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AIR AND WATER REQUIREMENTS

FOR FOAM DRILLING OPERATIONS

By

Jack A. Krug

SUBMITTAL

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Signed: Jack A. King
Student

Golden, Colorado

Date: October 8, 1971

Approved: B. J. Mitchell
Thesis Advisor

S. M. Bass
Head of Department

Golden, Colorado

Date: October 8, 1971

ABSTRACT

This study investigates a mathematical model and its solution for the application of foam in a drilling system consisting of a vertical-concentric pipe-hole arrangement with flow down the pipe and up the annulus. The mathematical model which was written for foam was the Bingham plastic model (Mitchell, 1970b) applied to a compressible fluid. Foam consisting of air, a surface active agent, and water, with the aqueous solution being the continuous phase and the air being discontinuous bubbles, shall be considered. Two equations were written describing the flow of foam: foam flowing down the pipe, and foam with rock chips flowing up the annulus. In order to maintain nearly constant fluid properties, the two equations were written explicitly in terms of pressure and depth and solved by iterations with a constant pressure increment. For each iteration, the rheological properties of foam were evaluated at the average increment pressure. Adjustments to account for the rock chips volume and mass were made to the annular Bingham plastic flow equation.

Air volume rate, water volume rate, and surface annular pressure are the variables in the drilling system. Surface injection pressure, drilling rate, hole size, and pipe size were kept constant for each solution. Boundary conditions of foam flow of 1.5 fps at the bottom of the annulus and a quality (ratio of air volume to water plus air volume) of 0.96 at the surface of the annulus were imposed upon the solution of the mathematical model. With these boundary conditions,

the air and water volume rates, and surface annular pressure were calculated using a high-speed digital computer. Solutions for various hole and pipe combinations, drilling rates, and surface injection pressures are listed in tabular form at the end of this paper.

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CHAPTER ONE

INTRODUCTION

The use of foam in drilling operations in the petroleum industry dates back to the early trials of air drilling during the late 1940's. (P. Moore, 1966, p. 144). Foam was used in air drilling as a means of stabilizing a sloughing formation and controlling natural water flows in the wellbore during drilling operations. If air were used to drill an unconsolidated formation, the hole would usually cave. When a water producing formation was drilled with air, the wetted cuttings often stuck to the drillpipe and the wall of the hole until circulation was lost and the pipe was packed in the hole. Foam was used to minimize these problems. Foam has proven itself to have an excellent capacity to stabilize a sloughing formation. (Dresser Magcobar, 1970, p. 1). Foam, when used in the drilling of a water producing formation, has a tendency to use the water which flows into the wellbore as part of the water constituent of the foam. The cuttings are not wetted by the water and do not stick to the drillpipe or the wall of the hole. At the present time (1971), there is little published literature describing the practical application for a foam drilling operation.

In this study, foam consisting of air, a surface active agent, and water shall be considered. The surface active agent and the water are the continuous phase with the air appearing as discontinuous bubbles. Mist shall be defined as a fluid consisting of the above components, except the air shall be the continuous phase and the aqueous solution shall appear as droplets.

In the practical application of foam, the following variables must be controlled: 1) air volume, 2) aqueous volume, 3) injection pressure, and 4) annulus choke-pressure.

It is the purpose of this study to present a mathematical model and its solution for the application of foam in a system having the following components: vertical hole, concentric annulus between the hole and the pipe, and continuous circulation of foam down the pipe and up the annulus carrying the wetted cuttings from the bottom of the pipe. (See Figure 1). The solution of the mathematical model was computed by selecting air and aqueous volumes for various pipe and hole configurations. Using an iteration process, the aqueous volume, air volume, and surface annulus pressure have been calculated for a depth range of 1,000 ft. to 4,000 ft., a surface injection pressure of 200 psi to 400 psi, and a drilling rate of 0 fps to 1.5 fps.

