cementing compositions should be stirred for 90 minutes in a consistometer at 40°F (4°C) before pouring into the pre-conditioned molds for curing. For curing at temperatures below 32°F (0°C), test specimens should be sealed in a container of fresh water at the higher of test temperature or 35°F (2°C). Submerge the sealed container in a mineral oil or glycol bath at test temperature in a manner consistent with avoiding contamination of the fresh water and specimens.

Example: For 24-hour compressive strengths:

a. Stir cement slurry for 90 minutes at 40°F (4°C) and atmospheric pressure.

b. Quickly pour slurry into pre-conditioned molds, seal in a suitable container filled with fresh water [for tests below 32°F (0°C)], and submerge in curing bath.

c. Cure slurry for 22 hours at 20°F (–7°C) or 40°F (4°C), and monitor temperature.

d. Remove cubes from molds 30 minutes before breaking and place them in 40°F (4°C) water. The specimens should be crushed at the loading rates described in 7.5.6.1.

14.6 FREEZE-THAW CYCLING AT ATMOSPHERIC PRESSURE

Slurry should be prepared as in 14.2 (do not precondition the slurry as in 14.5) and cured under the following sequence (it is suggested that the cycle begin on a Monday):

a. 48 hours at 40°F (4°C) Monday.
b. 24 hours at 20°F (–7°C) Wednesday.
c. 24 hours at 40°F (4°C) Thursday.
d. 72 hours at 100°F (38°C) Friday.
e. 72 hours at 170°F (77°C) Monday.
f. 24 hours at 100°F (38°C) Thursday.
g. 72 hours at 20°F (–7°C) Friday.
h. Raise to 40°F (4°C) and repeat cycle on Monday.

14.7 COMPRESSIVE STRENGTH CYCLIC TESTING

The cement cubes should be examined and broken after 1 and 3 cycles under these conditions (14 days and 42 days). Cure all compressive strength cubes under water and in molds during cycles with top of cement exposed to water. Break control specimens after 48 hours at 40°F (4°C) for reference.

15 Well Simulation Slurry Stability Tests

15.1 INTRODUCTION

The purpose of this test is to determine the static (quiescent) stability of a cement slurry. The cement slurry is conditioned to simulate dynamic placement in a wellbore. The slurry is then left static to determine if free fluid separates from the slurry or to determine if the cement slurry experiences particle sedimentation. Both the free fluid result and the sedimentation result are required to understand the static stability of the slurry under downhole conditions. Free fluid can be formed with minimal sedimentation and sedimentation can take place without free fluid being formed. Therefore, both results must be evaluated to determine slurry stability. Excessive free fluid and settling are normally considered detrimental to cement sheath quality. The amount of free fluid or settling that is acceptable will vary with the application. Table 13 can be used to record the results of these tests.

15.2 SLURRY MIXING

The cement slurry should be prepared according to Section 5. Immediately after mixing the slurry, measure the density of the slurry using a pressurized fluid density balance, if performing the sedimentation test described in 15.6.

15.3 SLURRY CONDITIONING

Any consistometer referenced in Section 9 may be used. The following procedure applies to the most commonly used equipment:

a. Place the slurry in the container of the pressurized consistometer and begin a thickening time test according to the procedure in Section 9, API Recommended Practice 10B. Apply pressure and heat or cool according to the thickening time schedule which most closely simulates actual field conditions. If desired, the slurry may be held at the specified temperature and pressure for 30, ±$^1/_2$ minutes or other desired conditioning period before proceeding to the next step. If the conditioning temperature is greater than 194°F (90°C) cool the slurry to approximately 194°F (90°C) for safety.

Note: The 194°F (90°C) safety temperature assumes a boiling point for water of 212°F (100°C). If the boiling point of water in your area is less than 212°F (100°C), adjust test temperatures accordingly.

b. Release the pressure slowly [about 200 psi/sec (1,380 kPa/sec)]. Remove the slurry cup from the consistometer, keeping the container upright so oil does not mix with the slurry. Remove the top locking ring, drive bar and collar from the shaft and the diaphragm cover. Syringe and blot oil from the top of the diaphragm. Remove the diaphragm and the support ring. Syringe and blot any remaining oil from the top of the slurry. If the contamination is severe, discard the slurry and begin the test again. Remove the paddle and stir the slurry briskly with a spatula to ensure a uniform slurry.

At this point, proceed with either 15.4 or 15.5 for a free fluid test. For a sedimentation test, proceed to 15.6.

15.4 FREE FLUID TEST WITH HEATED STATIC PERIOD

Pour the slurry into a clear graduated tube. The ratio of the slurry-filled length to the inside tube diameter should be greater than 6:1 and less than 8:1. The clear tube must be inert to well cements and must not deform during the test. The clear tube must be graduated such that the slurry volume placed in the tube can be visually determined with a precision of ±2 mL. The free fluid test slurry volume must be between 100 mL and 250 mL, inclusive. Document the slurry volume placed in the tube when the tube is vertical. Document the tube dimensions as well.

A test chamber for curing the slurry during the static period should be preheated or precooled to BHCT or 176°F (80°C), whichever is cooler. 176°F (80°C) was chosen to minimize the effects of condensation on the test results and assumes a boiling point for water of 212°F (100°C). If the boiling point of water in your area is less than 212°F (100°C), adjust the 176°F (80°C) test temperature accordingly. This chamber may be an atmospheric heating or cooling bath/oven/jacket/chamber, or a suitable pressurized heating/cooling chamber that uses hydrocarbon oil to transmit heating/cooling to the slurry.

Note: Bath/oven/jacket/chamber or pressurized chamber will be designated as a chamber for the rest of this section. When hydrocarbon oil is used the oil should have a flash point that satisfactorily meets the safety requirements of the organization performing the test.

15.4.1 Free Fluid Tests at Temperatures Less Than 176°F (80°C)

Immediately place the graduated tube in a heating or cooling chamber that is preheated or precooled to BHCT. Cover the opening of the graduated tube to prevent evaporation. The chamber must be able to heat or cool the entire slurry. The tube can be tilted to simulate hole angle, if desired. Appropriate precautions should be taken to ensure the static curing is performed at essentially vibration free conditions.

The temperature is maintained at BHCT for the remainder of the test. The test duration is two hours from the time the slurry is poured into the clear tube. After the two hour test period the free fluid (clear or colored fluid on top of the cement slurry inside of the clear tube) should be measured. The volume measurement should be made with a precision of ±0.2 mL.

The percent free fluid is then calculated:

$$\text{\% Free Fluid} = \frac{(\text{mL of Free Fluid})(100)}{\text{mL of Slurry}}$$

15.4.2 Free Fluid Test at Temperatures Greater Than or Equal to 176°F (80°C)

Place the graduated tube in a preheated [176°F (80°C)] oil filled heating chamber. Optionally, tilt the tube to simulate hole angle. Further heat the slurry to BHCT in the time required to take the slurry from a depth with 176°F (80°C) circulating temperature to BHCT. Some heating chambers may not be able to heat fast enough and in that case heat as fast as possible but minimize overshooting the BHCT. Maintain the slurry at BHCT until it is time to start cooling the chamber back down to 176°F (80°C). The time required to cool various pieces of equipment from elevated temperatures back to 176°F (80°C) will vary. The pressure on the curing chamber should be maintained high enough throughout the test so the slurry cannot boil (See Table 8). The pressure applied can simulate bottom hole conditions, if desired. So as to prevent vibration, constant pump cycling should be avoided. The schedules found in Section 9 can be used to aid in selecting pressure and temperature change rates. Appropriate precautions should be taken to ensure the static curing is performed at essentially vibration free conditions.

The two hour test period is initiated when the conditioned slurry is poured into the graduated tube. Slurries will need to be cooled to 176°F (80°C) before the free fluid can be measured. This cooling time is part of the 2 hour test period. After the two hour test period, the free fluid (clear or colored fluid on top of the cement slurry inside of the clear tube) should be measured. Free fluid for slurries immersed in hydrocarbon oil will collect above the cement but below the oil. The volume measurement of the free fluid should be made with a precision of ±0.2 mL.

The percent free fluid is then calculated:

$$\% \text{ Free Fluid} = \frac{(\text{mL of Free Fluid})(100)}{\text{mL of Slurry}}$$

15.5 FREE FLUID TEST WITH AMBIENT TEMPERATURE STATIC PERIOD

Pour 250 mL of the slurry from 15.3 into a 250 mL graduated glass cylinder. The zero to 250 mL graduated portion of the cylinder shall be no less that 232 mm nor more than 250 mm in length, graduated in 2 mL increments or less. The slurry should be stirred by hand with a spatula during pouring to assure a uniform sample of the slurry. The two hour test period is initiated when the conditioned slurry is poured into the graduated tube. The graduated cylinder should be sealed with plastic film wrap or equivalent material to prevent evaporation. The graduate may be inclined at an angle to simulate wellbore deviation. Appropriate precautions should be taken to ensure the static curing is performed at essentially vibration free conditions.

