Recommended Practice on the Rheology and Hydraulics of Oil-well Drilling Fluids

API RECOMMENDED PRACTICE 13D
FOURTH EDITION, MAY 2003

American Petroleum Institute

Helping You Get The Job Done Right.SM

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Upstream Segment

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Recommended Practice on the Rheology and Hydraulics of Oil-well Drilling Fluids

1 Scope

1.1 The objective of this Recommended Practice (RP) is to provide a basic understanding of and guidance about drilling fluid rheology and hydraulics, and their application to drilling operations. The methods for the calculations used herein do not take into account the effects of temperature and compressibility on the density of the drilling fluid.

1.2 Rheology is the study of the deformation and flow of matter. Drilling fluid hydraulics pertains to both laminar and turbulent flow regimes.

1.3 For this RP, rheology is the study of the flow characteristics of a drilling fluid and how these characteristics affect movement of the fluid. Specific measurements are made on a fluid to determine rheological parameters of a fluid under a variety of conditions. From this information the circulating system can be designed or evaluated regarding how it will accomplish certain desired objectives. Drilling fluid rheology is important in the following determinations:

a. Calculating friction loss in pipe or annulus.
b. Determining the equivalent circulating density of the drilling fluid.
c. Determining the flow regime in the annulus.
d. Estimating hole cleaning efficiency.
e. Evaluating fluid suspension capacity.
f. Determining the settling velocity of drill cuttings in vertical holes.

1.4 The discussion of rheology in this RP is limited to single-phase liquid flow. Some commonly used concepts pertinent to rheology and flow are presented. Mathematical models relating shear stress to shear rate and formulas for estimating pressure drops, equivalent circulating densities and settling velocities of drill cuttings are included.[1]

1.5 Conversion factors and examples are included for all calculations so that U.S. Customary units can be readily converted to metric (SI) units.[2]

1.6 Where units are not specified, as in the development of equations, any consistent system of units may be used.

1.7 The concepts of viscosity, shear stress, and shear rate are very important in understanding the flow characteristics of a fluid. The measurement of these properties allows a mathematical description of circulating fluid flow. The rheological properties of a drilling fluid directly affect its flow characteristics and all hydraulic calculations. They must be controlled for the fluid to perform its various functions.

[1]See Reference 13.
[2]See Reference 3.

2 References

2.1 STANDARDS

Unless otherwise specified, the most recent editions or revisions of the following standards shall, to the extent specified herein, form a part of this RP.

API

1. RP 13B-1 *Recommended Practice Standard Procedure for Field Testing Water-based Drilling Fluids*
2. RP 13B-2 *Recommended Practice Standard Procedure for Field Testing Oil-based Drilling Fluids*
3. Chapter 15 "Guidelines for the Use of the International System of Units (SI) in the Petroleum and Allied Industries"

2.2 OTHER REFERENCES

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3 Symbols

For the purposes of this RP, the following definitions of symbols apply:

A	Surface area
D	Diameter
D_n	Bit nozzle diameter
D_p	Equivalent particle diameter
D_1	Inner annulus diameter
D_2	Outer annulus diameter
F	Force
G	Gravity constant
K	Fluid consistency index
K_a	Fluid consistency index in annulus
K_p	Fluid consistency index in pipe
K_s	Fluid consistency index in settling
L	Length
L_m	Measured depth
L_v	True vertical depth
Re	Reynolds number
Re_a	Reynolds number in annulus
Re_p	Reynolds number in pipe
P	Pressure
P_a	Pressure drop in annulus
P_c	Circulating pressure
P_h	Hydrostatic pressure
P_n	Pressure drop in bit nozzles
P_p	Pressure drop in pipe
PV	Plastic viscosity ($PV = \eta$)
Q	Volumetric flow rate
R	Fann Viscometer reading
R_3	Fann Viscometer reading at 3 rpm
R_{100}	Fann Viscometer reading at 100 rpm
R_{300}	Fann Viscometer reading at 300 rpm
R_{600}	Fann Viscometer reading at 600 rpm
T	Temperature
V	Velocity
V_a	Average velocity in annulus
V_p	Average velocity in pipe
V_s	Average settling velocity
V_o	Volume of settling particle
YP	Yield point
a	Friction factor constant
b	Friction factor exponent
f	Friction factor
f_a	Friction factor in annulus
f_p	Friction factor in pipe
n	Power Law exponent
n_a	Power Law exponent in annulus
n_p	Power Law exponent in pipe
n_s	Power Law exponent in settling

Ψ	Ratio of particle surface areas
α	Pressure constant
β	Temperature constant
γ	Shear rate
γ_s	Settling shear rate
γ_w	Shear rate at wall
γ_{wa}	Shear rate at annulus wall
γ_{wp}	Shear rate at pipe wall
η	Plastic viscosity ($\eta = PV$)
θ	Angle
μ	Viscosity
μ_e	Effective viscosity
μ_{ea}	Effective viscosity in annulus
μ_{ep}	Effective viscosity in pipe
μ_{es}	Effective viscosity in settling
ρ	Density of fluid
ρ_c	Equivalent circulating density
ρ_p	Density of a particle
τ	Shear stress
τ_w	Shear stress at wall
τ_{wa}	Shear stress at wall in annulus
τ_{wp}	Shear stress at wall in pipe
τ_y	Yield stress
ω	Angular momentum

4 Basic Concepts

4.1 FLOW REGIMES

4.1.1 The behavior of a fluid is determined by the flow regime, which in turn has a direct effect on the ability of that fluid to perform its basic functions. The flow can be either laminar or turbulent, depending on the fluid velocity, size and shape of the flow channel, fluid density, and viscosity. Between laminar and turbulent flow, the fluid will pass through a transition region where the movement of the fluid has both laminar and turbulent characteristics. It is important to know which of the flow regimes is present in a particular situation to evaluate the performance of a fluid.

4.1.2 In laminar flow, the fluid moves parallel to the walls of the flow channel in smooth lines. Flow tends to be laminar when moving slowly or when the fluid is viscous. In laminar flow, the pressure required to move the fluid increases with increases in the velocity and viscosity.

4.1.3 In turbulent flow, the fluid is swirling and eddying as it moves along the flow channel, even though the bulk of the fluid moves forward. These velocity fluctuations arise spontaneously. Wall roughness or changes in flow direction will increase the amount of turbulence. Flow tends to be turbulent with higher velocities or when the fluid has low viscosity. In turbulent flow, the pressure required to move the fluid increases linearly with density and approximately with the square of the velocity. This means more pump pressure is required to move a fluid in turbulent flow than in laminar flow.

4.1.4 The transition between laminar and turbulent flow is controlled by the relative importance of viscous forces and inertial forces in the flow. In laminar flow, the viscous forces dominate, while in turbulent flow the inertial forces are more important. For Newtonian fluids, viscous forces vary linearly with the flow rate, while the inertial forces vary as the square of the flow rate.[3]

4.1.5 The ratio of inertial forces to viscous forces is the Reynolds number. If consistent units are chosen, this ratio will be dimensionless and the Reynolds number (*Re*) will be:

$$Re = \frac{DV\rho}{\mu} \tag{1}$$

where

D = diameter of the flow channel,

V = average flow velocity,

ρ = fluid density,

μ = viscosity.

4.1.6 The flow of any particular liquid in any particular flow channel can be either laminar, transitional, or turbulent. The transition occurs at a critical velocity. For typical drilling fluids, it normally occurs over a range of velocities corresponding to Reynolds number between 2000 and 4000.

4.2 VISCOSITY

4.2.1 Viscosity is defined as the ratio of shear stress to shear rate. The traditional units of viscosity are dyne-sec./cm^2, which is termed poise. Since one poise represents a relatively high viscosity for most fluids, the term centipoise (*cP*) is normally used. A centipoise is equal to one-hundredth of poise or one millipascal-second.

$$\mu = \frac{\tau}{\gamma} \tag{2}$$

where

μ = viscosity,

τ = shear stress,

γ = shear rate.

4.2.2 Viscosity is not a constant value for most drilling fluids. It varies with shear rate. To check for rate dependent effects, shear stress measurements are made at a number of

[3]See References 7, 8 and 25.

shear rates. From these measured data, rheological parameters can be calculated or can be plotted as viscosity versus shear rate.

4.2.3 The term effective viscosity is used to describe the viscosity either measured or calculated at the shear rate corresponding to existing flow conditions in the wellbore or drill pipe. This special term is created to differentiate the viscosity as discussed in this section from other viscosity terms. To be meaningful, a viscosity measurement must always specify the shear rate.

4.3 SHEAR STRESS

4.3.1 Shear stress is the force required to sustain a particular rate of fluid flow and is measured as a force per unit area. Suppose, in the parallel-plate example (see Figure 1), that a force of 1.0 dyne is applied to each square centimeter of the top plate to keep it moving. Then the shear stress would be 1.0 dyne/cm^2. The same force in the opposite direction is needed on the bottom plate to keep it from moving. The same shear stress of 1.0 dyne/cm^2 is found at any level in the fluid.

4.3.2 Shear stress (τ) is expressed mathematically as:

$$\tau = \frac{F}{A} \quad (3)$$

where

F = force,

A = surface area subjected to stress.

4.3.3 In a pipe, the force pushing a column of liquid through the pipe is expressed as the pressure on the end of the liquid column times the area of the end of the column:

$$F = P\frac{\pi D^2}{4} \quad (4)$$

where

D = diameter of pipe,

P = pressure on end of liquid column.

4.3.4 The area of the fluid surface in contact with the pipe wall over the length is given by:

$$A = \pi DL \quad (5)$$

where

A = surface area of the fluid,

L = length.

4.3.5 Thus, the shear stress at the pipe wall is expressed as:

$$\tau_w = \frac{F}{A} = \frac{DP}{4L} \quad (6)$$

4.3.6 In an annulus with inner and outer diameters known, the shear stress is expressed in the same manner:

$$F = \frac{P\pi D_2^2}{4} - \frac{P\pi D_1^2}{4} = P\pi\frac{D_2^2 - D_1^2}{4} \quad (7)$$

where

D_1 = inner diameter of pipe,

D_2 = outer diameter of pipe.

and

$$A = \pi D_2 L + \pi D_1 L = \pi L(D_2 + D_1) \quad (8)$$

so that

$$\tau_w = \frac{F}{A} = \frac{P\frac{\pi}{4}(D_2 - D_1)(D_2 + D_1)}{\pi L(D_2 + D_1)} = \frac{P(D_2 - D_1)}{4L} \quad (9)$$

4.4 SHEAR RATE

4.4.1 Shear rate is a velocity gradient measured across the diameter of a pipe or annulus. It is the rate at which one layer of fluid is moving past another layer. As an example, consider two large flat plates parallel to each other and one centimeter (cm) apart. The space between the plates is filled with fluid. If the bottom plate is fixed while the top plate slides parallel to it at a constant velocity of 1 cm/sec., the velocities indicated in Figure 1 are found within the fluid. The fluid layer near the bottom plate is motionless while the fluid layer near the top plate is moving at almost 1 cm/sec. Halfway between the plates the fluid velocity is the average 0.5 cm/sec.

4.4.2 The velocity gradient is the rate of change of velocity (ΔV) with distance from the wall (h). For the simple case of Figure 1, the shear rate is $\Delta V/h$ and will have units of 1/time. The reciprocal second (1/sec. or sec.$^{-1}$) is the standard unit of shear rate.

4.4.3 This reference example is unusual in that the shear rate is constant throughout the fluid. This situation is not the case with a circulating fluid. In laminar flow inside a pipe, for example, the shear rate is highest next to the pipe wall. An average shear rate may be used for calculations, but the shear rate itself is not constant across the flow channel.

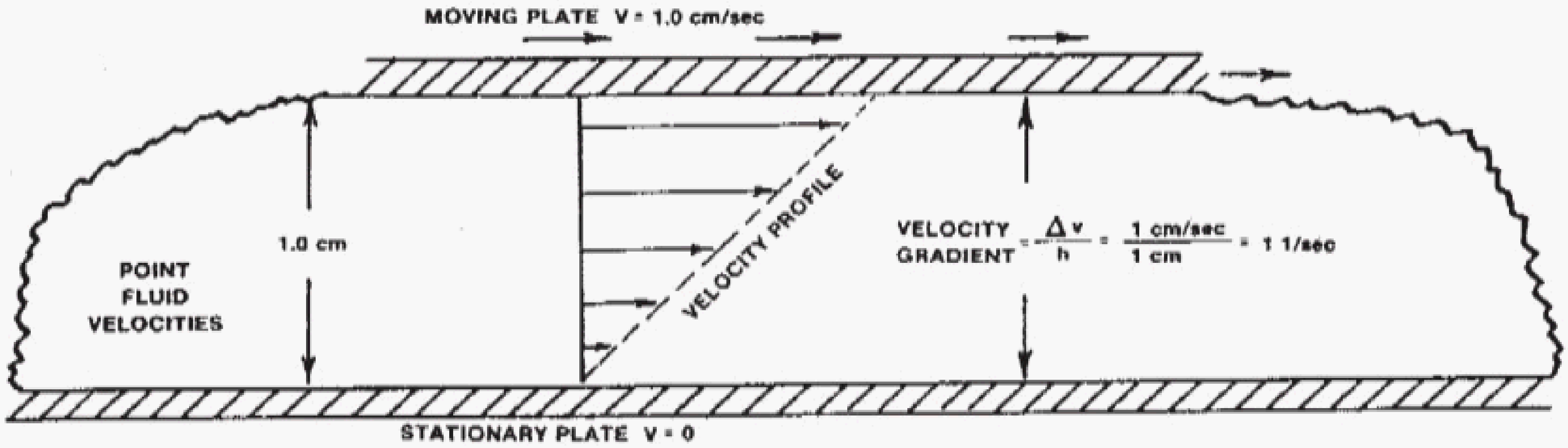

Figure 1—Parallel Plates Showing Shear Rate in Fluid-filled Gap as One Plate Slides Past Another

4.4.4 It is important to express the above concept mathematically so that models and calculations can be developed. Shear rate (γ) is defined as:

$$\gamma = \frac{dV}{dr} \tag{10}$$

where

dV = velocity change between fluid layers,

dr = distance between fluid layers.

4.4.5 Shear rate (γ_{wp}) can be expressed as a function of the average velocity (V) and the diameter of the pipe (D).[4]

$$\gamma_{wp} = f(V,D) = \frac{8V_p}{D} \tag{11}$$

in which

$$V_p = \frac{Q}{A} = \frac{4Q}{\pi D^2} \tag{12}$$

where

Q = volumetric flow rate,

A = surface area of cross section,

D = pipe diameter,

V = velocity,

V_p = average velocity in pipe.