After the two hour test period, the free fluid (clear or colored fluid on top of the cement slurry inside of the clear tube) should be measured. The volume measurement of the free fluid should be made with a precision of ±0.2 mL.

The percent free fluid is then calculated:

$$\% \text{ Free Fluid} = \frac{(\text{mL of Free Fluid})(100)}{250 \text{ mL of Slurry}}$$

15.6 SEDIMENTATION TEST

15.6.1 Pour the slurry from 15.3 into a sedimentation tube until it is approximately $^3/_4$ inch (20 mm) from the top. The sedimentation tube should have an inner diameter of 25 mm, ±5 mm. The tube length should be a minimum of 100 mm. The most common tube length is approximately 200 mm. See Figure 17. The inside of the tube, and all joints, should be lightly greased to ensure that it is leak-tight and so that the set cement can be removed without damage. The tube must be inert to well cements and not deform during the course of the test. The slurry in the filled tube should be puddled to dislodge any air bubbles. The tube should then be filled completely. A top closure can be used to prevent spillage of the slurry. The top closure should allow pressure communication. The filled tube should be placed in a water filled preheated/precooled heating/cooling chamber in a vertical position. The chamber should be preheated or precooled to BHCT or 194°F (90°C) whichever is cooler (see safety note in 15.3).

15.6.2 The slurry temperature should be adjusted further to simulate temperature changes in the wellbore. Sufficient pressure must be maintained to prevent boiling of the slurry (see Table 8). The pressure applied can simulate bottom hole conditions, if desired. Constant pump cycling should be avoided to minimize vibration. The schedules in Sections 7 and 9 can be used to aid in selecting the temperature and pressure.

15.6.3 Allow the slurry to cure for 24 hours or until set before removing it from the heating/cooling chamber.

15.6.4 Cool the chamber to 194°F (90°C), if required (see safety note in 15.3). Release pressure from the chamber, if required. Remove the tube from the heating/cooling chamber and bring the tube to 80, ±10°F (27, ±6°C) by placing it in a water bath. Once the tube has cooled remove the cement from the tube. Keep the cement sample immersed in water, as much as possible, to prevent it from drying out. The length of the set cement specimen should be measured. Mark the specimen approximately $^3/_4$ inch (20 mm) from the bottom and from the top of the sample. The middle section, between the marks, should then be divided by further marks into roughly equal pieces with a minimum of 2 segments. The sample should be broken or cut at these marks. The sections must be kept in order. Keep the sections immersed in water until each is weighed. A balance with a precision of 0.01 gram is necessary, 0.001 gram is preferred.

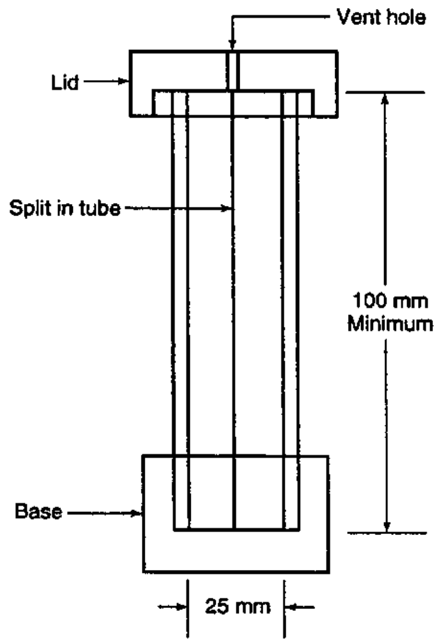


Figure 17—Typical Sedimentation Tube

15.6.5 The preferred way to determine the density of each section is to place a beaker containing water on the balance and tare the balance to zero. Remove a section to be measured from the water bath and gently dry it with a paper towel. Place this section on the balance beside the beaker. Record a weight and remove the section from the balance. Retare the balance to zero. Next place a noose of thin line around the section. Pick up the section by the line and suspend the section in the water in the beaker such that the sample is totally surrounded by water. The sample should not touch the bottom or sides of the beaker. Air bubbles should not be clinging to the section. Obtain the weight of the sample suspended in water. Remove the sample from the water and retare the balance. Repeat the procedure for each set cement section.

15.6.6 By applying the Principle of Archimedes, calculate the specific gravity of each cement core section.

$$S.G. = \frac{\text{Weight of section in air, g}}{\text{Weight of section in water, g}}$$

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

Note: It is normal for cement slurries to experience a small density increase upon setting.

The liquid slurry density was measured prior to curing to permit the calculation of the % density difference between the liquid sample and the set sample.

$$\%\ \text{Density Difference} = \frac{(\text{Density of Cement Segment}\ \ \text{Density of Cement Slurry})(100)}{(\text{Density of Cement Slurry})}$$

The density difference for well cements can vary greatly and depends on many factors. The amount of density difference that is acceptable will vary with the application.

Table 13—Free Fluid and Sedimentation Results Data Sheet

Slurry Mixing and Conditioning

Cement Temperature: ______
Mix Water Temperature: ______
Slurry Initial Temperature: ______
Slurry Final Temperature: ______
Time to Final Temperature: ______
Optional Additional Conditioning Period: ______
Pressure Profile:
Initial Pressure: ______
Final Pressure: ______
Time to Final Pressure: ______

Free Fluid Test

Length of Graduated Tube Section: ______
Graduated tube I.D.: ______

Less than 176°F (80°C)
Slurry Volume: ______
Test Temperature: ______
Test Angle: ______
Measured Free Fluid Volume: ______mL
% Free Fluid: ______

Greater than or equal to 176°F (80°C)
Slurry Volume: ______
Final Temperature: ______
Time to Final Temperature: ______ minutes
Initial Test Pressure: ______
Final Test Pressure: ______
Time to Final Test Pressure: ______
Test Angle: ______
Time to Cool the Slurry to 194°F (90°C): ______
Measured Free Fluid Volume: ______mL
% Free Fluid: ______
Section 7 Schedules Employed: ______Yes or ______No
If Yes, Schedule Number: ______

Ambient Static Period
Test Angle: ______
Measured Free Fluid Volume: ______mL
% Free Fluid: ______

Sedimentation Test

Preheated or Precooled Chamber Temperature: ______
BHCT: ______
Time to BHCT: ______
BHST: ______
Time to BHST: ______
Initial Test Pressure: ______
Pressure at BHCT: ______
Time to Pressure at BHCT: ______
Pressure at BHST: ______
Time to Pressure at BHST: ______
Time at BHST: ______hours
Time to Cool the Chamber to 194°F (90°C): ______
Length of Sedimentation Tube: ______
Length of Set Specimen: ______
Section 9 Schedules Employed: ______Yes or ______No
If Yes, Schedule Number: ______
Section 7 Schedules Employed: ______Yes or ______No
If Yes, Schedule Number: ______

Slurry Density: ______

Density Profile:
Top Sample Density: ______; % Density Diff: ______
Next Sample Density: ______; % Density Diff: ______
Next Sample Density: ______; % Density Diff: ______
Next Sample Density: ______; % Density Diff: ______
Next Sample Density: ______; % Density Diff: ______
Bottom Sample Density: ______; % Density Diff: ______

Note: The heating/cooling, pressurizing, and cooling information that is requested in the results reporting form will allow other laboratories to reproduce the test. The information requested is sufficient only if the heating/cooling rate, pressurizing rate, and cool down rate are linear. If the rates are not linear, specify the exact heating/cooling, pressurizing, and cool down schedules.

16 Compatibility of Wellbore Fluids

16.1 SCOPE

This procedure is intended for determining the degree of compatibility of wellbore fluids in cementing operations. This procedure includes rheology, static gel strength, thickening time, compressive strength, fluid loss and solids suspension. By the use of this procedure, the selection of proper preflushes and/or spacers may be made when required. User discretion should be exercised in the selection of the portion(s) of the procedure needed.

16.2 DEFINITIONS

The following definitions apply to this section:

16.2.1 compatible: Capable of forming a mixture that does not undergo undesirable chemical and/or physical reactions.

16.2.2 preflush: A fluid used to separate drilling fluids and cementing slurries. A preflush can be designed for use with either water based or oil based drilling fluids, and prepares both pipe and formation for the cementing operation. Preflushes are not typically densified with insoluble solid weighting agents. Preflushes are also referred to as washes.

16.2.3 spacer: A fluid used to separate drilling fluids and cementing slurries. A spacer can be designed for use with either water based or oil based drilling fluids, and prepares both pipe and formation for the cementing operation. Spacers are typically densified with insoluble solid weighting agents.