4.4.6 In an annulus of outside diameter (D_2) and inside diameter (D_1), the wall shear rate can be shown to be: [4]

$$\gamma_{wa} = f(V,D_1D_2) = \frac{12V_a}{D_2 - D_1} \tag{13}$$

in which

$$V_a = \frac{4Q}{\pi(D_2^2 - D_1^2)} \tag{14}$$

where

γ_{wa} = shear rate at annulus wall,

V = velocity,

Q = volumetric flow rate,

D_1 = inner annulus diameter,

D_2 = outer annulus diameter,

V_a = average velocity in annulus,

4.5 RELATIONSHIP OF SHEAR STRESS AND SHEAR RATE

4.5.1 In summary, the shear stress is the force per unit area required to sustain fluid flow. Shear rate is the rate at which the fluid velocity changes with respect to the distance from the wall. Viscosity is the ratio of the shear stress to shear rate. The mathematical relationship between shear rate and shear stress is the rheological model of the fluid.

4.5.2 When a drill cutting particle settles in a drilling fluid, the fluid immediately surrounding the particle is subjected to a shear rate defined as settling shear rate (γ_s):

$$\gamma_s = \frac{12V_s}{D_p} \tag{15}$$

where

V_s = average settling velocity (ft/sec.),

D_p = equivalent particle diameter (in.).

The settling shear rate is used to calculate the viscosity of fluid experienced by the settling particle.

[4]See References 7 and 30.

5 Types of Fluids

5.1 DESCRIPTION

5.1.1 Fluids can be classified by their rheological behavior. Fluids whose viscosity remains constant with changing shear rate are known as Newtonian fluids. Non-Newtonian fluids are those fluids whose viscosity varies with changing shear rate.

5.1.2 Temperature and pressure affect the viscosity of a fluid.[5] Therefore, to properly describe the drilling fluid flow, the test temperature and pressure must be known.

5.1.3 Some mathematical models used for hydraulic calculations are shown in this section.

5.2 NEWTONIAN FLUIDS

5.2.1 Those fluids in which shear stress is directly proportional to shear rate are called Newtonian. Water, glycerin, and light oil are examples.

5.2.2 A single viscosity measurement characterizes a Newtonian fluid.

5.3 NON-NEWTONIAN FLUIDS

5.3.1 Most drilling fluids are not Newtonian; the shear stress is not directly proportional to shear rate. Such fluids are called non-Newtonian.[6]

5.3.1.1 Drilling fluids are shear thinning when they have less viscosity at higher shear rates than at lower shear rates.

5.3.1.2 There are non-Newtonian fluids, which have dilatant behavior. The viscosity of these fluids increases with increasing shear rate. Dilatant behavior of drilling fluids rarely, if ever, occurs.

5.3.2 The distinction between Newtonian and non-Newtonian fluids is illustrated by using the API standard concentric cylinder viscometer.[7] If the 600-rpm dial reading is twice the 300-rpm reading, the fluid exhibits Newtonian flow behavior. If the 600-rpm reading is less than twice the 300-rpm reading, the fluid is non-Newtonian and shear thinning.

5.3.3 One type of shear thinning fluid will begin to flow as soon as any shearing force or pressure, regardless of how slight, is applied. Such fluid is termed pseudoplastic.[8] Increased shear rate causes a progressive decrease in viscosity.

5.3.4 Another type of shear thinning fluid will not flow until a given shear stress is applied. This shear stress is called the yield stress.

[5]See References 5, 6, and 24.
[6]See References 18 and 29.
[7]See Reference 28.
[8]See Reference 16.

5.3.5 Fluids can also exhibit time dependent effects. Under constant shear rate, the viscosity decreases with time until equilibrium is established. Thixotropic fluids experience a decrease in viscosity with time while rheopectic fluids experience an increase in viscosity with time.

5.3.6 Thixotropic fluids can also exhibit a behavior described as gelation or gel strength. The time dependent forces cause an increase in viscosity as the fluid remains static. Sufficient force must be exerted on the fluid to overcome the gel strength to begin flow.

5.3.7 The range of rheological characteristics of drilling fluids can vary from an elastic gelled solid at one extreme, to a purely viscous Newtonian fluid at the other. The circulating fluids have a very complex flow behavior, yet it is still common practice to express the flow properties in simple rheological terms.

5.3.8 General statements regarding drilling fluids are usually subject to exceptions because of the extraordinary complexity of these fluids.[9]

5.4 RHEOLOGICAL MODELS

5.4.1 Rheological models are intended to provide assistance in characterizing fluid flow. No single, commonly-used model completely describes rheological characteristics of drilling fluids over their entire shear rate range. A knowledge of rheological models combined with practical experience is necessary to fully understand fluid performance.

5.4.2 Bingham Plastic Model: The most common rheological model used for drilling fluids is the Bingham Plastic Model. This model describes a fluid in which the shear stress/shear rate ratio is linear once a specific shear stress has been exceeded. Two parameters, plastic viscosity and yield point, are used to describe this model. Because these constants are determined between the specified shear rates of 511 $sec.^{-1}$ and 1022 $sec.^{-1}$, this model characterizes a fluid in the higher shear rate range.

5.4.3 Power Law: The Power Law is used to describe the flow of shear thinning or pseudoplastic drilling fluids. This model describes a fluid in which shear stress versus shear rate is a straight line when plotted on a log-log graph. Since the constants, n and K, from this model are determined from data at any two speeds, it more closely represents an actual fluid over a wide range of shear rates.

5.4.4 Herschel-Buckley (Modified Power Law) Model: The modified Power Law is used to describe the flow of a pseudoplastic drilling fluid, which requires a yield stress to flow. A graph of shear stress minus yield stress versus shear rate is a straight line on log-log coordinates. This model has the advan-

[9]See References 20, 21 and 32.

tages of the Power Law and more nearly describes the flow of a drilling fluid since it also includes a yield value.

5.4.5 The rheological parameters recorded in an API Drilling Fluid Report are plastic viscosity and yield point from the Bingham Plastic Model.

5.4.6 The mathematical treatment of Bingham Plastic and Power Law is discussed in Section 7.

5.4.7 The flow characteristics of a drilling fluid are controlled by the viscosity of the base fluid (the continuous phase) and any solid particles, oil, or gases within the fluid (the discontinuous phases) and the flow channel characteristics, and the volumetric flow rate. Any interactions among the continuous and discontinuous phases, either chemical or physical, have a marked effect on the rheological parameters of a drilling fluid. The constants calculated by use of Bingham Plastic, Power Law and other models are only indicators that are commonly used to guide fluid conditioning to obtain the desired rheological properties.

6 Equipment for Measurement of Rheological Properties

6.1 ORIFICE VISCOMETER-MARSH FUNNEL

6.1.1 Description

The Marsh funnel is widely used as a field measuring instrument. The measurement is referred to as the funnel viscosity and is a timed rate of flow, usually recorded in seconds per quart. The instrument is dimensioned so that by following standard procedures the outflow time of one quart of fresh water is 26 sec. ± 0.5 sec. at 70°F ± 5°F (21°C ± 2°C).

6.1.2 Uses

Funnel viscosity is a rapid, simple test that can be made routinely on a particular drilling fluid system. It is, however, a one-point measurement and, therefore, does not give any information as to why the viscosity may be high or low. No single funnel viscosity measurement can be taken to represent a consistent value for all drilling fluids of the same type or of the same density.

6.1.3 Operating Procedures

Refer to API RP 13B-1 *Recommended Practice Standard Procedure for Field Testing Water-based Drilling Fluids* , or RP 13B-2 *Recommended Practice Standard Procedure for Field Testing Oil-based Drilling Fluids* , Sections entitled "Marsh Funnel."

6.2 CONCENTRIC CYLINDER VISCOMETER

6.2.1 Low-temperature, Non-pressurized Instruments

6.2.1.1 Description

Concentric cylinder viscometers are rotational instruments powered by an electric motor or a hand crank. Fluid is contained in the annular space between two cylinders. The outer sleeve or rotor sleeve is driven at a constant rotational velocity. The rotation of the rotor sleeve in the fluid produces a torque on the inner cylinder or bob. A torsion spring restrains the movement. This mechanism is illustrated in Figure 2. In most cases, a dial attached to the bob indicates displacement of the bob. Instrument constants have been so adjusted that plastic viscosity and yield point are obtained by readings from rotor sleeve speeds of 300 and 600 rpm. Instruments are also available that are not direct indicating but use x-y recorders to record the acquired data.

6.2.1.2 Selection of Instruments

Several models of low temperature, non-pressurized concentric cylinder viscometers are commonly used in testing drilling fluids.[10] They differ in drive, available speeds, methods of readouts and measuring angles. All permit rapid calcu-

[10]See Reference 28.

Table 1—Low-temperature, Non-pressurized Concentric Cylinder Viscometers

Model	Drive	Power	Readout	Rotor Speed, RPM	Vis. Range* *cP*	Max. Temp, °F
Model 280	Hand-cranked	—	Dial	300, 600 Stir	1 – 300	200
Model 35A	Motor	115V, 60 Hz	Dial	3, 6, 100, 200, 300,600	1 – 30,000	200
Chan 35	Motor	115V, 60 Hz 220V, 50 Hz	Dial	0.9, 2, 3, 6, 10, 20, 30, 60, 100, 200, 300, 600	1 – 100,000	200
OFI 800	Motor	12V DC 115V, 60 Hz 220V, 50 Hz	Dial	3, 6, 30, 60, 100, 200, 300, 600	1 – 100,000	200
Model 286	Motor	12V 115V 220V	Dial	1 – 625 variable	1 – 300	200
Haake VT500	Motor	115V, 60 Hz	Digital	0 – 600 variable	1 – 100,000	400
Haake RV2	Motor	115V, 60 Hz	Digital	0 – 1000 variable	1 – 10,000,000	400

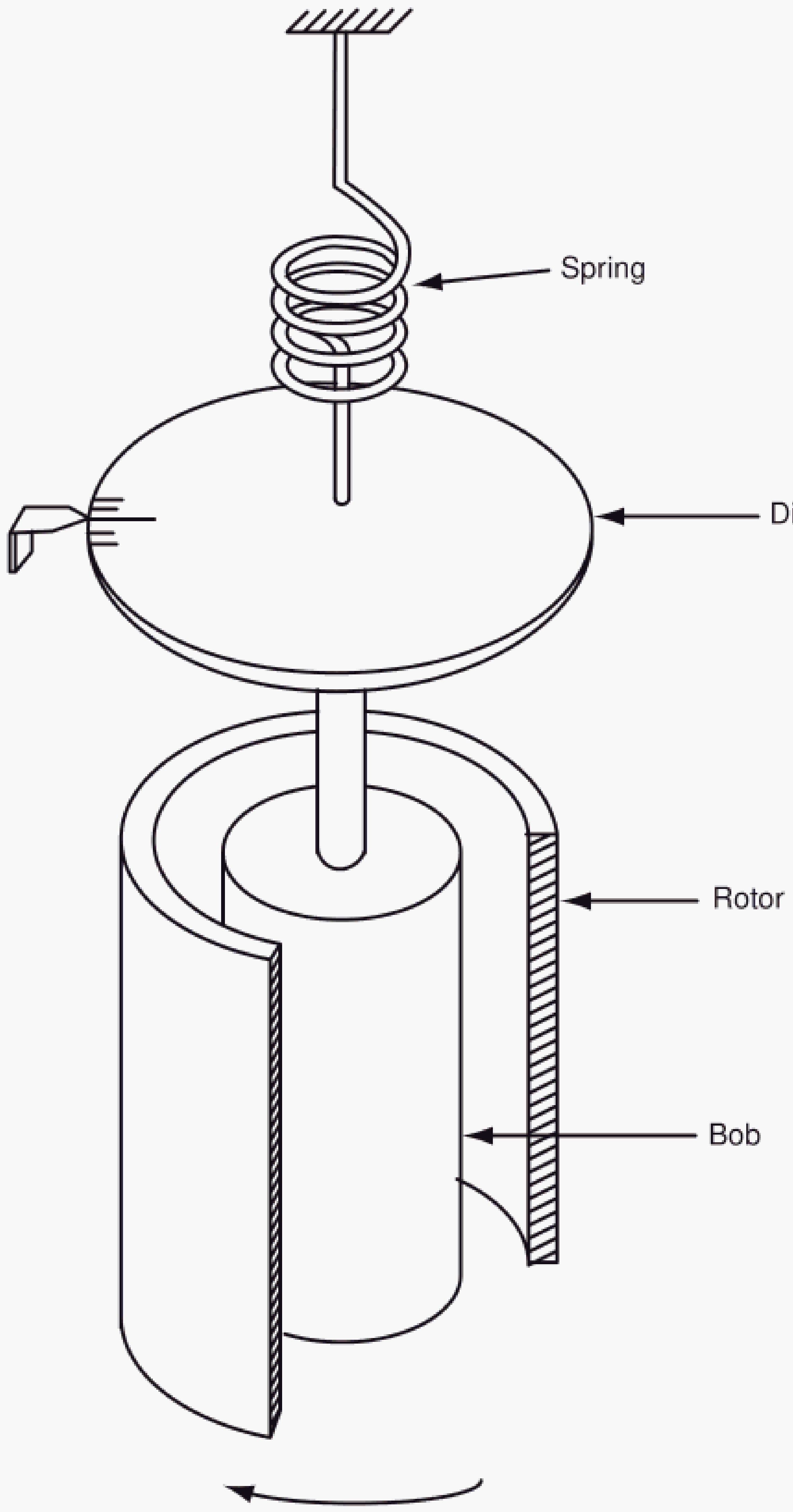

Figure 2—Concentric Cylinder Viscometer

lation of plastic viscosity and yield point from readings at 300 rpm and 600 rpm. Table 1 shows some of the models available and their operating limits. Illustrations of instruments are found in Figures 3 – 9.

6.2.1.3 Operating Procedures

Operating procedures for several models of concentric cylinder viscometers are detailed in API RP 13B-1 or API RP 13B-2. Specific operating procedures for those instruments not included in API RP 13B-1 or API RP 13B-2 can be obtained from the manufacturer.

6.2.2 High-temperature, Pressurized Instruments

6.2.2.1 Description

Several instruments are used to measure flow properties of drilling fluids at elevated temperatures and pressures. Each instrument has differences in temperature and pressure limitations, and design variation. A summary of available models is shown in Table 2.

Figure 3—Model 280

a. Model 50SL Viscometer: This instrument (shown in Figure 10) is designed in the same fashion as the non-pressurized viscometers. The upper operating limits are 1000 psig and 500°F. Fluid is contained in the annular space between two cylinders with the outer sleeve being driven at a controlled rotational velocity. Torque is exerted on the inner cylinder or bob by the rotation of the outer sleeve in the fluid. This torque is then measured to determine flow properties. This instrument has infinitely variable rotor speeds from 1 rpm – 625 rpm with a viscosity range of 1 – 300,000 *cP*. The temperature range of 0 – 500°F is programmable. A computer interface provides real-time graphic display and data storage.

b. Model 70 HPHT Viscometer: The high-pressure, high-temperature instrument (shown in Figure 11) has upper operating limits of 20,000 psi and 500°F. It is a concentric cylinder viscometer that uses the same geometry as the non-pressurized viscometers. Rotor speeds are variable up to 600 rpm. The rotor has external flights to induce circulation. Temperature, pressure, rpm, and shear stress are obtained through digital readout. The digital temperature control has ramp and soak capacities.

c. Model 75 HPHT Viscometer: The high-pressure, high temperature instrument (shown in Figure 12) has upper operating limits of 20,000 psig and 500°F. It is a concentric cylinder viscometer that uses the same geometry as the non-pressurized viscometers. Rotor speeds are variable up to 600 rpm. The rotor has external flutes to induce circulation. Temperature, pressure, rotary speed, and shear stress are microprocessor-

Figure 4—Model 35A

controlled and digitally displayed. Interface to a computer allows for additional programming and manipulation of data.

d. RV20/D100: This instrument (shown in Figure 13) is a high-temperature, pressurized rotational viscometer with upper operating limits of 1400 psi and 572°F. It consists of concentric cylinders mounted in an autoclave. The outer cylinder is bolted to the autoclave top and supports the inner cylinder on a ball bearing. The inner cylinder (or rotor) is connected by a magnetic coupling to a Rotovisco RV20. Computer control is available for automatically plotting flow curves. The instrument is continuously variable between 0 and 1200 sec.$^{-1}$ and provides automatic data analyses. The torque imparted on the rotor is measured by an electrical torsion bar, which provides rapid response. The angular movement of the torsion bar is a measurement of the transmitted torque; the shear stress is calculated from the torque

Figure 5—Model 800

value by means of an appropriate shear stress constant. A high-pressure, high-temperature version of this instrument is also available with upper operating limits of 14,000 psi and 662°F. (No photograph of this HPHT equipment is available.)

e. Model 7400: This instrument is a high-pressure, high-temperature, coaxial cylinder, couette-type rheometer (shown in Figure 14). Testing limits are 20,000 psi and 400°F. Torque range is 0 – 540,000 dyne/cm, measured by a precision strain gauge sensor. There are twelve evenly-spaced preset rotor speeds as well as infinitely variable from 0 – 600 rpm. Temperature is microprocessor controlled. The unit is provided with a data acquisition system that displays temperature, pressure,

Figure 6—Chan 35

Figure 7—Model 286

Figure 8—Model VT500

torque, and rotor speed in real time on a computer monitor. The test fluid is continually circulated in the sample container by the rotor design. The test fluid is separated from the pressurizing medium by a flexible piston to prevent contamination.

f. Model 1000 HPHT Viscometer: This instrument (shown in Figure 15) incorporates high-pressure up to 1000 psi and high temperatures up to 500°F. An optional chiller can be used for testing to 32°F. Low shear rates as low as 0.01 $sec.^{-1}$ are possible. The instrument uses traditional bobs and rotor for measurements with shear stress ranges from 0 – 4000 $dyne/cm^2$. The instrument is computer controlled using the ORCADA software system. Data is stored in an ASCII text format or in a Microsoft® Excel file.

Figure 9—Model RV20

6.2.2.2 Operating Procedures

Specific operating procedures for these instruments can be obtained from the manufacturer.

6.3 TELESCOPIC-SHEAR VISCOMETER MODEL 5STDL CONSISTOMETER

6.3.1 Description

This is a high-pressure, high-temperature instrument in which the test fluid is subjected to telescopic shear. The upper operating limits are 20,000 psi and 500°F. Axial movement of an iron bob is caused by two alternately energized electromagnets positioned at ends of the sample cavity. The fluid is sheared in the annular space between two coaxial cylinders, the outer forming the sample container and the moving bob being the inner member. Bob movement is retarded in proportion to the viscosity of the test fluid. The travel time is a measurement of relative viscosity.

6.3.2 Uses

Absolute viscosity is not determined with this instrument and the results are usually considered as relative viscosity. A constant force is imposed on the bob by the electromagnets so that it must accelerate from zero to its terminal velocity in the test fluid. In typical drilling fluids, the bob may not always travel at uniform velocity so that the analysis at a constant and defined shear rate in the annulus may not be possible.

6.3.3 Operating Procedures

Specific operating procedures for this instrument should be obtained from the manufacturer.

6.4 PIPE VISCOMETER

6.4.1 Description

Pipe viscometers are highly varied in form and intent. The instrument is a tube or pipe of length sufficient to develop

Figure 10—Model 50 SL

fully the shear rates and type of flow of interest. This tube is coupled with a pumping source of size sufficient to meet desired parameters. Careful control and measurement of flow rate are necessary and usually are accomplished by using a variable speed pump and flow meters. When the desired flow rate is obtained, the pressure drop of the fluid is measured through a specified test section of the pipe. Viscosity may then be calculated from standard equations using the shear rate, pressure drop, diameter and length. The configuration of the viscometer may be altered to investigate annular flow by placing a pipe of a smaller diameter inside the pipe viscometer tube and flowing in the annulus.

6.5 PORTABLE CAPILLARY VISCOMETER

6.5.1 Description

A portable capillary viscometer consists of a fluid reservoir, heating jacket, pressure gauge, three-port valve, coiled capillary tube and two interchangeable straight capillary tubes. A drilling fluid sample is placed in the reservoir and pressured by nitrogen from a portable source. The nitrogen forces the drilling fluid out through either the coiled capillary tube or one of the two interchangeable straight capillary tubes, depending upon the positioning of the port valve. The coiled tube is used in the low shear rate range (10 – 10,000 $sec.^{-1}$). The two straight tubes are used in the higher shear rate range (1,000 – 100,000 $sec.^{-1}$). No matter which tube is in use, the length must be sufficient to insure that flow is fully developed before entering the test section. During each measurement, the pressure drop, indicated by the gauge, and the flow rate are recorded. The reservoir pressure is varied to cover the desired range of shear rates. The gel strength of the fluid is measured in the coiled tube. The pressure required to begin flow is measured after the drilling fluid has remained stationary for the desired gelation time.

6.5.2 Calculation

Equations for determining shear stress, shear rate and viscosity from such instruments are discussed in Sections 4 and 7.

6.5.3 Operating Procedures

Specific operating procedures for this instrument should be obtained from the manufacturer.

7 Data Analysis

7.1 DESCRIPTION

This section describes methods for analyzing drilling fluid rheological data and presents a way for estimating the effects of temperature and pressure.

Table 2—High-temperature, Pressurized Concentric Cylinder Viscometers

Model	Viscosity Range *cP**	Rotor Speed Rpm	Maximum Temperature °F	Maximum Pressure, psi
Model 7400	0 – 54,000	0 – 600 variable	400	20,000
Fann 50SL	1 – 300,000	1 – 625 variable	500	1,000
Fann 70	1 – 300,000	1 – 625 variable	500	20,000
Fann 75	1 – 300,000	1 – 625 variable	500	20,000
Haake RV20/D100	1 – 10,000	0 – 1000 variable	662	14,000

7.2 RHEOLOGICAL FLOW CURVES

Rheological data can be shown on linear, semi-log or log-log graphs of shear rate versus shear stress or viscosity. The data have also been plotted as viscometer dial readings versus viscometer rpm. It is preferable to show the dependent variable, shear stress (τ), viscosity (μ) or viscometer dial reading on the vertical axis. Values of shear stress can be expressed in dyne/cm^2 or lb./100 ft^2. Viscosity is usually expressed as centipoise (*cP*). Shear rate is expressed as reciprocal second (sec.$^{-1}$).The foregoing only applies to instruments similar to the concentric cylinder viscometer described in Section 6.

Shear stress or viscosity versus shear rate relationships are useful in classifying fluids and in the mathematical treatment of data. Figure 16 is a linear plot and Figure 17 is a log-log plot of several flow models.

7.3 MATHEMATICAL FLOW MODELS

These models provide a means of using viscometer data or shear stress/shear rate relationships to develop usable information. They are a means of determining the effective viscosity as described in 4.2 from which hydraulic calculations are made.

Effective viscosity is defined by the following equation:

$$\mu_e = \frac{\tau}{\gamma} \qquad (16)$$

where

τ = shear stress,

γ = shear rate,

μ_e = effective viscosity at the specified shear rate.

The effective viscosity relationship obtained in this manner can be used in many of following calculations.