Note: The following test procedures are the same for preflushes and spacers. Therefore, the term spacer will be used to refer to both fluids hereafter.

16.3 PREPARATION OF TEST FLUIDS

16.3.1 Preparation of Spacer

The spacer should be freshly prepared and aged in accordance with the supplier's instructions.

16.3.2 Preparation of Mud

Representative field mud should be used. Mud samples should be thoroughly mixed prior to testing.

16.3.3 Preparation of Cementing Slurries

The cement slurries should be prepared according to Section 5 or Appendix A. A fresh quantity of cementing slurry should be prepared for each test.

16.3.4 Preparation of Fluid Mixtures

Mixtures prepared in this section should be used for rheological, static gel strength, solids suspension, thickening time, compressive strength, and fluid loss testing. Data for base fluids should be obtained before mixtures are prepared. All fluid mixtures in this section are expressed as volume percentage of the total mixture. The mixture for each test procedure should be prepared by stirring the proper ratio of base fluids with a spatula until homogeneous. The volume of the mixture should be sufficient to perform the desired test procedure.

16.4 RHEOLOGY

Rheological properties should be performed on mixtures of cement/mud, cement/spacer, and mud/spacer. The recommended ratios are 95/5, 75/25, 50/50, 25/75 and 5/95 for each fluid combination as well as a 25/50/25 mixture of mud/spacer/cement. The ratios may be prepared according to Table 14. The rheological properties should be measured according to Section 12. The data may be recorded on Table 15.

Table 14—Compatibility Mixing Ratios

Percent by Volume Mud or Cement/Spacer	Mixing Scheme
1. 95/5	760 mL Mud or Cement / 40 mL Spacer
2. 75/25	100 mL Spacer plus 375 mL of #1
3. 5/95	760 mL Spacer / 40 mL Mud or Cement
4. 25/75	100 mL Mud or Cement plus 375 mL of #3
5. 50/50	Equal parts of #1 and #3
6. 25/50/25 Mud/Spacer/Cement	Equal parts of #5 Mud/Spacer and #5 Cement/Spacer

16.5 THICKENING TIME

Thickening time tests should be run on mixtures of cement/spacer. The recommended ratios are 95/5 and 75/25. The thickening time test should be performed according to Section 9. At user discretion, tests may be run on mixtures of cement/mud, spacer/mud and cement/mud/spacer.

16.6 COMPRESSIVE STRENGTH

Compressive strength tests should be run on mixtures of cement/spacer. The recommended ratios are 95/5 and 75/25. The compressive strength test should be conducted in accordance with either Section 7 or Section 8. At user discretion, tests may be run on mixtures of cement/mud and cement/mud/spacer.

16.7 SOLIDS SUSPENSION AND STATIC GEL STRENGTH

16.7.1 This procedure is designed to investigate the behavior of fluid mixtures during and following cement slurry placement. Selection of the fluid mixtures and ratios should be made based on results obtained from 16.4 and/or 16.5 at user discretion.

Table 15—Rheological Compatibility of Mud Cement and Spacer Data Sheet

Cement: ____________________

Spacer: ____________________

Mud: ____________________

Fluid Mixture	Test Temp	Viscometer Dial Readings							PV	YP
% BV	(°F)/(°C)	300	200	100	60	30	6	3	(cps)	(#/100 ft²)/(Pa)
100% Cement										
100% Spacer										
100% Mud										
95% Mud 5% Cmt										
75% Mud 25% Cmt										
50% Mud 50% Cmt										
25% Mud 75% Cmt										
5% Mud 95% Cmt										
95% Mud 5% Spacer										
75% Mud 25% Spacer										
50% Mud 50% Spacer										
25% Mud 75% Spacer										
5% Mud 95% Spacer										
95% Cmt 5% Spacer										
75% Cmt 25% Spacer										
50% Cmt 50% Spacer										
25% Cmt 75% Spacer										
5% Cmt 95% Spacer										
25% Mud 50% Spacer 25% Cmt										

16.7.2 Initiate a thickening time test on the selected mixtures according to Section 7. When the specified time for heat-up has been reached, read the consistency in B_c and then cease stirring. After an elapsed time of 10 minutes, resume stirring while observing for any momentary gel strength development or solids settling as indicated by a maximum deflection in consistency at the instant of start up. Continue stirring the cement slurry until one-half of the thickening time of the base cement slurry has been reached. Read the consistency in B_c and cease stirring. After an elapsed time of 10 minutes, resume stirring while observing for any momentary gel strength development or solids settling. This cycle may be repeated as often as desired at user discretion.

16.8 FLUID LOSS

Fluid loss tests should be run on mixtures of cement/spacer. The recommended ratios are 95/5 and 75/25. The fluid loss test should be conducted in accordance with Section 10. At user discretion, tests may be run on mixtures of cement/mud and cement/mud/spacer.

17 Pozzolans

17.1 GENERAL

This section covers the recommended terminology, procedures, and properties for pozzolans used in well cements.

17.2 DEFINITIONS

17.2.1 fly ash: Defined by the ASTM as "finely divided residue that results from the combustion of ground or powdered coal." Fly ashes are called artificial pozzolans and are the most commonly used pozzolans in well cements.

17.2.2 fly ash, class C: ASTM Class C fly ash is obtained by burning lignite or subbituminous coals. Class C fly ash may be produced with some content of calcium monoxide (lime) which hydrates to form calcium hydroxide.

17.2.3 fly ash, class F: ASTM Class F fly ash is produced as the combustion residue from anthracite or bituminous coals.

17.2.4 pozzolans: Defined by the ASTM as "siliceous and aluminous materials, which in themselves possess little or no cementitious value but will in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

17.2.5 pozzolans, class N: ASTM Class N pozzolans are naturally occurring materials such as volcanic ashes, tuffs, pumice's, etc. Class N pozzolans are not widely used in well cementing.

17.3 PHYSICAL AND CHEMICAL PROPERTIES

17.3.1 Pozzolan's physical and chemical specifications are listed in ASTM C 618, *Fly Ash and Raw or Calcined Natural Pozzolan use as a Mineral Admixture in Portland Cement Concrete.*

17.3.2 The average bulk density of pozzolan is used to select storage container capacity. The average bulk density may vary between 54 and 90 lbs/ft³ (865 and 1,442 km/m³) and should be determined by using the following procedure:

a. A clean, dry 100 mL (TC Type) graduated cylinder is used for both loose and packed apparent density. The accuracy of the graduated cylinder should be checked by filling with 99.75 g of distilled water which equals 100 mL volume at 23°C.

b. Place about 200 mL of the sample to be tested in a jar (1 qt. or liter) sealed with a lid and hand shake to "fluff" material for 30 seconds.

c. Over a one minute period loosely fill the tared graduate with fluffed material to the 100 mL mark. Weigh the sample and record for calculation of loose apparent bulk density.

d. The material is "packed" by gently tapping the cylinder on a hard surface cushioned with a pad to prevent breakage of the cylinder. Record the volume of material after each 100 taps and continue tapping, until compacted volume is unchanged. Record the packed volume of material directly from the cylinder graduations. This volume is used to calculate the packed apparent bulk density.

e. Calculate the common field units for bulk density as follows:

62.43/100 (mL) x Weight (g)
= Loose Apparent Bulk Density (lb/ft³)[a]

62.43/Packed Volume (mL) x Weight (g)
= Packed Apparent Bulk Density (lb/ft³)[a]

[a]Multiply by 16.01846 for kg /mL.

f. Report average bulk density in pounds per cubic foot as the average of the loose and packed determinations.

17.3.3 The specific gravity (S.G.) of pozzolan should be measured in either a Le Chatelier flask, according to ASTM designation: C188, *Standard Test Method for Density of Hydraulic Cement*, or in a gas pycnometer. Certain pozzolans may contain particles with a specific gravity less than the kerosene or naphtha specified in ASTM C188. Suitable fluids with a specific gravity that prevents floating of these particles may be used. Preferably a gas pycnometer may be used to measure the specific gravity of the pozzolan containing unusually light particles.

Pozzolans with no particles lighter than water can be tested for specific gravity according to ASTM designation: C 128 Standard Test Method for Specific Gravity and Absorption of fine Aggregate.