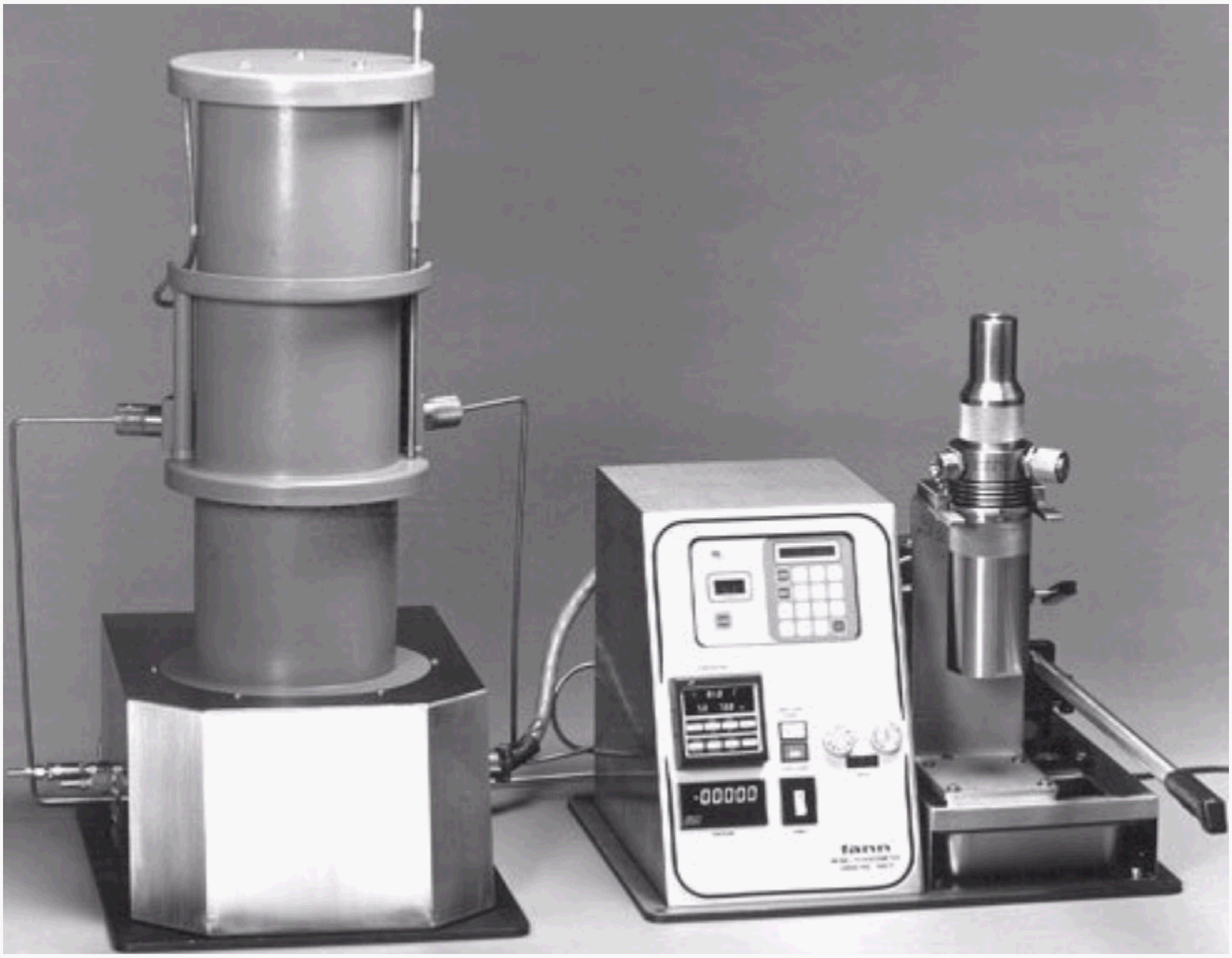

Figure 11—Model 70

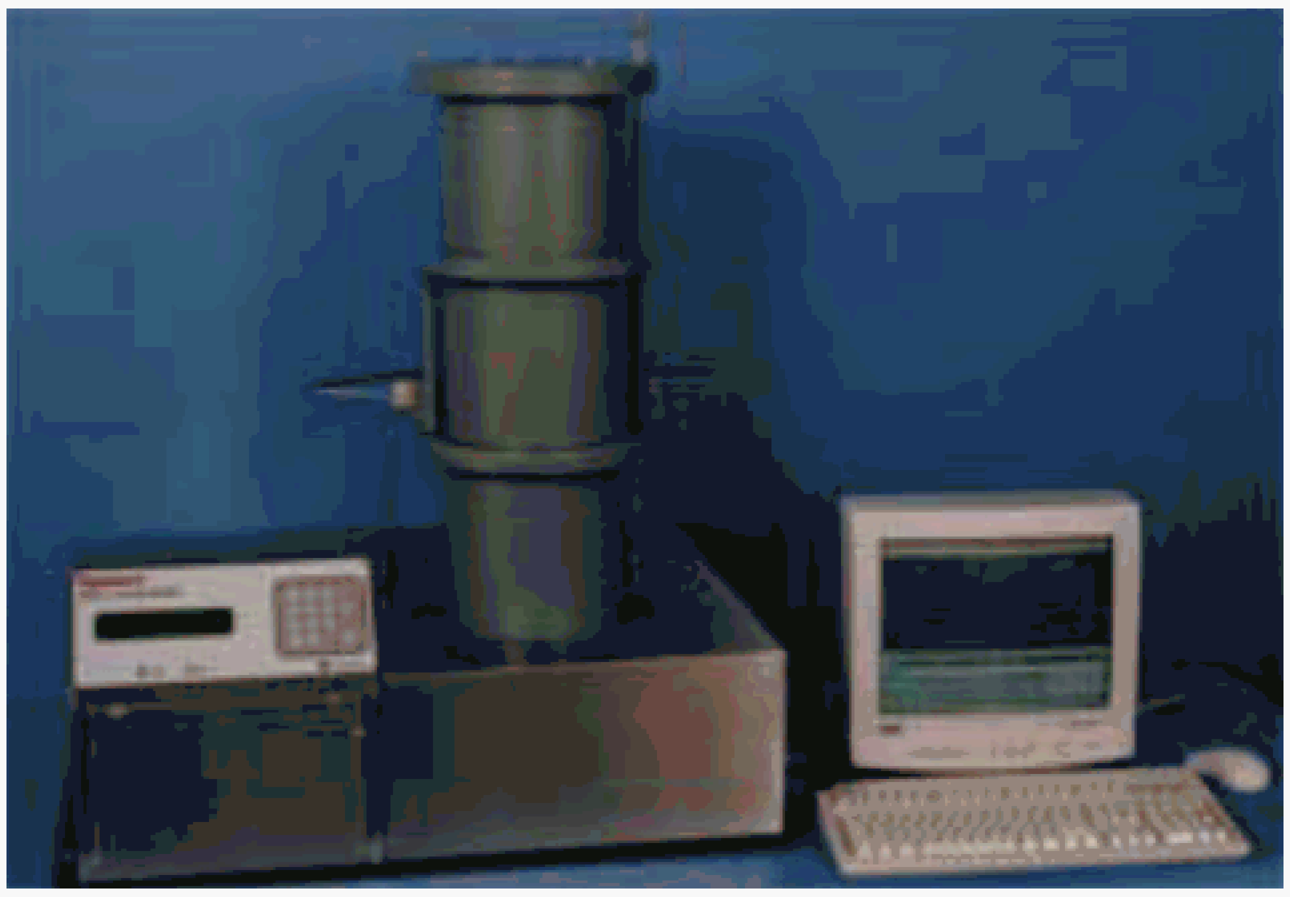

Figure 12—Model 75

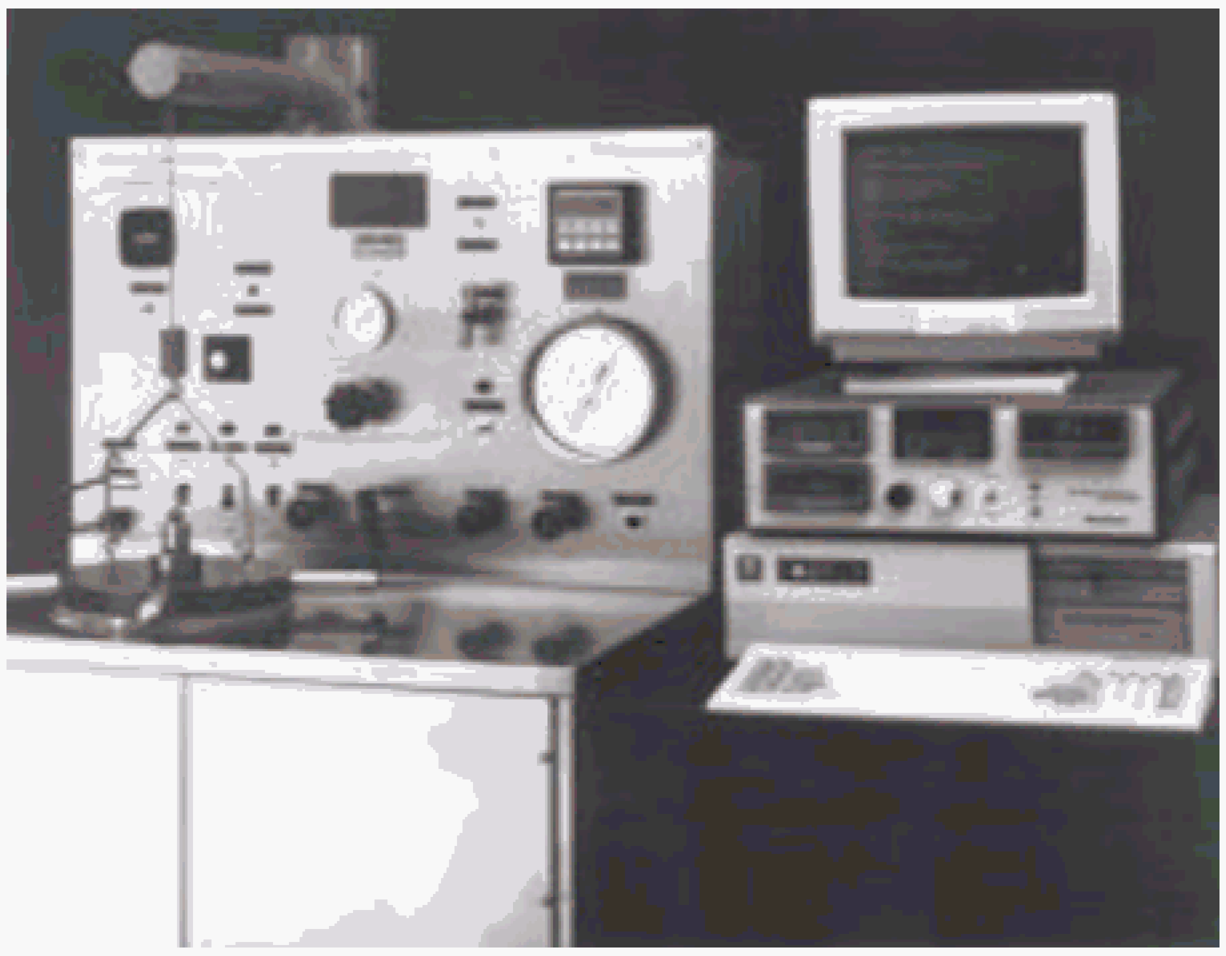

Figure 14—Model 7400

Figure 13—Model RV20/D100

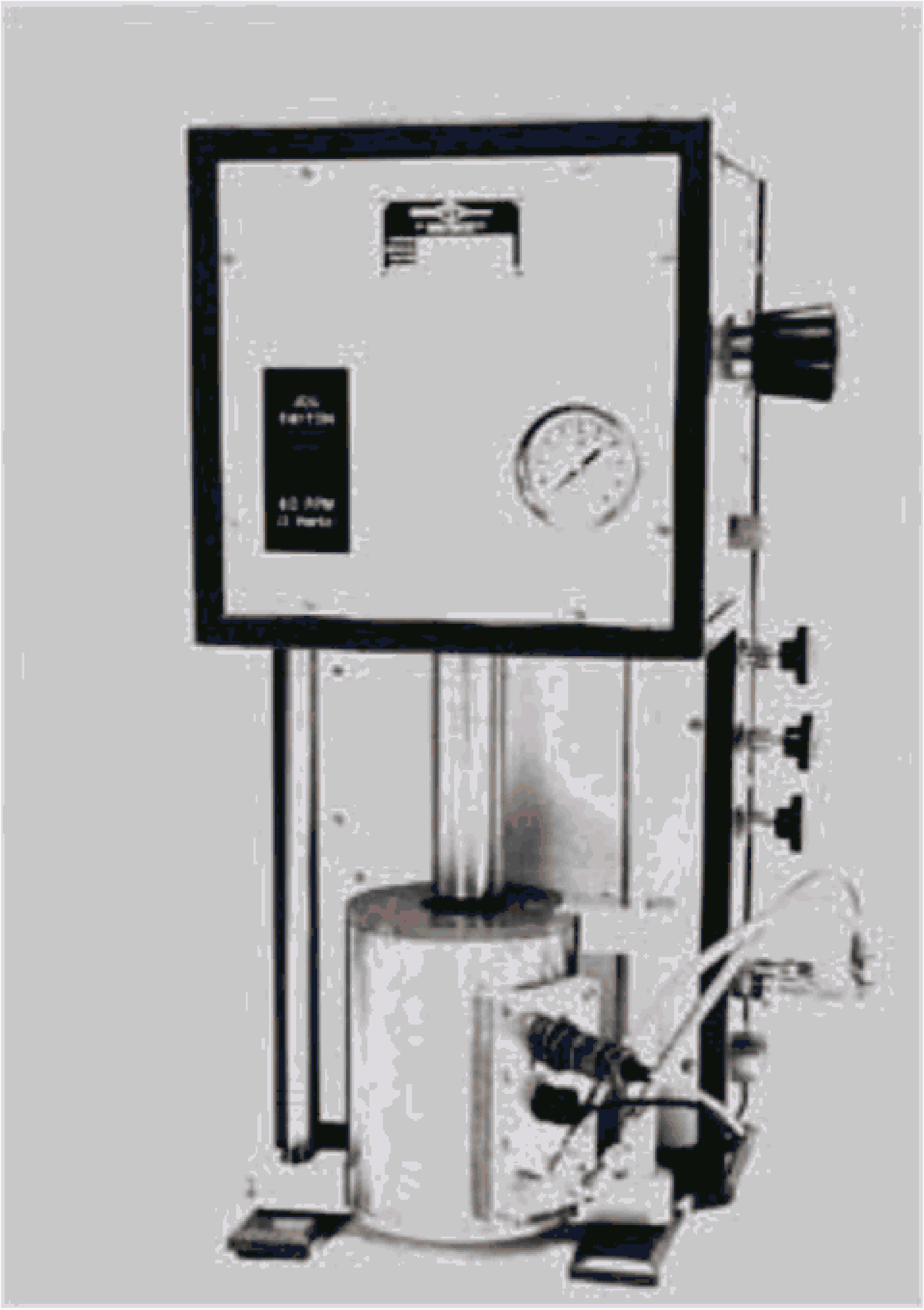

Figure 15—Model 1000 HPHT Viscometer

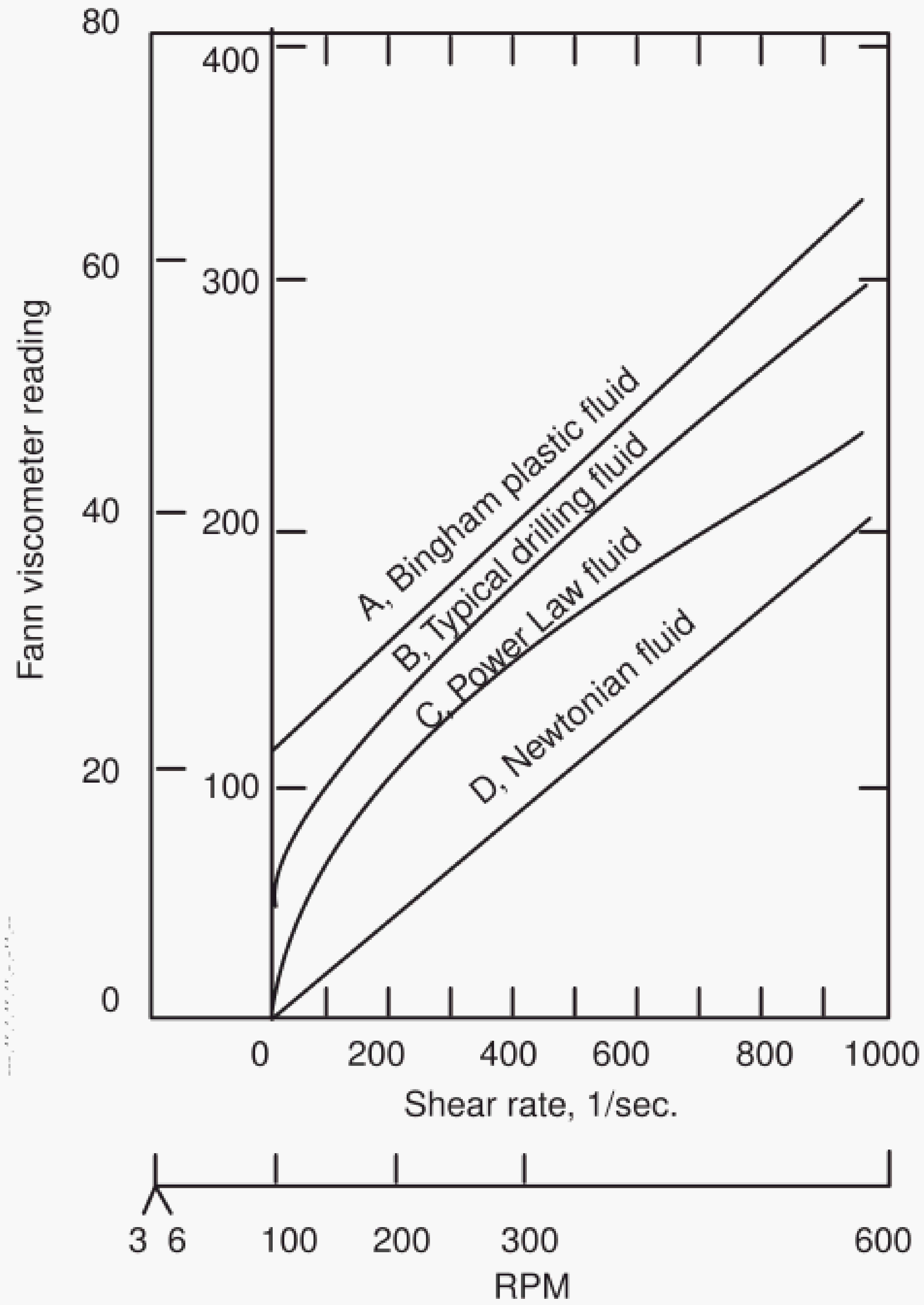

Figure 16—Linear Shear Stress—Shear Rate Plots

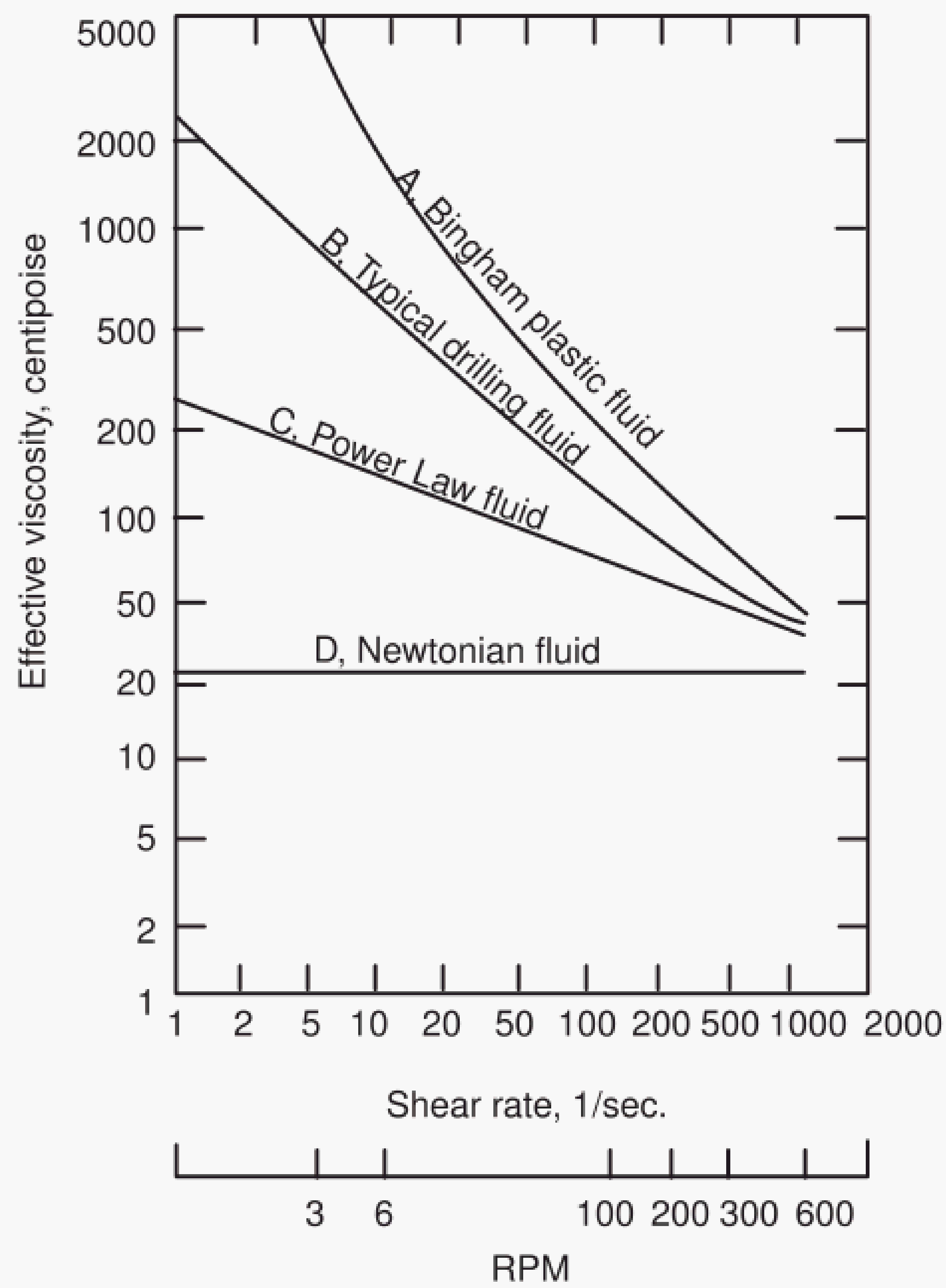

Figure 17—Log-log Effective Viscosity—
Figure Shear Rate Plots

7.3.1 Newtonian Model

Newtonian fluids, as defined in 5.1, follow a simple linear equation in laminar flow:

$$\tau = \mu\gamma \quad (17)$$

When the shear stress (τ) of a Newtonian fluid is plotted against the shear rate (γ) in linear coordinates, a straight line through the origin results. The Newtonian viscosity (μ) is the slope of this line. The effective viscosity of a Newtonian fluid can be expressed as:

$$\mu_e = \frac{\tau}{\gamma} = \mu \quad (18)$$

Since the shear stress/shear rate ratio is a constant for any shear rate, the effective viscosity is equal to the Newtonian viscosity and is independent of shear rate.

7.3.2 Non-Newtonian Models[11]

7.3.2.1 Bingham Plastic Model

A Bingham Plastic fluid is one in which flow occurs only after a finite stress, known as yield stress or yield point, is applied. The stress required to initiate flow can vary from a small to a large value. After the yield stress has been exceeded, the shear stress is proportional to the shear rate.

$$\tau - \tau_y = \eta\gamma \quad (19)$$

where

τ_y = yield point (or yield stress),

η = plastic viscosity.

Analysis of Bingham Plastic data can be found in 7.4.

[11]See References 16, 17, 25, 29 and 30.

7.3.2.2 Power Law

The Power Law is:

$$\tau = K\gamma^n \quad (20)$$

where

K = fluid consistency index,

n = Power Law exponent.

A plot of shear stress versus shear rate in linear coordinates results in a curve. It is apparent from the power relationship form, however, that a plot of shear stress versus shear rate in log-log coordinates gives a straight line where n is the slope and K is the intercept at $\gamma = 1$. Logarithmic plots of effective viscosity (μ_e) versus shear rate (γ) are shown as B and C in Figure 17. The idealized straight line plot shown as C is seldom encountered in actual practice. Plots of field drilling fluid data more nearly resemble line B. See 7.5 for specific mathematical procedures that can be used to determine the Power Law parameters for drilling fluids.

7.3.2.3 Herschel-Buckley (Modified Power Law) Model

The Herschel-Buckley model is a three-parameter model, which combines the features of the Newtonian, Bingham Plastic and Power Law. It allows for a yield stress followed by Power Law behavior at higher stress levels. The Herschel-Buckley model is:

$$\tau - \tau_y = K\gamma^n \quad (21)$$

where

τ_y = yield stress, lb./100 ft^2.

If the yield stress is equal to zero, Power Law behavior is described. If the flow exponent n is equal to 1, Bingham Plastic behavior is described. If the yield stress is equal to zero and n=1, Newtonian behavior is described and K is the Newtonian viscosity. A subsequent log-log plot of ($\tau - \tau_y$) versus γ will be similar to that of a Power Law plot with the slope being the exponent n and the intercept at $\gamma = 1$, the constant K.

7.4 ANALYSIS OF BINGHAM PLASTIC MODEL DATA

7.4.1 Very few fluids actually follow the Bingham Plastic Model over the shear rate range of interest, but the empirical significance of the constants has become so firmly entrenched in drilling fluid technology that the yield point (τ_y), in lb./100 ft^2, and plastic viscosity (η) in cP, are two of the best known properties of drilling fluids. They are calculated from the standard concentric cylinder viscometer (see 6.2) readings at 600 rpm and 300 rpm (R_{600} and R_{300}) as follows:

$$PV = R_{600} - R_{300} \quad (22)$$

$$YP = R_{300} - PV \quad (23)$$

7.4.2 The average velocity of a drilling fluid in the pipe is determined by the use of the formula:

$$V_p = \frac{0.408Q}{D^2} \quad (24)$$

where

V_p = average velocity of the fluid in the pipe (ft/sec.),

Q = volumetric flow rate (gal/min),

D = inner diameter of pipe (in.).

7.4.3 In the annulus, the average velocity is determined by:

$$V_a = \frac{0.408Q}{D_2^2 - D_1^2} \quad (25)$$

where

V_a = average velocity of the fluid in the annulus (ft/sec.),

D_1 = inner annulus diameter (in.),

D_2 = outer annulus diameter (in.).

7.4.4 An explicit expression for shear rate at the pipe wall as a function of velocity cannot be derived from the Bingham equation; but in a pipe of diameter (D), the effective viscosity can be approximated by:

$$\mu_e = \frac{6.65\tau_y D}{V_p} + \eta \quad (26)$$

where

τ_y = yield stress (lb./100 ft^2),

η = plastic viscosity (cP).

7.4.5 In the annulus, the effective viscosity can be approximated by:

$$\mu_e = \frac{5.45\tau_y(D_2 - D_1) + \eta}{V_a} \quad (27)$$

Note: In the above equation, the constant 5.45 is true only for a D_1/D_2 ratio of 0.5 but varies only slightly from 5.49 to 5.43 over a range of diameter ratios from 0.3 to 0.9.[12]

7.5 MATHEMATICAL ANALYSIS OF POWER LAW DATA

The rheological parameters n and K can be calculated from any two shear rate-shear stress data points. Since it is rare that a log-log plot of all rheological data will be a straight line, it is better to determine n and K at the shear rates that exist inside a pipe and in an annulus. Better accuracy will result from the use of n and K in the 5 – 200 $sec.^{-1}$ shear rate range for the annulus and in the 200 – 1000 $sec.^{-1}$ shear rate range for inside pipe.

The viscometer dial readings from a standard six-speed instrument can be used to determine the Power Law constants. Normal practice is to use the 3-rpm and 100-rpm readings for the low shear rate range and the 300-rpm and 600-rpm reading for the high shear rate range. If a two-speed instrument is being used, the 100-rpm reading can be estimated from the 300-rpm and 600-rpm data by use of the equation:

$$R_{100} = \frac{R_{300}^{2.59}}{R_{600}^{1.59}} \quad (28)$$

where

R_{100} = viscometer reading at 100 rpm,

R_{300} = viscometer reading at 300 rpm,

R_{600} = viscometer reading at 600 rpm.

7.5.1 The general formulas for n and K are:

$$n = \frac{\log(\tau_2/\tau_1)}{\log(\gamma_2/\gamma_1)} \quad (29)$$

$$K = \frac{\tau_2}{\gamma_2^n} \quad (30)$$

where

n = Power Law exponent,

K = fluid consistency index (dyne $sec.^n/cm^2$),

τ_1 = shear stress at shear rate 1,

τ_2 = shear stress at shear rate 2,

γ_1 = shear rate 1,

γ_2 = shear rate 2.

7.5.2 Using data obtained at 600 rpm and 300 rpm, the parameters to be used for inside pipe calculations are:

$$n_p = \frac{\log(R_{600}/R_{300})}{\log(1022/511)} = 3.32\log\frac{R_{600}}{R_{300}} \quad (31)$$

$$K_p = \frac{5.11R_{300}}{511^{n_p}} \text{ or } \frac{5.11R_{600}}{1022^{n_p}} \quad (32)$$

7.5.3 Using data obtained at 100 rpm and 3 rpm, the parameters to be used for annular calculations are:

$$n_a = \frac{\log(R_{100}/R_3)}{\log(170.2/5.11)} = 0.657\log(R_{100}/R_3) \quad (33)$$

$$K_a = \frac{5.11R_{100}}{170.2^{n_a}} \text{ or } \frac{5.11R_3}{511^{n_a}} \quad (34)$$

7.5.4 Using data obtained at 100 rpm and 3 rpm, the parameters to be used in calculating settling velocities are:

$$n_s = 0.657\log(R_{100}/R_3) \quad (35)$$

$$K_s = \frac{5.11R_{100}}{170.2^{n_s}} \text{ or } \frac{5.11R_3}{5.11^{n_s}} \quad (36)$$

7.5.5 The general Power Law equation for effective viscosity (cP) is:

$$\mu_e = 100K\gamma^{n-1} \quad (37)$$

7.5.6 The effective viscosity (cP) in a pipe is:

$$\mu_{e_p} = 100K_p\left(\frac{96V_p}{D}\right)^{(n_p-1)}\left(\frac{3n_p+1}{4_{n_p}}\right)^{n_p} \quad (38)$$

7.5.7 The effective viscosity (cP) in an annulus is:

$$\mu_{e_a} = 100K_a\left(\frac{144V_a}{D_2-D_1}\right)^{(n_a-1)}\left(\frac{2n_a+1}{3_{n_a}}\right)^{n_a} \quad (39)$$

7.5.8 The effective viscosities μ_{ep} and μ_{ea} can be used to determine pressure losses as outlined in Section 8.

[12]See Reference 22.

7.5.9 The effective viscosity (cP) of fluid surrounding a settling particle is:

$$\mu_{e_s} = 100K_s\left(\frac{12V_s}{D_p}\right)^{(n_s-1)} \quad (40)$$

7.5.10 The effective viscosity μ_{es} can be used to determine settling velocities as outlined in Section 9.

7.6 EFFECTS OF TEMPERATURE AND PRESSURE ON VISCOSITY[13]

7.6.1 Temperature Effect

As the temperature increases, the effective viscosity decreases. The temperature effect[14] is described mathematically as:

$$\mu_e(T_2) = \mu_e(T_1)\exp\left[\beta\left(\frac{T_2-T_1}{T_1T_2}\right)\right] \quad (41)$$

where

$\mu_e(T_2)$ = effective viscosity at temperature 2,

$\mu_e(T_1)$ = effective viscosity at temperature 1,

T_1 = absolute temperature 1,

T_2 = absolute temperature 2,

β = temperature constant.

This approximation holds until a thermal decomposition or transition point of any component of the drilling fluid is reached. Above this temperature, the fluid flow properties do not follow any mathematical model. The temperature constant, β, must be determined at each shear rate for each drilling fluid. As a general rule, the temperature effect is high for oil-based fluids containing asphalt, moderate for oil-based fluids with oil-wet inorganic solids as viscosifiers, and low for water-based fluids.

7.6.2 Pressure Effect

As the pressure increases, the effective viscosity increases. The pressure effect is described mathematically as:

$$\mu_e(P_2) = \mu_e(P_1)\exp\lfloor\alpha(P_2-P_1)\rfloor \quad (42)$$

[13]See References 22 and 23.

[14]See References 17 and 32.

where

$\mu_e(P_2)$ = effective viscosity at pressure 2,

$\mu_e(P_1)$ = effective viscosity at pressure 1,

α = pressure constant,

P_1 = pressure 1,

P_2 = pressure 2.

The pressure constant, α, must be determined for each drilling fluid. For water-based fluids, the pressure effect on shear stress is extremely small and can be neglected. However, for oil-based fluids the pressure has an appreciable effect on the effective viscosity. As a general rule, the pressure effect is greater for oil-based fluids with asphaltic viscosifiers than for those that use oil-wet inorganic solids as viscosifiers.

Note: Absolute temperature is in degrees Rankine (460 + °F). Pressure is in psig.

7.6.3 Application

The use of viscosity measurements at surface conditions for calculating hydraulics may give erroneous results.[15] For accurate work, the viscosity of the drilling fluid should be determined at the temperatures and pressures encountered in the well. To do this requires a high-temperature, high-pressure viscometer for data collection and a computer to analyze the data. However, corrections can be made to surface conditions. These correction factors are average values obtained from measurements on various types of drilling fluids under conditions of high temperature and high pressure. Although the use of these correction factors will give good estimates, they are not as accurate as downhole viscosities that can be obtained by measurement under downhole conditions. Figures 18, 19 and 20 show the correction factor to be used with water-based fluids, oil-based fluids containing asphalt, and oil-based fluids containing oil-wet inorganic viscosifiers, respectively. To obtain the correction factor:

a. Select the proper graph to be used.

b. At the temperature of interest, draw a line to the proper pressure curve.

c. From the intersection of the temperature-pressure lines, draw a line to the correction factor axis and read the correction factor.

d. Multiply the effective viscosity by the correction factor.