17.4 SLURRY CALCULATIONS

17.4.1 The terms bulk density and absolute density should be understood to prevent confusion. They both have density units, i.e., lbs/ft^3, lbs/gal, grams/mL, etc. However, bulk and absolute density values for Portland cement are very different. The bulk density for Portland cement can vary but it is usually about 12.57 lbs/gal (94 lbs/ft^3) (1506.22 kg/m^3). The absolute density for Portland cement can vary but it is usually about 26.18 lbs/gal (3137.06 kg/m^3). Bulk density includes the air space around particles and that is why it is a smaller number than the absolute density. Bulk density is used to calculate storage requirements for dry powdered cement or other dry powdered materials. Absolute density is the density of the material without air around the particles and is thus a much larger number. Absolute density is used to calculate liquid slurry properties such as slurry density, slurry water requirement, and slurry yield. Absolute density in lbs/gal or kg/m^3 can also be obtained by multiplying the specific gravity of a material by the density of water at 4°C, 8.3454 lbs/gal or 1,000 kg/m^3, respectively.

17.4.2 An item which may cause confusion when calculating the weights of pozzolan and Portland cement for an equivalent sack of pozzolan and Portland cement blend is that in many cementing handbooks an absolute volume factor (inverse of absolute density) is given for determining slurry calculations. The absolute density of the pozzolan and of the Portland cement are required to perform the following calculations. The manufacturer of the pozzolan or cement should supply the absolute density of the material (or the specific gravity to be used in calculating the absolute density as previously stated).

17.4.3 When used with Portland cement in well cementing, the pozzolan amount is based on the absolute volume replacement of a portion of the Portland cement by an equivalent absolute volume of fly ash. These volumes are designated by a ratio of percentages such as (35:65). The first number refers to pozzolan and the second number refers to Portland cement. A (35:65) blend represents 35 absolute volume percent pozzolan mixed with 65 absolute volume percent cement. This designation is often not specific enough and should be further specified.

For example, (35 percent ASTM Class F Fly Ash: 65 percent API Class G Cement) would be a better designation. Including the manufacturer and mill of the pozzolan and cement is even better. In order to have a starting place to perform slurry calculations for pozzolan/Portland cement blends a definition for a sack of cement must be given. A sack of cement is defined as 94 lbs (42.64 kg) of Portland cement.

A sack of cement, 94 lbs (42.64 kg), has an absolute volume. The absolute volume can vary depending upon the absolute density of the cement. Normally, cement has an absolute density of about 26.20 lbs/gal (3,140 kg/m^3). The absolute density of Portland cement can vary between 25.87 lbs/gal (3,100 kg/m^3) and 27.12 lbs/gal (3,250 kg/m^3). The correct absolute density value for the selected cement should be used.

An example calculation for obtaining the absolute volume of a sack of cement with a low absolute density of 26.00 lbs/gal (3115.49 kg/m^3) is as follows:

$$(94 \text{ lbs}) / (26.00 \text{ lbs/gal}) = 3.62 \text{ gal}$$

Once the absolute volume of the sack of cement is known then the pozzolan and Portland cement percentages of the absolute volume can be calculated.

17.4.4 Expanding on the above examples. If a sack of cement is 3.62 gal (0.0137 m^3) and a 35:65 blend is wanted, then the pozzolan represents 1.27 gal (35 percent of 3.62 gal) and the Portland cement represents 2.35 gal (65 percent of 3.62 gal). The absolute gallons of pozzolan (1.27 gal) and the absolute volume of Portland cement (2.35 gal) are then used to calculate the pounds of each material from the absolute density values of pozzolan and Portland cement. Expanding further on the example: 2.35 gal x 26.00 lbs/gal = 61.1 lbs (27.71 kg) of Portland cement. Pozzolan absolute density can vary between 15.02 lbs/gal (1800 kg/m^3 and 24.20 lbs/gal (2900 kg/m^3) and the correct value must be known for the pozzolan material that will be used. Assume for example purposes that the absolute density of the pozzolan to be used is 20.50 lbs/gal. Then the weight of pozzolan is 26.0 lbs (11.79 kg) (1.27 gal x 20.50 lbs/gal).

Combining the pounds of pozzolan and the pounds of cement give 87.1 lbs (39.51 kg) (61.1 lbs + 26.0 lbs) of blend. For this example, 87.1 lbs (39.51 kg) of blend would be an equivalent sack.

17.4.5 A definition for equivalent sack of pozzolan/Portland cement blend is the weight of the blend in pounds that has the same absolute volume as 94 lbs (42.64 kg) of the Portland cement used in the blend. Once the weight of the equivalent sack is known, most other additives are based on this weight. For instance, let's assume that the blend has 6 percent bentonite and 0.2 percent retarder. The weight of bentonite per sack of blend is (6%) x (87.1 lbs) = 5.23 lbs of bentonite per equivalent sack. The weight of retarder per sack of blend is (0.2%) x (87.1 lbs) = 0. 17 lbs per equivalent sack.

The equivalent sack weight is now known. The additives weights in the blend are also known. Therefore, slurry density and slurry yield can be calculated if the amount of mix water is known.

Conversely, if the slurry density is known, then the slurry yield and mix water requirements can be calculated. Once the value for slurry yield is determined, the number of equivalent sacks of blend for a given job can be determined from pipe and hole configuration, caliper logs, etc.

Assume the job requires 125 equivalent sacks. Then, (125 sks) x (61.1 lbs/sk) = 7,638 lbs of Portland cement would be required. For the same 125 sack job, (125 sks) x (26.0 lbs/sk) = 3,250 lbs of pozzolan would be required. The amounts of bentonite and retarder required are, respectively, (125 sks) x (5.23 lbs/sk) = 654 lbs (296.54 kg) and (125 sks) x (0. 17 lbs/sk) = 22 lbs (9.64 kg).

17.5 BULK VOLUME OF A BLEND

17.5.1 The bulk volume of a blend of pozzolan and Portland cement will vary depending on the amount of small particle packing between larger particles during the blending operation and other factors such as humidity, vibration, time, air content, and the compacting force on the materials.

17.5.2 Examples of field bulk volume measurements using actual one sack blend weights are listed below:

Blend	Aerated	Packed	Average (one sack)
A	1.171 ft^3	1.03 ft^3	1.101 ft^3
B	1.171 ft^3	1.03 ft^3	1.101 ft^3
C	1.171 ft^3	0.88 ft^3	1.025 ft^3

The recommended practice to determine the bulk volume of an equivalent of pozzolan/Portland cement blend is to average the aerated (loose or fluffed) and the packed bulk volume values as noted above.

Note: Blend A = (35% ASTM Class F Fly Ash: 65% API Class A Cement).
Blend B = (50% ASTM Class F Fly Ash: 50% API Class A Cement).
Blend C = (50% ASTM Class F Fly Ash: 50% API Class H Cement).

APPENDIX A—PROCEDURE FOR PREPARATION OF LARGE SLURRY VOLUMES

A.1 General

This procedure is recommended only when an individual test requires a slurry volume greater than 600 mL. It is not intended to be used in place of Section 5.

A.2 Apparatus

All equipment should be the same as outlined in Section 5 except the mixing device as described in A.2.1.

A.2.1 MIXING DEVICE

The mixing device for preparation of large slurry volumes should be a four-quart size, bottom drive, blade-type mixer. Examples of mixing devices in common use are shown in Figure A-1. The mixing container and the mixing blade should be constructed of corrosion-resistant material. The mixing assembly should be constructed so that the blade can be separated from the drive mechanism. The mixing blade should be separated from the mixing assembly and weighed prior to use and replaced with a new blade when 10 percent weight loss has occurred. The blade should also be visually inspected for damage prior to each use and replaced as necessary. Should the mixing device leak at any time during the mixing procedure, the contents should be discarded, the leak repaired and the procedure restarted.

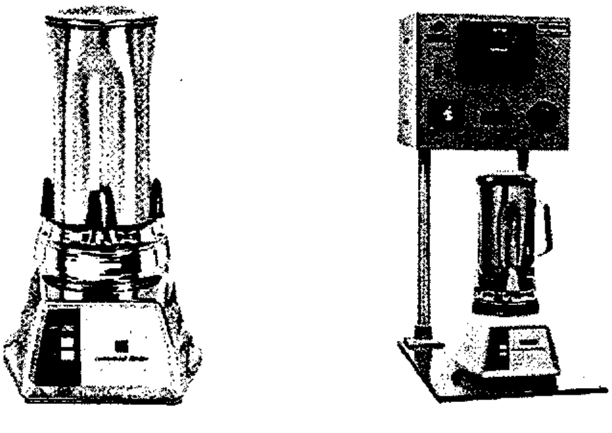


Figure A-1—Examples of Typical Cement Mixing Devices

A.3 Procedure

The procedure should be the same as outlined in Section 5 except as described below.

A.3.1 LABORATORY DENSITY AND VOLUME CALCULATIONS

A slurry volume of no less than 2,000 mL and no more than 4,000 mL should be prepared. Laboratory blend requirements may be calculated by use of the formulas found in 5.3.2.

A.3.2 MIXING CEMENT AND WATER

The mixing container with the required weight of mix water and any liquid additives should be placed on the mixer base. The motor should be turned on "slow" speed (6,000 rpm or greater under no load). If additives are present in the mix water, stir at the above rotational speed to thoroughly disperse them in the mix water prior to the addition of the cement. In certain cases, the order of addition of the additives to the mixing water may be critical. Special mixing procedures and mixing time should be documented. The cement or cement/dry additive blend should then be added to the mixing container at a uniform rate, in not more than 15 seconds if possible. Some slurry designs may require longer to completely wet the cement blend; however, the time used to add the blend should be kept at a minimum. When all of the dry materials have been added to the mix water, the cover should be placed on the mixing container and mixing should be continued at "high" speed (14,000 rpm or greater under no load) for the times specified in Table A-1. If possible, rotational speed under load should be measured and documented.

Table A-1—Slurry Mixing Time

Slurry Volume (mL)	High Speed Mixing Time (Seconds)
2,000	30
3,000	45
4,000	55

APPENDIX B—CALIBRATION PROCEDURES FOR THERMOCOUPLES, TEMPERATURE MEASURING SYSTEMS, AND CONTROLLERS

B.1 General

There are several satisfactory methods for calibrating thermocouples including methods supplied by equipment manufacturers. The reader is referred to ASTM E220, *Standards Methods for Calibration of Thermocouples by Comparison Techniques,* for a more complete discussion of these procedures. No ASTM procedures for calibration of temperature measuring systems are available.

B.2 Thermocouple Calibration

B.2.1 EQUIPMENT

The individual pieces of equipment needed to carry out the calibration will depend on the particular technique selected. The following discussion highlights those features which need special attention, regardless of the technique:

a. Heating Environment—The heating medium shall permit proper immersion of both the test thermocouple (the one being calibrated) and the reference thermocouple or reference thermometer. The medium may be a liquid bath, a fluidized solids bath, a heated block or a furnace. The equipment shall be capable of maintaining a stable temperature which is uniform throughout the test section.
b. Temperature Measurement—The reference temperature of the heating medium may be measured by using either a thermometer or a thermocouple. The accuracy of the reference measuring device shall be traceable to a National Bureau of Standards (NBS) certification of test.

If a thermocouple is used to sense the reference temperature, the voltage output from the reference thermocouple and test thermocouple shall be determined as described in ASTM E220. In this case, tables of temperature vs. voltage for the type thermocouple being used must be consulted to determine the temperature. Alternately, a direct-reading, temperature-compensated readout instrument may be used. The accuracy of the instrument shall be traceable to NBS certification.

B.2.2 PROCEDURE

With the exception of the indicating instruments, the specific procedures are detailed in ASTM E220. The items listed here are those needing special attention or related to the use of the indicating type of equipment:

a. The test and reference thermocouple or thermometer shall be placed as close together in the heating medium as possible.
b. After each change in the heating level, the temperature shall be allowed to remain at a stable value for 15 minutes before reading the reference temperature (or voltage) and the test thermocouple temperature (or voltage).
c. Several (more than three) test temperatures which span the operating range of the equipment shall be used in the calibration procedure.
d. If the test thermocouple does not accurately sense the temperature, a calibration curve shall be drawn and used to correct the indicated temperatures from the test thermocouple. Occasionally, small inaccuracies in thermocouple response can be compensated for during the calibration of the temperature measuring system being used in conjunction with the thermocouple (see B.3).
e. If the test thermocouple error is greater than that specified by the manufacturer, the thermocouple shall be replaced by one which meets the thermocouple accuracy limits. The special type "J" thermocouple has error limits equal to or better than ±2°F (±1.1°C) up to 530°F (277°C).

B.3 Calibration of Temperature Measuring Systems and Controllers

B.3.1 EQUIPMENT

The calibration of temperature measuring systems and controllers requires a millivolt source, the correct connecting thermocouple extension cable for the type thermocouple being used and, possibly, a thermometer and a table of reference voltages. Signal sources, or calibrators, are of two types, i.e., uncompensated and cold junction compensated. Several commercial calibrators are available which are cold junction compensated and have a digital display of the temperature equivalent of the millivolt signal being supplied. The accuracy of all calibration equipment shall be traceable to NBS certification. Some older galvanometer type temperature indicating instruments and controllers require a stronger signal for operation than the newer potentiometric and digital type temperature measuring systems and controllers and will require a calibrator with sufficient signal strength to give an accurate calibration.

B.3.2 PROCEDURE

The manufacturer's procedure for calibrating temperature measuring systems and controllers shall be followed. The following are reminders of items needing special attention. The thermocouple extension cable shall be fitted with a proper thermocouple grade adapter to permit plugging it into the same receptacle used for connecting the test equipment thermocouple. Care shall be taken to ensure the correct polarity of the connections. Calibrators, temperature measuring

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systems, and controllers shall be allowed proper warm-up time as specified by the manufacturer for greatest accuracy.

a. Thermocouple calibrators with cold junction compensation need only be properly connected with the proper thermocouple extension cable and thermocouple connectors. The temperature measuring systems and/or controllers using this signal shall have the same temperature readout within the accuracy of the temperature or controllers as supplied by the manufacturer.
b. Uncompensated thermocouple calibrators will require a thermometer to determine the cold junction temperature of the thermocouple extension cable connection of the calibrator. This cold junction temperature will be set on the calibrator by the operator.

c. The use of an uncompensated millivolt potentiometer requires that the temperature at the calibrator/thermocouple extension cable terminals be read with a thermometer of known accuracy. The millivolt equivalent of this temperature is then subtracted from the equivalent test millivolt signal to obtain the calibrator millivolt signal used. These voltages may be found in reference mv/temperature tables for the type thermocouple in use.

APPENDIX C—ADDITIONAL INFORMATION RELATING TO TEMPERATURE DETERMINATION

C.1 Introduction

This appendix contains background information relating to the development of the cementing schedules contained in Section 9. This information is important in the development of a correct test schedule but was considered too unwieldy to include in the well-simulation thickening time test procedure itself. Additional information about the development of correlations to predict down hole temperatures for cementing operations is available in the API Research Document, *Temperatures for API Operating Thickening Time Test Schedules.*

C.2 Development of Predicted Bottom-Hole Circulating Temperature Correlation

The correlation for the predicted bottom-hole circulating temperature (PBHCT) was developed from temperature measurements in 66 wells. Data were obtained for wells drilled with water based and oil based drilling fluids. Well depths ranged from 7,750 feet to 24,840 feet.

A maximum recorded bottom-hole static temperature (MaxRBHST) and a minimum recorded bottom-hole circulating temperature (MinRBHCT) were measured in each well. Measurements were made using temperature sensors run near the end of the drill string on a clean-up trip prior to running casing. The MaxRBHST was the highest temperature recorded prior to commencing circulation of the wellbore. For wells used to develop the correlation, the static time (non-circulating period) ranged from 24 hours to 138 hours with an average of 37.7 hours. The MinRBHCT was the pseudo-stabilized temperature at the end of the circulating period. The average circulation time for wells used to develop this correlation was 6.7 hours.

In developing this correlation, it was determined that the circulating temperature was a function of the well depth and a temperature gradient. Other factors such as drilling fluid type, circulating rate, circulating time, inlet temperature of the circulated fluid, and drill pipe/hole size were evaluated for their effect on the circulating temperature. No clearly distinguishable effects of these factors were observed or determined from the data collected. Therefore, the MinRBHCT was correlated only to the well depth and a pseudo-temperature gradient (PsTG).

The PsTG is calculated from the difference between the MaxRBHST and the assumed surface temperature (AST) of 80°F, and the true vertical depth (TVD) of the well. The PsTG is calculated according to either of the following equations:

$$PsTG, \text{°F/100 ft} = \frac{MaxRBHST - 80\text{°F}}{TVD/100\text{ ft}} \quad \text{(C.1a)}$$

$$PsTG, \text{°C/100 m} = \frac{MaxRBHST - 27\text{°C}}{TVD/100\text{ m}} \quad \text{(C.1b)}$$

Where:

TVD = true vertical depth of the well where the temperature was measured (in feet or meters).

The true temperature gradient may be different from the PsTG of the well, depending upon the difference between the MaxRBHST and the undisturbed formation temperature (UFT) at the depth the temperature measurement was made. The longer a wellbore is allowed to remain static prior to measurement of the temperature, the closer the MaxRBHST should be to the UFT.

Although the PBHCT correlation is based upon field measurements, there can be error associated with its use for predicting the circulating temperature in a well. The error range between this correlation and the field measured data from which the correlation was derived is shown in Figure C-1. The standard deviation is 16.6 °F. Whenever possible, measurements of downhole temperatures are preferred over calculated estimates.