[15]See Reference 29.

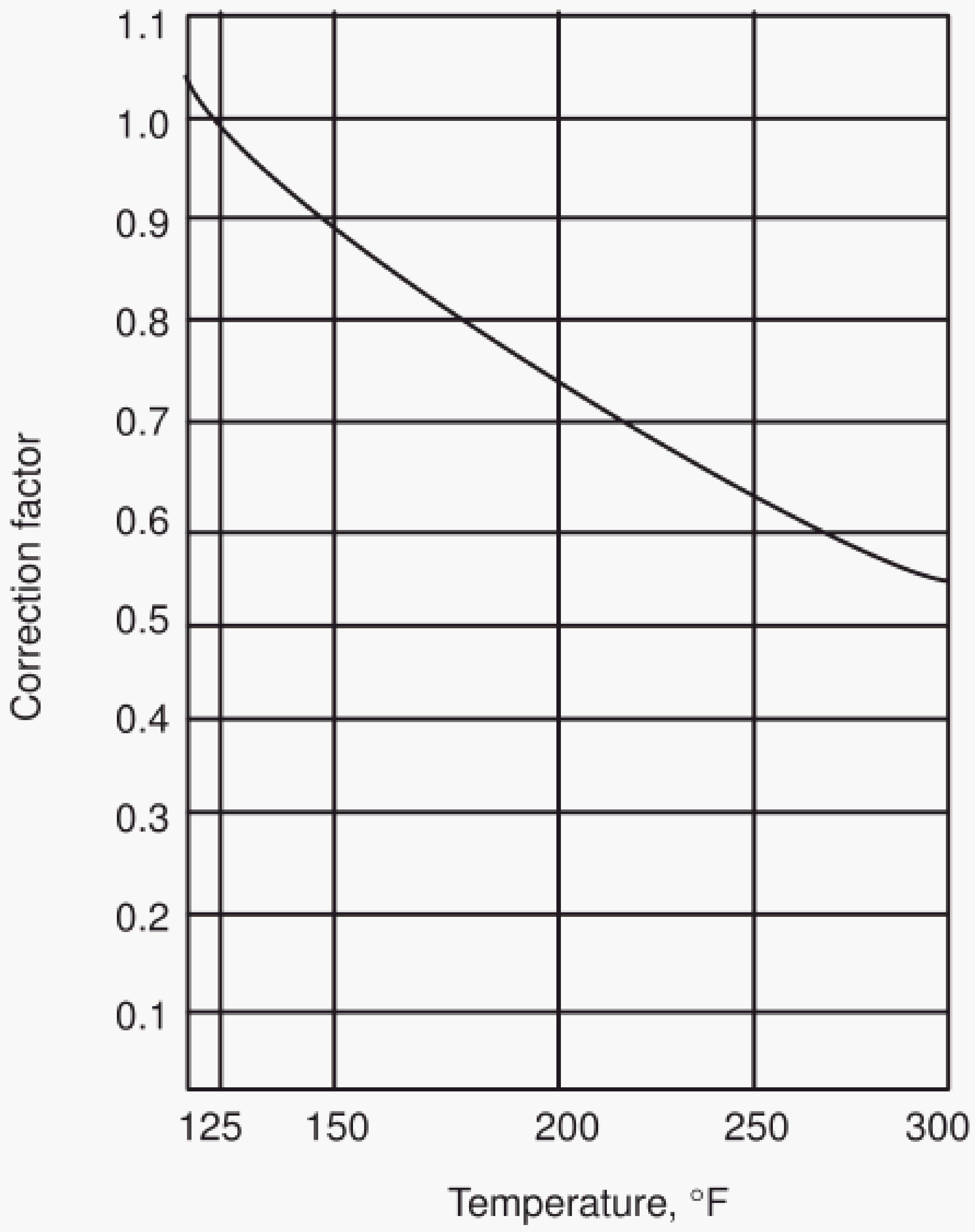

Figure 18—Downhole Viscosity Correction Factor Water-based Drilling Fluid

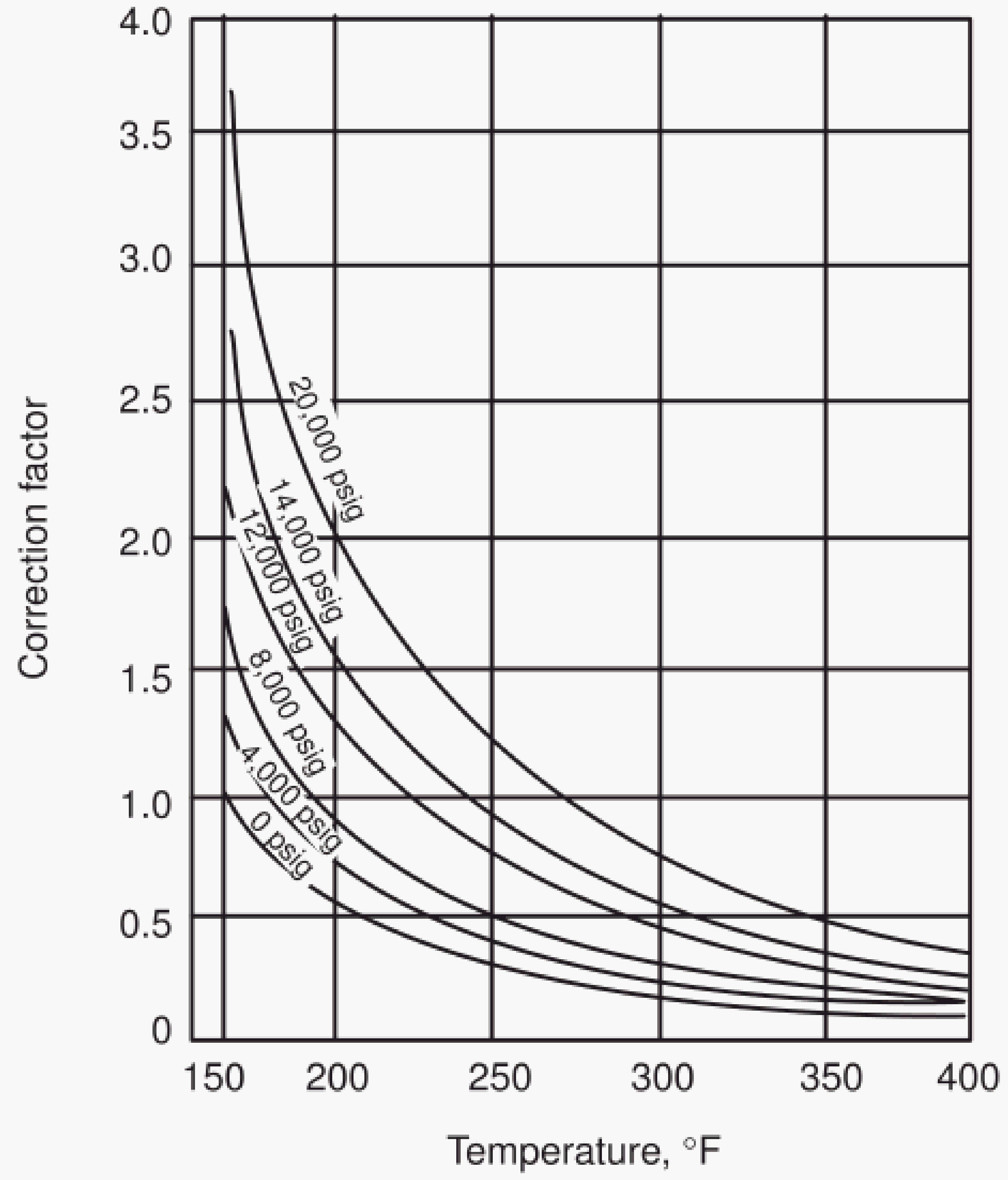

Figure 19—Downhole Viscosity Correction Factor Containing Asphalt Oil-based Drilling Fluids

8 Application of Rheological Data

8.1 DESCRIPTION

Rheological data are used to determine drilling fluid hydraulics. The calculations shown in this section have been simplified; however, the results obtained are sufficiently accurate for field operations.

8.2 FRICTION LOSS IN PIPE

8.2.1 Calculation of Reynolds Number[16]

After obtaining the effective viscosity (μ_{ep}) as a function of the operating shear rate at the pipe wall (γ_{wp}), the Reynolds number in the pipe (Re_p) is calculated from:

$$Re_p = \frac{928 V_p D \rho}{\mu_{ep}} \qquad (43)$$

Note: μ_{ep} can be calculated according to Eq. (39).

8.2.2 Calculation of the Friction Factor[17]

a. If the Reynolds number is less than or equal to 2100, the friction factor in the pipe is:

[16]See References 14, 19 and 27.
[17]See Reference 31.

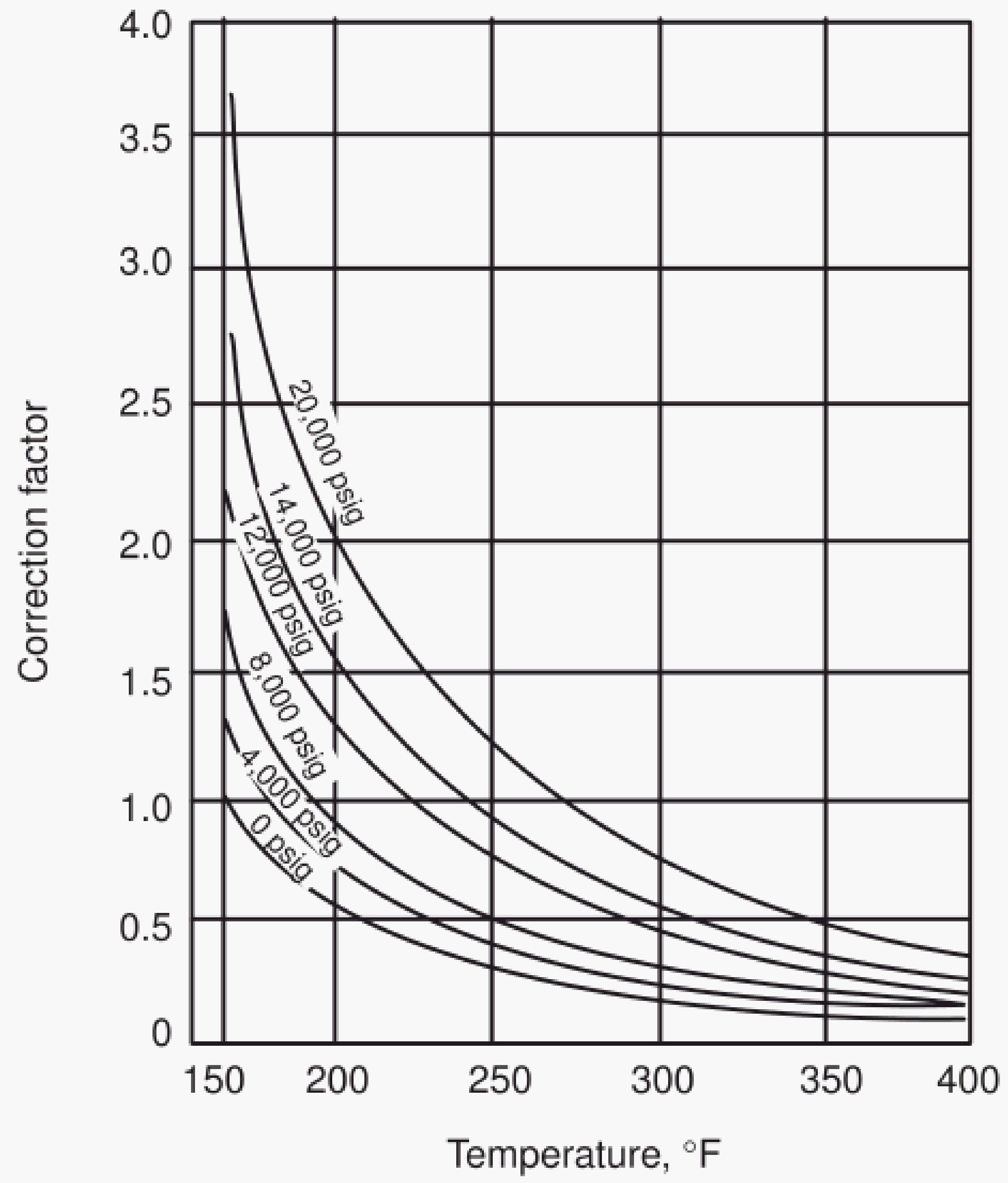

Figure 20—Downhole Viscosity Correction Factor Oil-based Fluids Containing Oil-wet Inorganic Viscosifiers

$$f_p = \frac{16}{Re_p} \quad (44)$$

b. If the Reynolds number is greater than 2100, the friction factor can be estimated from:

$$f_p = \frac{a}{(Re_p)^b} \quad (45)$$

where

f_p = friction factor in pipe,

a = $(\log n_p + 3.93)/50$,

b = $(1.75 - \log n_p)/7$.

8.2.3 Calculation of Friction Loss Pressure Gradient in Drill Pipe

The appropriate friction factor, which is dimensionless, is then substituted into the Fanning equation to obtain the friction loss pressure gradient.

$$\frac{P_p}{L_m} = \frac{f_p V_p^2 \rho}{25.81 D} \quad (46)$$

where

L_m = length of drill pipe (ft).

Note: Reynolds number and friction loss must be calculated for each section of pipe having different inside diameters.

8.3 FRICTION LOSS IN AN ANNULUS

8.3.1 Calculation of Reynolds Number

The Reynolds number in the annulus is calculated from the following equation:

$$Re_a = \frac{928 V_p (D_2 - D_1)\rho}{\mu_{ea}} \quad (47)$$

Note: μ_{ea} can be calculated according to Eq. 40.

8.3.2 Calculation of the Friction Factor

a. If the Reynolds number is less than or equal to 2100, the friction factor in the annulus is:

$$f_a = \frac{24}{Re_a} \quad (48)$$

b. If the Reynolds number is greater than 2100, the friction factor can be estimated from:

$$f_a = \frac{a}{(Re_a)^b} \quad (49)$$

where

f_a = friction factor in annulus,

a = $(\log n_a + 3.93)/50$,

b = $(1.75 - \log n_a)/7$.

Note: Calculated annular pressure losses in the turbulent flow regime based on current API RP 13D procedures will give lower friction pressure loss values than under the same conditions measured in flowloop testing. Calculated annular pressure losses in the laminar flow regime do provide a good comparison in flow loop testing. Based on this analysis, using the Power law behavior index (n) and consistancy factor (K) based on the drill pipe when the flow in the annulus is turbulent may give more accurate results.

8.3.3 Calculation of the Friction Loss Pressure Gradient

The appropriate friction factor is then substituted in the Fanning equation for an annulus to obtain the friction loss pressure gradient (P_a/L) in lb./in.^{2}/ft:

$$\frac{P_a}{L_m} = \frac{f_a V_a^2 \rho}{25.81(D_2 - D_1)} \quad (50)$$

Note: Reynolds number and friction loss must be calculated for each section of the annulus having different annular diameters.

8.3.4 Average Friction Loss Pressure Gradient

If more than one section of annulus is present, an average friction loss pressure gradient for the well is calculated by use of the following equation:

$$\text{Ave}P_a L_m = \frac{(P_{a1}/L_1)L_1 + (P_{a2}/L_2)L_2 + \ldots}{L_m} \quad (51)$$

8.4 FRICTION LOSS IN BIT NOZZLES

The friction loss (P_n) in bit nozzles (assuming a nozzle efficiency of 0.95) in lb./in.^{2} is calculated by use of the equation:[18]

$$P_n = \frac{156\rho Q^2}{(D_{n1}^2 + D_{n2}^2 + ...)^2} \qquad (52)$$

where

ρ = drilling fluid density (lb./gal),

Q = volumetric flow rate (gal/min.),

D_n = diameter of bit nozzles ($^1/_{32}$ in.).

8.5 HYDROSTATIC PRESSURE GRADIENT

The hydrostatic pressure gradient (P_h/L_v) in lb./gal can be obtained from the equation:

$$P_h/L_v = 0.052\rho \qquad (53)$$

where

L_v = true vertical depth (ft).

8.6 CIRCULATING PRESSURE GRADIENT

The hydrostatic pressure gradient plus the friction loss pressure gradient in the annulus gives the circulating pressure gradient (P_c/L) in the annulus. This can be calculated as follows:

$$P_c/L = P_h/L_v + P_a/L_m \qquad (54)$$

Note: If more than one annular section is present, use the average friction loss pressure gradient in the annulus (Ave P_a/L_m) to calculate the circulating pressure gradient.

8.7 EQUIVALENT CIRCULATING DENSITY

The equivalent circulating density (ρ_c) in lb./gal is calculated by use of the equation:

$$\rho_c = \frac{19.625 P_c}{L_v} \qquad (55)$$

8.8 STANDPIPE PRESSURE

The total pressure required to circulate the fluid down the drill string, through the bit and back to the surface is the sum of all pressure losses in the circulating system.

$$P_{sp} = \sum\left(\frac{P_{pi}}{L_{pi}}\right)L_{pi} + \sum\left(\frac{P_{aj}}{L_{aj}}\right)L_{aj} + P_n \qquad (56)$$

where

P_{sp} = standpipe pressure (lb./in.^{2}).

The calculated standpipe pressure should be comparable to that measured on the rig.

9 Settling Velocity of Drill Cuttings

9.1 DESCRIPTION

9.1.1 Settling velocity (slip velocity) refers to the velocity at which a particle falls in a fluid. The factors controlling the settling velocity are: the size and shape of the particle, the density of the particle and the density and rheological properties of the fluid through which the particle settles.[19]

9.1.2 Calculations of settling velocities, as outlined in this section, pertain only to vertical or near vertical boreholes.

9.2 SETTLING OF PARTICLES IN WATER

9.2.1 Drilled cuttings are irregularly shaped particles. The equivalent diameter of an irregularly shaped particle can be determined from its volume according to:

$$D_p = \sqrt[3]{\frac{6V_o}{\pi}} \qquad (57)$$

where

V_o = volume of particle, in.^{3},

D_p = equivalent particle diameter, in.

The volume of a particle can be determined from its dimensions or its submerged volume. Either a nominal or an equivalent diameter is used to describe particle size. Since settling velocity calculations are based on settling of spheres, a correction factor must be applied to account for the geometry of irregular shaped particle. Table 3 provides an estimate of the equivalent spherical diameter for irregularly shaped particles.[20]

9.2.2 The settling velocity of various sized particles in water is shown in Figure 21. This log-log plot distinctly shows that for particles of the same density, the settling velocity increases directly with the particle size.[21]

[18]See Reference 28.

[19]See References 4, 9, 10, 11, 12 and 26.
[20]See Reference 15.
[21]See Reference 11.

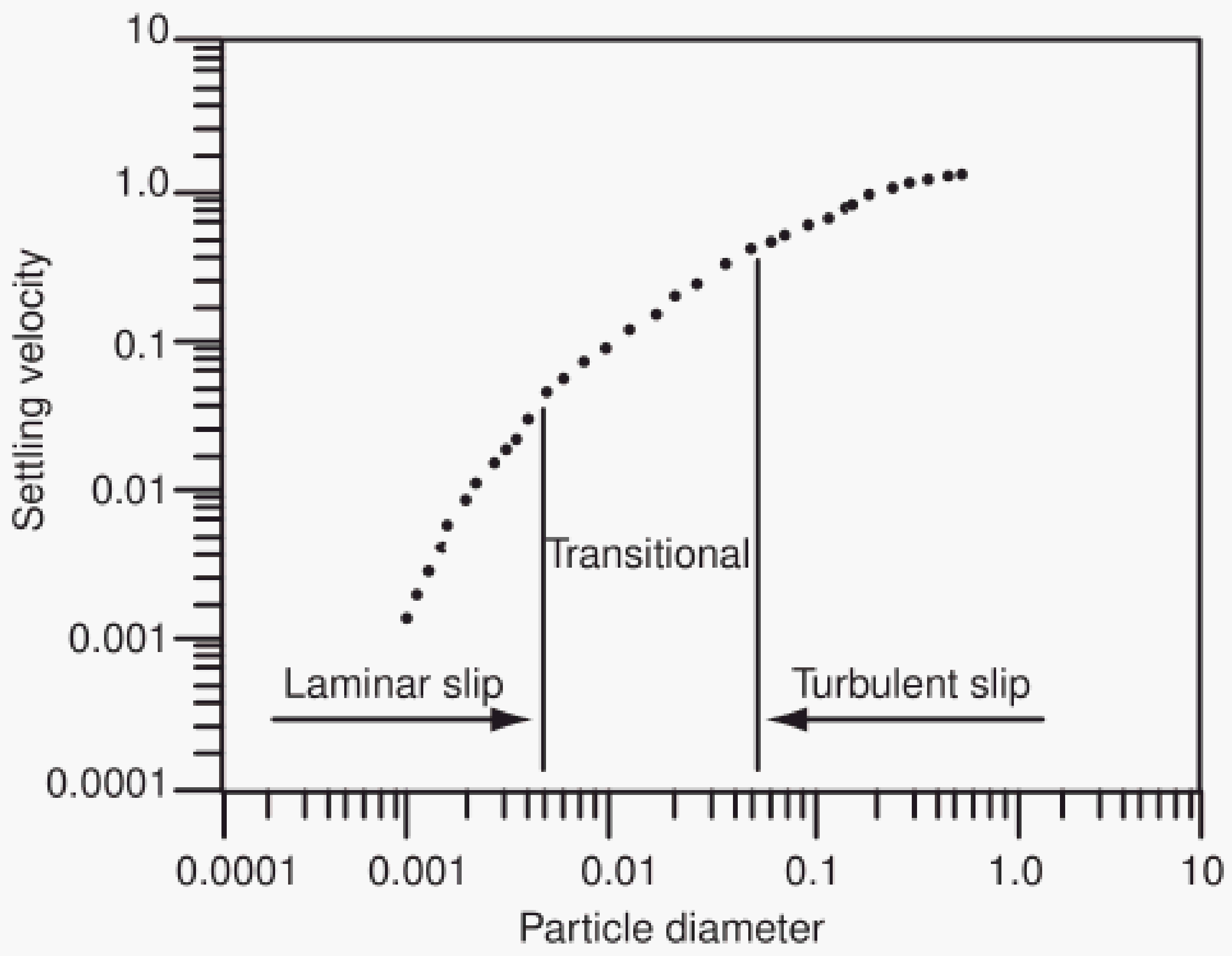

Figure 21—Settling Velocity of Drill Cuttings in Water

9.2.3 There are three different slip regimes, which control the settling velocity-laminar, transitional, and turbulent slip.

a. In laminar slip, the settling velocity increases with the square of the particle diameter. The viscosity of the fluid through which the particle settles has a dominant effect. This is known as Stokes' Law.

b. In turbulent slip, the settling velocity is proportional to the square root of the particle size and the density of the fluid has a dominant role.

c. Transitional slip is the region between laminar and turbulent slip. Both density and viscosity are important in describing settling in transitional slip.

9.3 ESTIMATION OF SETTLING VELOCITY

9.3.1 Settling velocities may be estimated by use of the correlation:[22]

$$V_s = 0.0002403e^{5.030\Psi}\left(\frac{\mu_{es}}{D_p\rho}\right)\left(\sqrt{1 + (920790.49e^{-5.030\Psi})D_p\left(\frac{\rho_p}{\rho} - 1\right)\left(\frac{D_p\rho}{\mu_{es}}\right)^2} - 1\right) \quad (58)$$

where

V_s = settling velocity, ft/sec.,

Ψ = (surface area of sphere with same volume as particle) ÷ (surface area of particle),

μ_{es} = effective viscosity of non-Newtonian fluids in settling, *cP*,

D_p = equivalent diameter of particle, in.,

ρ = density of fluid, lb./gal,

ρ_p = density of particle, lb./gal.

9.3.2 For most commonly encountered irregular particles, the value of Ψ is approximately 0.8 and Eq. (59) is simplified to:

$$V_s = 0.01294\left(\frac{\mu_{es}}{D_p\rho}\right)\left(\sqrt{1 + (17106.35)(D_p)\left(\frac{\rho_p}{\rho} - 1\right)\left(\frac{D_p\rho}{\mu_{es}}\right)^2} - 1\right) \quad (59)$$

9.3.3 For Newtonian fluids, the viscosity is independent of the shear rate and the effective viscosity is the same as the Newtonian viscosity. The settling velocity can be estimated by a single calculation.

9.3.4 For non-Newtonian fluids, the effective viscosity depends on the shear rate. The viscosity can be calculated by use of the Power Law shown in 7.5. Since the shear rate is determined by the settling velocity, a numerical iteration method must be used to estimate the settling velocities for non-Newtonian fluids.

Table 3—Equivalent Diameters of Irregularly Shaped Particles

Volume, in.^{3}	Equivalent Fraction Diameter, in.	Equivalent Decimal Diameter, in.
0.0010	1/8	0.125
0.0082	1/4	0.250
0.0276	3/8	0.375
0.0650	1/2	0.500
0.1280	5/8	0.625
0.2210	3/4	0.750
0.3510	7/8	0.875
0.5230	1	1.000
0.7460	1 1/8	1.125
1.2230	1 1/4	1.250
1.3610	1 3/8	1.375
1.7670	1 1/2	1.500

EXAMPLE:

Suppose a particle has the following dimensions:

Length: 1 in.
Width: 1/2 in.
Thickness: 1/4 in.

The volume of the particle is 0.125 in.^{3} Referring to Table 3, the equivalent diameter is 0.625, or 5/8 in.

[22]Refer to Reference 12.

APPENDIX A—RHEOLOGICAL EXAMPLE CALCULATIONS

A.1 Well Information

a. Flow rate, Q = 280 gal/min.
b. Drilling fluid density, ρ = 12.5 lb./gal
c. Drill pipe
  1. Length, L = 11,400 ft
  2. Outside diameter, D_1 = 4.5 in.
  3. Inside diameter, D = 3.78 in.
d. Drill collars
  1. Length, L = 600 ft
  2. Outside diameter, D_1 = 6.5 in.
  3. Inside diameter, D = 2.5 in.
e. Surface casing
  1. Length, L = 3,000 ft
  2. Inside diameter, D_2 = 8.835 in.
f. Bit
  1. Diameter, D_2 = 8.5 in.
  2. Nozzles = 11, 11, 12 $^{1}/_{32}$ in.
g. Drilling fluid viscosity
  1. Fann Viscometer reading at 600 rpm
    a. τ = 65 lb./100 ft^2
    b. γ = 1022 sec.$^{-1}$
  2. Fann Viscometer reading at 300 rpm
    a. τ = 39 lb./100 ft^2
    b. γ = 511 sec.$^{-1}$
  3. Fann Viscometer reading at 100 rpm
    a. τ = 20 lb./100 ft^2
    b. γ = 170.2 sec.$^{-1}$
  4. Fann Viscometer reading at 3 rpm
    a. τ = 3 lb./100 ft^2
    b. γ = 5.11 sec.$^{-1}$

A.2 Power Law Constants (n)

a. Drill pipe

$$n_p = 3.32 \log (R_{600}/R_{300}) \qquad \text{(A-1)}$$
$$= 3.32 \log (65/39)$$
$$= 0.737$$

b. Annulus

$$n_a = 0.657 \log (R_{100}/R_3) \qquad \text{(A-2)}$$
$$= 0.657 \log (20/3)$$
$$= 0.541$$

A.3 Fluid Consistency Index (K)

a. Drill pipe

$$K_p = 5.11\ R_{600}/(1022)^{np} \qquad \text{(A-3)}$$
$$= 5.11(65)/(1022)^{0.737}$$
$$= 2.011 \text{ dyne sec.}^{-n}/\text{cm}^2$$

b. Annulus

$$K_a = 5.11 R_{100}/(170.2)^{na} \qquad \text{(A-4)}$$
$$= 5.11(20)/(170.2)^{0.541}$$
$$= 6.346\ dyne \text{ sec.}^{-n}/\text{cm}^2$$

A.4 Average Velocity in a Pipe (V_p)

$$V_p = \frac{0.408Q}{D^2} \qquad \text{(A-5)}$$

a. Drill pipe

$$V_p = \frac{(0.408)(280)}{(3.78)^2} = 8.00 \text{ ft/sec.} \qquad \text{(A-6)}$$

b. Drill collars

$$V_p = \frac{(0.408)(280)}{(2.50)^2} = 18.28 \text{ ft/sec.} \qquad \text{(A-7)}$$