C.3 Well Simulation Casing Cementing Tabular Schedules

These schedules represent average well conditions developed from surveys of cementing operations. To develop these schedules, the time required for the cement slurry to reach the bottom, mud weight and starting pressure were collected from a survey of 584 casing cementing operations conducted between 1987 and 1989. Average values for each of these variables were determined for average depths from 1,000 feet to 22,000 feet in the survey data. A linear regression analysis performed on these average values was used to prepare tabular schedules.

The final temperature listed in the tabular schedules is the predicted bottom-hole circulating temperature (PBHCT). The PBHCT values are taken from two sources. For well depths of 10,000 feet or shallower, the PBHCT are from the API Recommended Practice 10B, 20th Ed., 1977. For depths greater than 10,000 feet, the PBHCT values are from the correlation developed from the well survey. Two sources for PBHCT are used because of the lack of circulating temperature data for depths shallower than about 10,000 feet. Only two of the 66 data points used to develop the correlation were from depths shallower than 10,000 feet.

C.4 Well Simulation Liner Cementing Tabular Schedules

These schedules represent average well conditions developed from surveys of cementing operations. To develop these schedules, the time for the leading edge of cement slurry to reach bottom, mud weight and starting pressure were collected from a survey of 125 liner cementing operations conducted between 1986 and 1989. Values for each of these variables were determined in the same manner described for the development of casing cementing thickening time schedules. The predicted bottom-hole circulating temperatures in the liner cementing schedules were taken from the operating casing-cementing tabular schedules for the corresponding well depth.

C.5 Development of Predicted Squeeze Cementing Temperature Correlation

The correlation for the predicted squeeze temperature (PSqT) was developed from temperature measurements in 40 wells. Data were obtained for wells drilled with water based and oil based drilling fluids. Well depths were from 7,750 feet to 24,840 feet.

A maximum recorded bottom-hole static temperature (MaxRBHST) and a recorded squeeze temperature (RSqT) were measured in each well. Measurements were made using temperature sensors run near the end of the drill string on a clean-up trip prior to running casing. The MaxRBHST was the highest temperature recorded prior to commencing circulation of the wellbore. For wells used to develop the correlation, the static time (non-circulating period) ranged from 24 hours to 138 hours with an average of 38.1 hours. The RSqT was the temperature recorded after pumping one drillstring volume of drilling fluid while taking returns up the annulus. The average time required to pump one drill string volume was 36.9 minutes.

In developing this correlation, it was determined that the squeeze temperature was a function of the well depth and a temperature gradient. Other factors such as drilling fluid type, circulating rate, inlet temperature of the circulating fluid, and drill pipe/hole size were evaluated for their effect on the squeeze temperature. No clearly distinguishable effects of these other factors were observed or determined from the data collected. There were insufficient data for the wells investigated to determine the effect of fluid type (water or drilling fluids) on squeeze temperature. Therefore, the RSqT was correlated only to the well depth and pseudo-temperature gradient (PsTG).

Although the PSqT correlation is based upon field measurements, there can be error associated with its use for predicting the squeeze temperature in a well. The error range between this correlation and the field measured data from which the correlation was derived is shown in Figure C-2. The standard deviation is 13.0°F. Whenever possible, measurements of downhole temperatures are preferred over calculated estimates.

C.6 Development of Well Simulation Squeeze Cementing Tabular Schedules

Two types of tabular well simulation thickening time schedules for squeeze cementing operations were prepared: continuous pumping schedules and hesitation squeeze schedules.

To develop these schedules, the time for the cement to reach the bottom of the workstring, fluid weight, circulating pressure, final squeeze pressure, and time to apply final squeeze pressure were collected from a survey of 180 squeeze cementing operations conducted between 1985 and 1987. Average values for each of these variables were determined for average depths from 1,000 feet to 18,000 feet in the survey data. These average values were curve fit using a polynomial function and the predicted values from the curve fit were used to prepare tabular schedules. Starting surface pressures were taken from the API Specification 10, 5th Edition (July, 1990) squeeze cementing tabular schedules. The PSqT in the tabular schedules are from the correlation.

For continuous pumping squeeze tabular schedules, the temperature of the cement slurry is increased to the PSqT and the BHP in the amount of time required for the leading edge of cement slurry to reach the bottom of the workstring. The amount of time is based upon the correlation for average time to bottom developed from the survey data. The temperature is held constant at the PSqT while the pressure is increased to the final squeeze pressure over time. The time over which the pressure is increased is based upon the correlation developed from the survey data. Temperature is held at the PSqT and pressure is held at the final squeeze pressure for the duration of the thickening time test.

Hesitation squeeze schedules are the same as the continuous pumping squeeze cementing schedules until the squeeze pressure is reached. Pressure on the cement slurry is held at the final squeeze pressure for the duration of the test. After reaching the final squeeze pressure, the hesitation squeeze schedule increases temperature of the slurry from the PSqT to the pseudo undisturbed temperature (PsUT) at a heating rate of 0.2°F/minute. The PsUT is calculated using the following equation:

$$PsUT = [(PsTG)\ (TVD/100)] + 80°F \qquad \text{(C.2)}$$

Where:

PsUT = pseudo undisturbed temperature, °F.
PsTG = pseudo temperature gradient, °F/100 ft.
TVD = true vertical depth, ft.
80°F = assumed surface temperature.

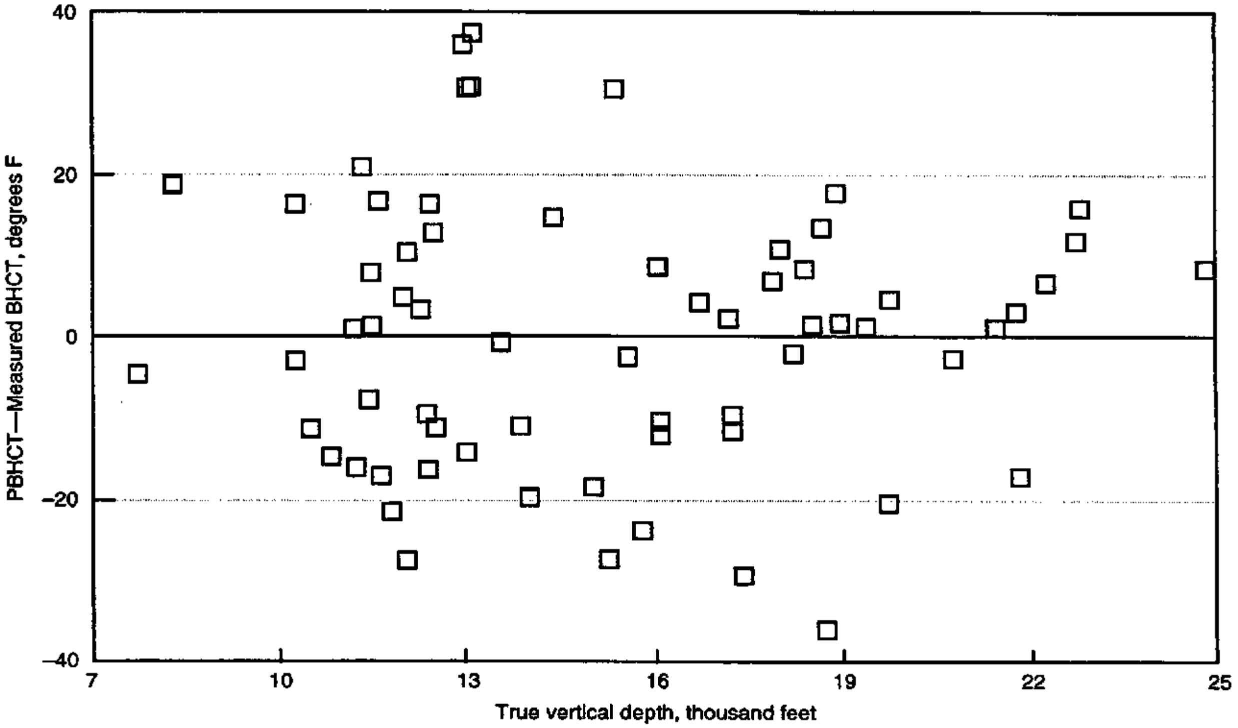

Figure C-1—Error Range of Predicted Versus Measured Bottom-hole Temperatures for 66 Data Points Used to Develop PBHCT Correlation

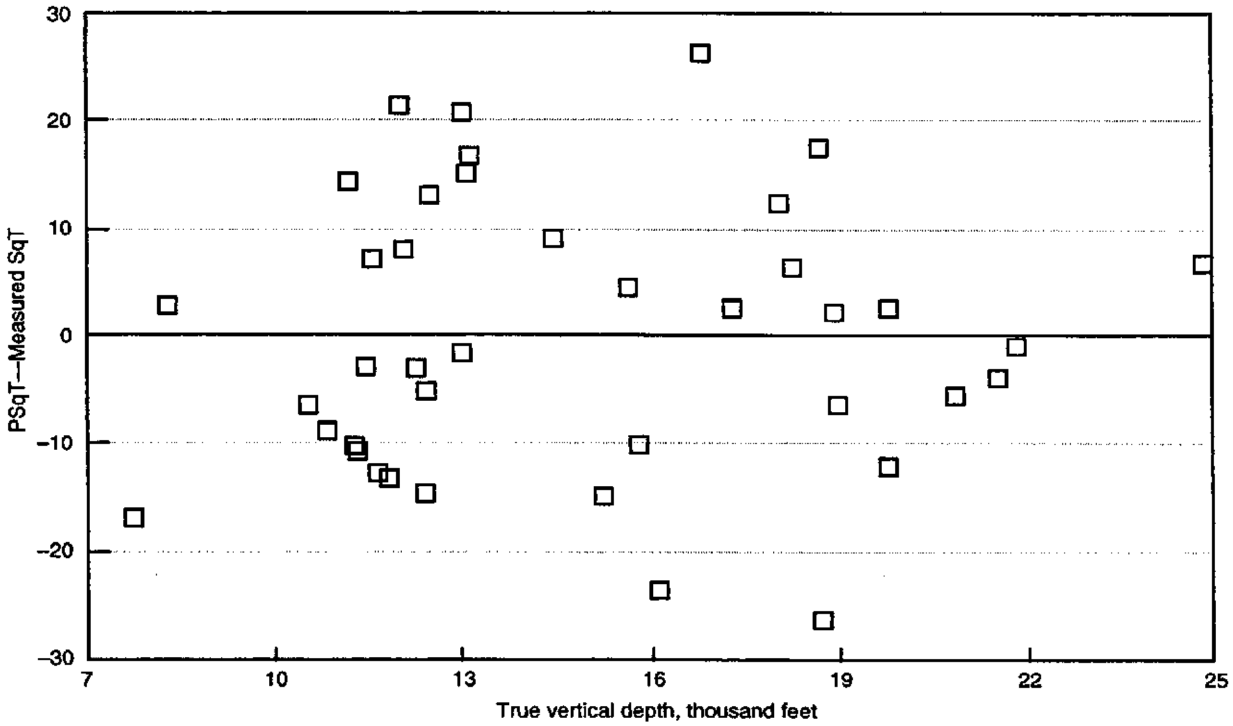

Figure C-2—Error Range of Predicted Versus Measured Squeeze Temperatures for the 40 Data Points Used to Develop the PSqT Correlation

The motor on the consistometer is cycled off (10 minutes) and on (5 minutes) during this final heating period. The motor cycling is designed to detect viscosity increases during static periods while "hesitating" during a squeeze operation. Cycling of the motor is continued for the duration of the test.

C.7 Application of Predicted Circulating and Squeeze Temperatures to Offshore Wells

Some of the data used in the development of correlations for predicting bottom-hole circulating temperatures and squeeze temperatures were from offshore wells. Only data from offshore wells in less than 250 feet of water were included in the data set used to develop the correlations. Also, the water depth was less than three percent of the true vertical depth at which the temperature was measured. The PsTG was calculated from sea level using the AST of 80°F.

PBHCT and PSqT from the correlations developed from this data may be significantly different from the temperatures at shallow depths below the seafloor in offshore wells. Whenever possible, measured temperatures are preferred over predicted temperatures.

C.8 Plug Cementing Tailored Schedules

The squeeze temperatures predicted using the equations were developed from down-hole temperature measurements after one workstring volume had been circulated. The average circulating time for the data used to prepare the PSqT correlation was 36.9 minutes. Predicted circulating temperatures from API Recommended Practice 10B, 20th Ed., 1977 were developed from downhole temperature measurements after a period of circulation typically greater than two hours.

Therefore, selection of test temperature for plug cementing should be based upon the anticipated amount of circulation time prior to the cementing operation. Whenever possible, measured temperatures should be used over predicted values.

C.9 Explanation of Some Temperature-Related Terms

C.9.1 Assumed Surface Temperature (AST)—The assumed temperature at the surface is used for purposes of calculating a Pseudo-Temperature Gradient (PsTG). The 1974 API data set used an AST value of 75°F for calculation of the PsTG values listed in API Specification 10, 5th Edition. The 1984 API data set used an AST value of 80°F, as does the 1991 selected data set.

C.9.2 Average Time-to-Bottom—This value was used in compiling the tabular casing and liner schedules found in Section 9. These values are based on actual times-to-bottom at each depth obtained from the API casing survey taken from 1987 to 1989 (covering 584 data points). The casing survey was for full casing strings and a few inner-string jobs, but no liners.

The curve for average time-to-bottom was developed by dividing the survey data into depth ranges, computing average time-to-bottom for each depth range, and using a simple linear regression analysis curve fit to these average values.

C.9.3 Maximum Recorded Bottom-Hole Static Temperature (MaxRBHST)—The MaxRBHST is the maximum temperature recorded at the bottom of a wellbore, after a static period (non-circulation normally of up to 24 hours or more) and prior to start of circulation. The longer the static period of non-circulation, the closer the MaxRBHST will approach the Undisturbed Formation Temperature (UFT). The MaxRBHST value is preferably determined by a temperature sensor run in the drill string that is tripped into the wellbore during a clean-up trip after logging and prior to running casing. Maximum recorded log temperatures are sometimes used. The 1974 data used in API Specification 10, 5th Edition (July 1, 1990), consisted of 41 data points that were used to determine the pseudo-temperature gradients contained in the "cementing schedules." These data points were obtained by temperature sensors at various static times from 7 hours to 76 hours. The average static period for all wells measured was 27.9 hours. The 1991 selected set of data, used in API Recommended Practice 10B, 22nd Edition, consists of 66 data points used to determine the pseudo-temperature gradients contained in the "casing cementing schedules" and equations. These data points also were obtained by temperature sensors at various static times from 24 hours to 138 hours. The average static period was also shown to be 37.7 hours. One attribute of the 1991 selected data set was that all static times were greater than 24 hours.

C.9.4 Minimum Recorded Bottom-Hole Circulating Temperature (MinRBHCT)—The MinRBHCT is the minimum temperature recorded at the bottom of a wellbore, after circulation time sufficient to achieve a nearly stabilized or steady-state circulating temperature. The MinRBHCT is usually determined by a temperature sensor run in the drill-string that is tripped into the wellbore during a clean-up trip after logging and prior to running casing. The temperature is obtained, after some time period of circulating the wellbore, prior to tripping the pipe off bottom. The MinRBHCT is dependent upon well geometry, fluid properties, circulation rate, etc., and is not necessarily the minimum bottom-hole circulating temperature of a cement slurry.

C.9.5 Predicted Bottom-Hole Circulating Temperature (PBHCT)—The PBHCT is the predicted temperature obtained from Section 9, tabulated schedules or equations, for the bottom-hole depth and Pseudo-Temperature Gradient (PsTG). This is a calculated value based on field data, and associated correlation techniques, used to develop the schedules and equations. When using the tabulated schedules, this is the temperature listed for the maximum time shown in that schedule. The PBHCT is used for both casing and liner schedules. The actual wellbore temperature is dependent upon well geometry, fluid properties, circulation rate, etc., and is not necessarily the bottom-hole circulating temperature of a cement slurry.

C.9.6 Predicted Squeeze Temperature (PSqT)—The PSqT is the predicted squeeze temperature obtained using Section 9 tabulated squeeze schedules or equations, for the selected depth and temperature gradient. When using the tabulated continuous pumping squeeze schedules, the PSqT is the temperature listed for the maximum time shown in that schedule. When using the tabulated hesitation squeeze schedules, the PSqT is the temperature in the schedule at the end of the first temperature ramp. The actual wellbore squeeze temperature is dependent upon well geometry, fluid properties, circulation rate, circulating time, and inlet temperature of the fluid.

C.9.7 Pseudo-Temperature Gradient (PsTG)—This is a calculated value based on field data and associated correlation techniques which were used to develop the schedules and equations. The PsTG is a temperature change per unit of depth, determined by an equation using an assumed surface temperature (AST) defined as 80°F, and a Maximum Recorded Bottom-Hole Static Temperature (MaxRBHST) as follows:

$$PsTG = \frac{MaxRBHST - 80°F}{(TVD/100)} \qquad (C.3)$$

Where:

PsTG = pseudo temperature gradient, °F/100 ft.
MaxRBHST = maximum recorded bottom-hole static temperature, °F.
TVD = true vertical depth, ft.