A.5 Average Velocity in an Annulus (V_a)

$$V_a = \frac{0.408Q}{(D_2^2 - D_1^2)} \qquad \text{(A-8)}$$

a. Annulus section 1

$$V_a = \frac{(0.408)(280)}{(8.835)^2 - (4.5)^2} = 1.98 \text{ ft/sec.} \qquad \text{(A-9)}$$

b. Annulus section 2

$$V_a = \frac{(0.408)(280)}{(8.5)^2 - (4.5)^2} = 2.20 \text{ ft/sec.} \qquad \text{(A-10)}$$

c. Annulus section 3

$$V_a = \frac{(0.408)(280)}{(8.5)^2 - (6.5)^2} = 3.81 \text{ ft/sec.} \qquad \text{(A-11)}$$

A.6 Effective Viscosity in a Pipe (μ_{ep})

$$\mu_{ep} = 100K_p\left(\frac{96V_p}{D}\right)^{(n_p-1)}\left(\frac{3_{n_p}+1}{4_{n_p}}\right)^{n_p} \quad \text{(A-12)}$$

a. Drill pipe

$$\mu_{ep} = 100(2.011)\left(\frac{96(8.00)}{3.78}\right)^{(0.737-1)} \quad \text{(A-13)}$$

$$\left(\frac{3(0.737)+1}{4(0.737)}\right)^{0.737} = 53cP$$

b. Drill collars

$$\mu_{ep} = 100(2.011)\left(\frac{96(18.28)}{2.5}\right)^{(0.737-1)} \quad \text{(A-14)}$$

$$\left(\frac{3(0.737)+1}{4(0.737)}\right)^{0.737} = 38cP$$

A.7 Effective Viscosity in an Annulus (μ_{ea})

$$\mu_{ea} = 100K_a\left(\frac{144V_a}{D_2-D_1}\right)^{(n_a-1)}\left(\frac{2_{n_a}+1}{3_{n_a}}\right)^{n_a} \quad \text{(A-15)}$$

a. Annulus section 1

$$\mu_{ea} = 100(6.346)\left(\frac{(144)(1.98)}{8.835-4.5}\right)^{(0.541-1)} \quad \text{(A-16)}$$

$$\left(\frac{2(0.541)+1}{3(0.541)}\right)^{0.541} = 106cP$$

b. Annulus section 2

$$\mu_{ea} = 100(6.346)\left(\frac{(144)(2.20)}{8.5-4.5}\right)^{(0.541-1)} \quad \text{(A-17)}$$

$$\left(\frac{2(0.541)+1}{3(0.541)}\right)^{0.541} = 98cP$$

c. Annulus section 3

$$\mu_{ea} = 100(6.346)\left(\frac{(144)(3.81)}{8.5-6.5}\right)^{(0.541-1)} \quad \text{(A-18)}$$

$$\left(\frac{2(0.541)+1}{3(0.541)}\right)^{0.541} = 55cP$$

A.8 Reynolds Number in Pipe (Re_p)

$$Re_p = \frac{928V_pD\rho}{\mu_{ep}} \quad \text{(A-19)}$$

a. Drill pipe

$$Re_p = \frac{928(3.78)(8)(12.5)}{53} = 6619 \quad \text{(A-20)}$$

b. Drill collar

$$Re_p = \frac{928(2.5)(18.28)(12.5)}{38} = 13950 \quad \text{(A-21)}$$

A.9 Reynolds number in Annulus (Re_a)

$$Re_a = \frac{928V_a(D_2-D_1)\rho}{\mu_{e_a}} \quad \text{(A-22)}$$

a. Annulus section 1

$$Re_a = \frac{928(4.335)(1.98)(12.5)}{106} = 939 \quad \text{(A-23)}$$

b. Annulus section 2

$$Re_a = \frac{928(4.0)(2.20)(12.5)}{98} = 1042 \quad \text{(A-24)}$$

c. Annulus section 3

$$Re_a = \frac{928(2.0)(3.81)(12.5)}{55} = 1607 \quad \text{(A-25)}$$

Note: Calculated annular pressure losses in the turbulent flow regime based on current API RP 13D procedures will give lower friction pressure loss values than under the same conditions measured in flowloop testing. Calculated annular pressure losses in the laminar flow regime do provide a good comparison in flowloop testing. Based on this analysis, using the Power Law Constant (n) and the Fluid Consistency Index (K) based on the drill pipe when the flow in the annulus is turbulent could give more accurate results.

A.10 Friction Factor in the Pipe (f_p)

The Reynolds number is > 2100

$$f_p = \frac{a}{(Re_p)^b} \quad \text{(A-26)}$$

$$a = (\log n_p + 3.93)/50 \quad \text{(A-27)}$$

$$b = (1.75 - \log n_p)/7 \quad \text{(A-28)}$$

a. Drill pipe

$$f_p = \frac{0.0759}{(6619)^{0.269}} = 0.00712 \quad \text{(A-29)}$$

b. Drill collar

$$f_p = \frac{0.0759}{13950^{0.269}} = 0.00583 \quad \text{(A-30)}$$

A.11 Friction Factor in the Annulus (f_a)

The Reynolds number is < 2100

$$f_a = \frac{24}{Re_a} \quad \text{(A-31)}$$

a. Annulus section 1

$$f_a = \frac{24}{939} = 0.0256 \quad \text{(A-32)}$$

b. Annulus section 2

$$f_a = \frac{24}{1042} = 0.0230 \quad \text{(A-33)}$$

c. Annulus section 3

$$f_a = \frac{24}{1607} = 0.0150 \quad \text{(A-34)}$$

A.12 Friction Loss Pressure Gradient in the Pipe (P_p/L_m)

$$\frac{P_p}{L_m} = \frac{f_p V_p{}^2 \rho}{25.81 D} \quad \text{(A-35)}$$

a. Drill pipe

$$\frac{P_p}{L_m} = \frac{(0.00712)(8)^2 12.5}{25.81(3.78)} = 0.0585 \text{lb./in.}^2\text{/ft} \quad \text{(A-36)}$$

Since the length of drill pipe is 11,400 ft, the friction loss in the drill pipe is:

$$(P_p/L_m)(L_m) = (0.0585)(11,400) = 666 \text{ lb./in.}^2 \quad \text{(A-37)}$$

b. Drill collars

$$\frac{P_p}{L_m} = \frac{(0.00583)(18.28)^2 12.5}{25.81(2.5)} = 0.377 \text{ lb./in.}^2\text{/ft} \quad \text{(A-38)}$$

Since the length of drill collars is 600 ft, the friction loss in the drill pipe is:

$$(P_p/L_m)(L_m) = (0.377)(600) = 226 \text{ lb./in.}^2 \quad \text{(A-39)}$$

c. Total friction loss in the drill collars is the sum of friction losses in the drill pipe and drill collars.

$$P_p = 666 + 226 = 892 \text{ lb./in.}^2 \quad \text{(A-40)}$$

A.13 Friction Loss Pressure Gradient in the Annulus (P_a/L_m)

$$(P_a/L_m)(L_m) = \frac{f_a V_a{}^2 \rho}{25.81(D_2 - D_1)} \quad \text{(A-41)}$$

a. Annulus section 1

$$P_a/L_m = \frac{(0.0256)(1.98)^2(12.5)}{25.81(8.835 - 4.5)} = 0.0112 \text{ lb./in.}^2\text{/ft} \quad \text{(A-42)}$$

The length of the annulus section 1 is 3000 ft. Therefore, the friction loss is:

$$(P_a/L_m) = (0.0112)(3000) = 34 \text{ lb./in.}^2 \quad \text{(A-43)}$$

b. Annulus section 2

$$P_a/L_m = \frac{(0.0230)(2.20)^2(12.5)}{25.81(8.5 - 4.5)} = 0.0134 \text{ lb./in.}^2\text{/ft} \quad \text{(A-44)}$$

The length of the annulus section 2 is 8400 ft. Therefore, the friction loss is:

$$(P_a/L_m)(L_m) = (0.0134)(8400) = 113 \text{ lb./in.}^2 \quad \text{(A-45)}$$

c. Annulus section 3

$$P_a/L_m = \frac{(0.0150)(3.81)^2(12.5)}{25.81(8.5 - 6.5)} = 0.0527 \text{ lb./in.}^2\text{/ft} \quad \text{(A-46)}$$

The length of the annulus section 3 is 600 ft. Therefore, the friction loss is:

$$(P_a/L_m)(L_m) = (0.0527)(600) = 32 \text{ lb/in.}^2 \quad \text{(A-47)}$$

d. Total friction loss in the annulus is the sum of friction losses in the three sections.

$$P_a = 34 + 113 + 32 = 179 \text{ lb./in.}^2 \quad \text{(A-48)}$$

e. The friction loss pressure gradient for the entire annulus is the total friction loss divided by the total depth:

$$P_a/L_m = 179/12,000 = 0.0149 \text{ lb./in.}^2\text{/ft} \quad \text{(A-49)}$$

A.14 Friction Loss in the Bit Nozzles (P_n)

$$P_n = \frac{156 \rho Q^2}{(D_{n1}^2 + D_{n2}^2 + ...)^2} \quad \text{(A-50)}$$

$$P_n = \frac{156(12.5)(280)^2}{((121)+(121)+(144))^2} = 1026 \text{ lb./in.}^2 \quad \text{(A-51)}$$

A.15 Hydrostatic Pressure Gradient (P_h/L)

$$P_h/L = 0.052\rho \quad \text{(A-52)}$$

$$P_h/L = 0.052(12.5) = 0.65 \text{ lb./in.}^2\text{/ft} \quad \text{(A-53)}$$

A.16 Circulating Pressure Gradient (P_c/L)

$$P_c/L = P_h/L + P_a/L \quad \text{(A-54)}$$

$$P_c/L = 0.65 + 0.0149 = 0.6649 \text{ lb./in.}^2\text{/ft} \quad \text{(A-55)}$$

A.17 Equivalent Circulating Density (ρ_c)

$$\rho_c = 19.265(P_c/L) \quad \text{(A-56)}$$

$$\rho_c = 19.265(0.6649) = 12.81 \text{ lb./gal} \quad \text{(A-57)}$$

APPENDIX B—SETTLING VELOCITY EXAMPLE CALCULATIONS

B.1 Well Information

a. Particle equivalent diameter, $D_p = 0.5$ in.
b. Particle density, $\rho_p = 22.5$ lb./gal
c. Mud density, $\rho = 12.5$ lb./gal
d. Mud viscosity
   1. Fann viscometer reading at 100 rpm
      a. $\tau = 20$ lb./100 ft^2
      b. $\gamma = 170.2$ sec.$^{-1}$
   2. Fann viscometer reading at 3 rpm
      a. $\tau = 3$ lb./100 ft^2
      b. $\gamma = 5.11$ sec.$^{-1}$

B.2 Power Law Constants (n_s)

$$n_s = 0.657\log(R_{100}/R_3) \quad \text{(B-1)}$$
$$= 0.657\log(20/3)$$
$$= 0.541$$

B.3 Fluid Consistency Index (K_s)

$$K_s = 5.11R_{11}/(170.2)^{ns} \quad \text{(B-2)}$$
$$= 5.11(20)/(170.2)^{0.541}$$
$$= 6.346$$

B.4 Initial Settling Shear Rate Estimate (γ_s)

Assume: $V_s = 1$ ft/sec.

$$\gamma_s = 12V_s/D_p \quad \text{(B-3)}$$
$$\gamma_s = 12(1)/0.5 = 24\text{sec.}^{-1}$$

B.5 Effective Viscosity (μ_{es})

$$\mu_{es} = 100K_s\gamma_s^{(ns-1)} \quad \text{(B-4)}$$
$$= 100(6.346)(24)^{(0.541-1)}$$
$$= 148cP$$

B.6 Settling Velocity First Approximation (V_s)

$$V_s = 0.01294\left(\frac{\mu_{es}}{D_p\rho}\right)\left(\sqrt{1+(17106.35)(D_p)\left(\frac{\rho_p}{\rho}-1\right)\left(\frac{D_p\rho}{\mu_{e_s}}\right)^2}-1\right) \quad \text{(B-5)}$$

$$V_s = 0.01294\left(\frac{148}{0.5(12.5)}\right)\left(\sqrt{1+(17106.35)(0.5)\left(\frac{22.5}{12.5}-1\right)\left(\frac{(0.5)(12.5)}{148}\right)^2}-1\right) \quad \text{(B-6)}$$

$$V_s = 0.808 \text{ ft/sec.}$$

B.7 Second Settling Shear Rate Estimate (γ_s)

$$\gamma_s = 12(0.808)/0.5 = 19.4 \text{ sec.}^{-1} \quad \text{(B-7)}$$

B.8 Effective Viscosity (μ_{es})

$$\mu_{es} = 100(6.346)(19.4)^{(0.541-1)} \quad \text{(B-8)}$$
$$\mu_{es} = 163cP$$

B.9 Settling Velocity Second Approximation (V_s)

$$V_s = 0.01294\left(\frac{163}{0.5(12.5)}\right)\left(\sqrt{1+(17106.35)(0.5)\left(\frac{22.5}{12.5}-1\right)\left(\frac{(0.5)(12.5)}{163}\right)^2}-1\right) \quad \text{(B-9)}$$

$$V_s = 0.785 \text{ ft/sec.}$$

B.10 Third Settling Shear Rate Estimate (γ_s)

$$\gamma_s = 12(0.785)/0.5 = 18.8 \text{ sec.}^{-1} \quad \text{(B-10)}$$

B.11 Effective Viscosity (μ_{es})

$$\mu_{es} = 100(6.346)(18.8)^{(0.541-1)} \quad \text{(B-11)}$$
$$\mu_{es} = 165cP$$

B.12 Settling Velocity Third Approximation (V_s)

$$V_s = 0.01294\left(\frac{165}{0.5(12.5)}\right)\left(\sqrt{1+(17106.35)(0.5)\left(\frac{22.5}{12.5}-1\right)\left(\frac{(0.5)(12.5)}{165}\right)^2}-1\right) \quad \text{(B-12)}$$

$$V_s = 0.782 \text{ ft/sec.}$$

This numerical iteration method is repeated until the settling velocities of two successive calculations are equal. In the example in this Appendix, the third and fourth approximations are equal. The calculated settling velocity is 0.782 ft/sec.

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