The PsTG is used in Section 9 to develop well simulation testing schedules of temperature and pressure versus time.

C.9.8 Pseudo Undisturbed Temperature (PsUT)—This is the temperature at a given depth calculated as follows:

$$PsUT = [(PsTG)(TVD/100)] + 80°F \qquad (C.4)$$

Where:

PsUT = pseudo undisturbed temperature, °F.
PsTG = pseudo temperature gradient, °F/100 ft.
TVD = true vertical depth, ft.

The PsUT at the bottom of the wellbore is equal to the Maximum Recorded Bottom-Hole Static Temperature (MaxRBHST). It is intended that the static time, for this equation, equal or exceed 24 hours.

C.9.9 Recorded Squeeze Temperature (RSqT)—This is the temperature recorded at the end of the workstring at the calculated time when a volume of fluid equal to internal volume of the work-string has been circulated. This also represents the temperature at the time when the leading edge of cement slurry would reach the end of the workstring. The RSqT is usually determined by a temperature sensor run in the work-string that is tripped into the wellbore during a clean-up trip. The work-string for the 1991 selected data set was at the bottom of the wellbore and the data were usually collected after logging and prior to running casing. The actual wellbore squeeze temperature is dependent upon well geometry, fluid properties, circulation rate, circulating time and inlet temperature of the fluid.

C.9.10 Static Time (Always spell out - no acronym)—This is the amount of time between the end of the last circulation of the wellbore and the time when the Maximum Recorded Bottom-Hole Temperature (MaxRBHT) was observed.

C.9.11 Undisturbed Formation Temperature (UFT)—This is the geologic formation temperature at a depth, prior to the first penetration by a drill bit, or the temperature attained at a depth in a well after the well is shut-in for a period long enough to return to the adjacent undisturbed (virgin) geologic formation temperature.

APPENDIX D—ALTERNATE APPARATUS FOR WELL SIMULATION THICKENING TIME TESTS

D.1 General

This appendix presents a description of an alternate pressurized consistometer for the well-simulation thickening time testing of cement slurries.

D.2 Apparatus

The apparatus uses a rotating paddle and a stationary cup design and is constructed such that the cement slurry can be subjected to the temperatures and pressures required by the well simulation test schedules described in 9.5. Paddle torque is sensed by motor load or alternate torque sensors to provide slurry consistency measurements equivalent to those of the typical consistometer described in 9.2. Slurry temperature and pressure control are provided as depicted in Figures D-1 and D-2.

The apparatus shall be capable of duplicating the test conditions and measurements required of the typical consistometer described in Section 7.3.

D.3 Calibration

The equipment manufacturer's procedures for the calibration of the pressurized consistometer including consistency measurement, temperature measurement, temperature controllers, motor speed, timer, and pressure gauges shall be followed. The same specifications and frequency of calibration apply to the use of this alternate device as the typical consistometer of 9.2.

D.4 Test Procedure

The equipment manufacturer's detailed procedures for the operation and maintenance of the equipment are to be followed and will satisfy the intent of the general procedures in Section 9. Some modifications may be necessary to accommodate the design variations of the alternate device. Do not exceed manufacturer's safety limits.

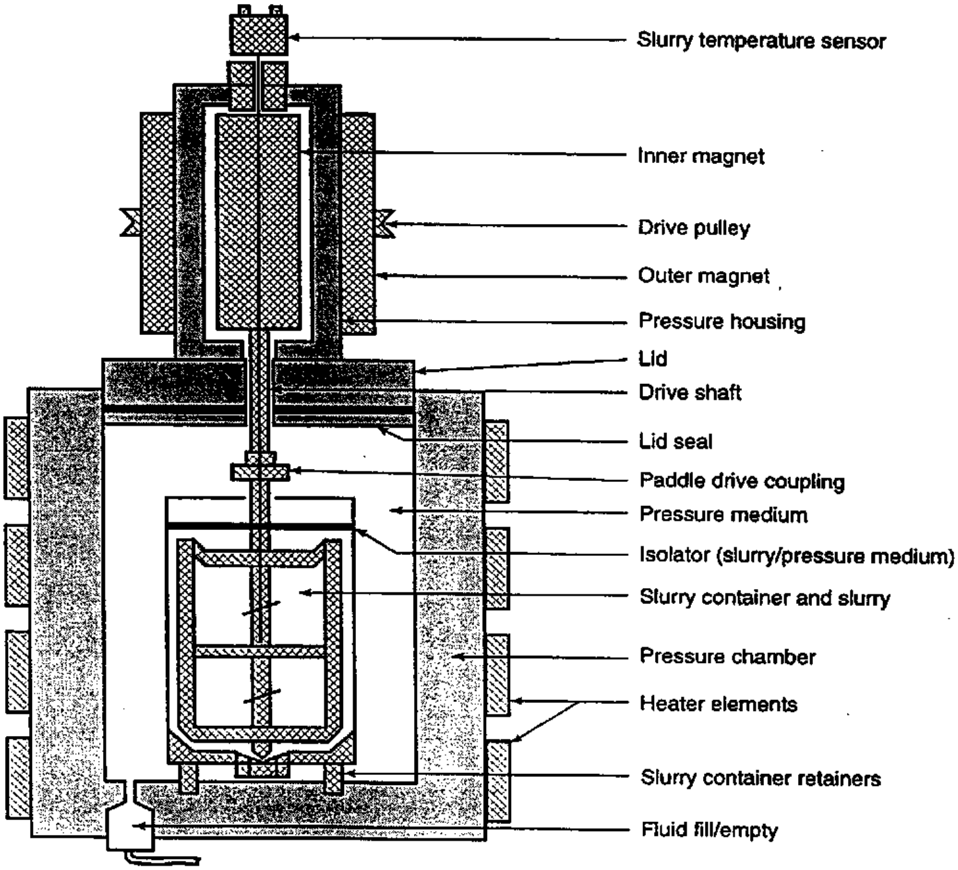

Figure D-1—Alternate Consistometer Design for Well Simulation Thickening Time, Example 1

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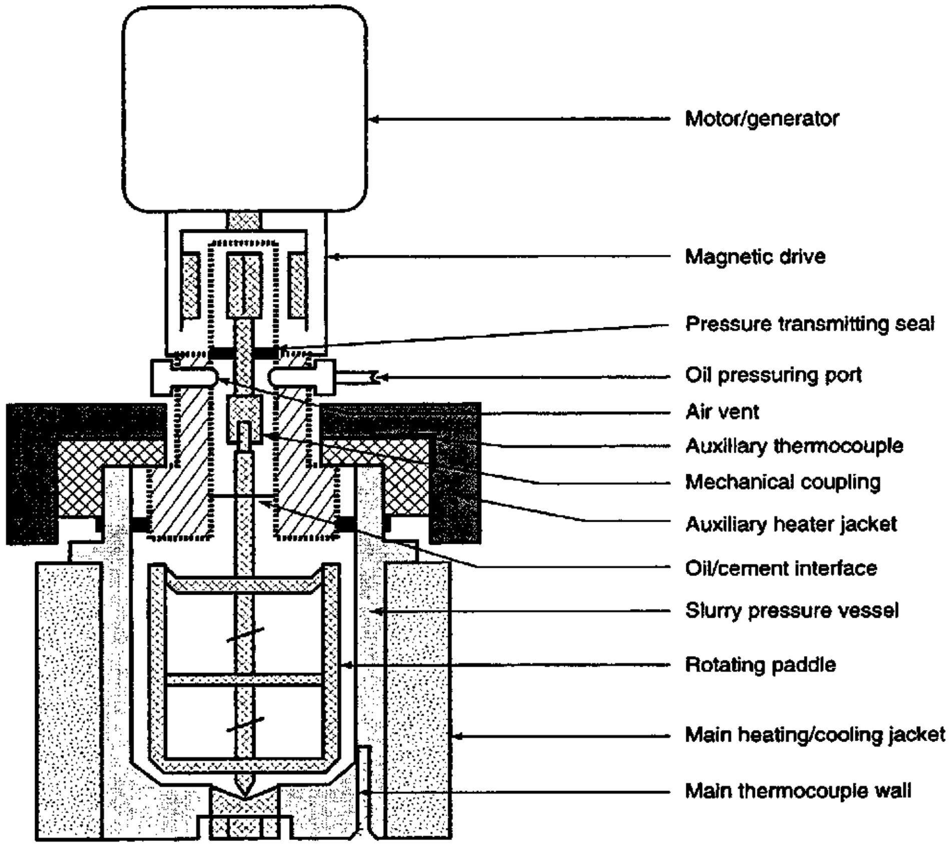

Figure D-2—Alternate Consistometer Design for Well Simulation Thickening Time, Example 2

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