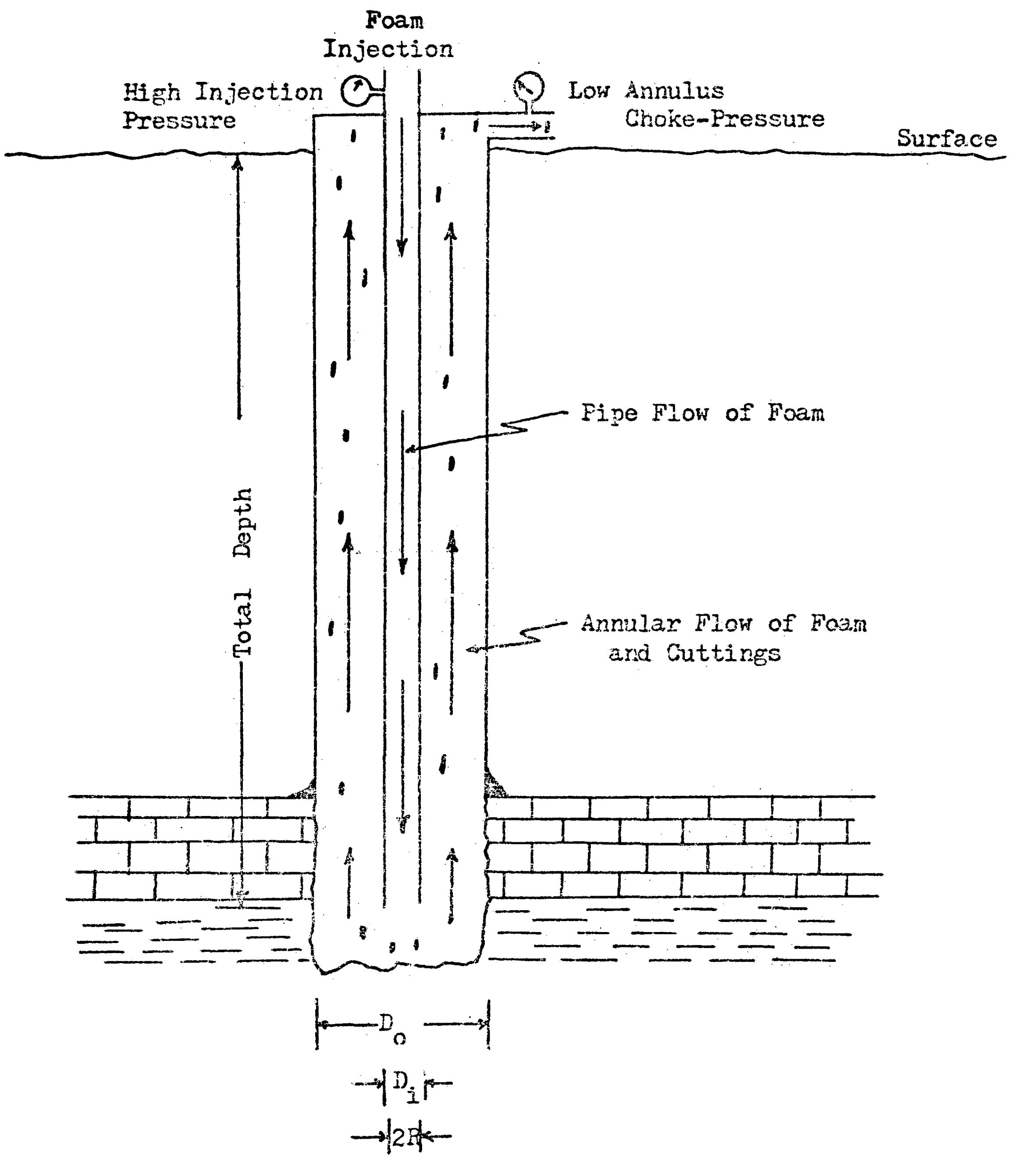


FIGURE: 1
SCHEMATIC DIAGRAM OF IDEALIZED
FOAM SYSTEM

CHAPTER TWO

REVIEW OF FOAM RHEOLOGY

Mitchell (1970a, p. 117-123) has shown through laboratory measurements that foam has a linear relationship of shear rate-shear stress for all foam qualities and all shear rates above 20,000 sec^{-1}. For shear rates below 20,000 sec^{-1}, the shear rate-shear stress relationship is linearized by subtracting the proper constant from the measured shear stress (τ). The power law model equation which describes the rheology of foam is

$$(\tau - \tau_y) = \mu_p \phi^n \qquad 1$$

where τ = measured shear stress

τ_y = yield shear stress

n = power coefficient

μ_p = plastic viscosity

ϕ = shear rate

The log form of Equation (1) is

$$\log (\tau - \tau_y) = n \log (\phi) + \log (\mu_p) \qquad 2$$

Power coefficients, plastic viscosities, and yield stresses are listed in Table 1 for a foam quality range of 0 to 0.96.

Based upon the data shown in Table 1, the power coefficient (n) has been chosen to be unity for all foam qualities. Therefore, Equation (1) is equivalent to the shear rate-shear stress relationship for a Bingham plastic model Figures 2 and 3 show the relationship between foam quality (Γ), ratio of air volume to the air volume

TABLE 1: SHEAR STRESS - SHEAR RATE RELATIONSHIPS FOR DRILLING FOAM (After Mitchell, 1970a)

Γ Quality Range %	μ_p Viscosity cps	τ_y Yield Stress lb_f/Ft^2	n Power-Coefficient
90-96	14.38	2.5	1.02
86-90	9.58	1.0	.99
80-86	7.21	.68	.97
75-80	5.76	.48	1.02
70-75	5.0+	.40	1.00
65-70	4.3	.23	1.00
60-65	3.7	.14	1.00
55-60	3.36	0	1.00
45-55	2.88	0	1.00
35-45	2.40	0	1.00
30-35	1.60	0	1.00
25-30	1.58	0	1.00
0-25	1.25	0	1.00
0	1.02		

The above shear rate shear stress foam data were taken by Mitchell (1970a) and shown to fit the following equation:

$$(\tau - \tau_y) = \mu_p \phi^n$$

plus water volume , yield stress (τ_y), and plastic viscosity (μ_p). (Mitchell, 1970b).

Quality Regions

Figures 2 and 3 have been divided into three quality regions: dispersed bubble, bubble interference, and bubble deformation. The dispersed bubble region exists for a quality range between 0 and 0.525. The viscosity of foam in this region is not a function of shear rate. (Mitchell, 1970a, p. 57)

The bubble interference region exists for a quality range between 0.525 and 0.74. It is interesting to note that uniform spheres packed loosely (cubically) produce a solids content of 0.52 by volume and when they are tightly packed (rhombohedrally) without deformation the concentration is 0.74. The shear stress, plastic viscosity, and yield stress of the foam in this region are a function of shear rate and foam quality. (Mitchell, 1970a, p. 57).

The bubble deformation region exists for a quality range between 0.74 and 0.96. All the bubbles in this region are assumed to be deformed. As the quality increases above 0.74, the bubbles cannot expand without deforming the surrounding bubbles. Maximum resistance to flow of foam exists in this region. The shear stress, plastic viscosity, and yield stress of the foam in this region are also functions of shear rate and foam quality. (Mitchell, 1970a, p. 57). For foam qualities greater than 0.96, mist flow is assumed to exist.

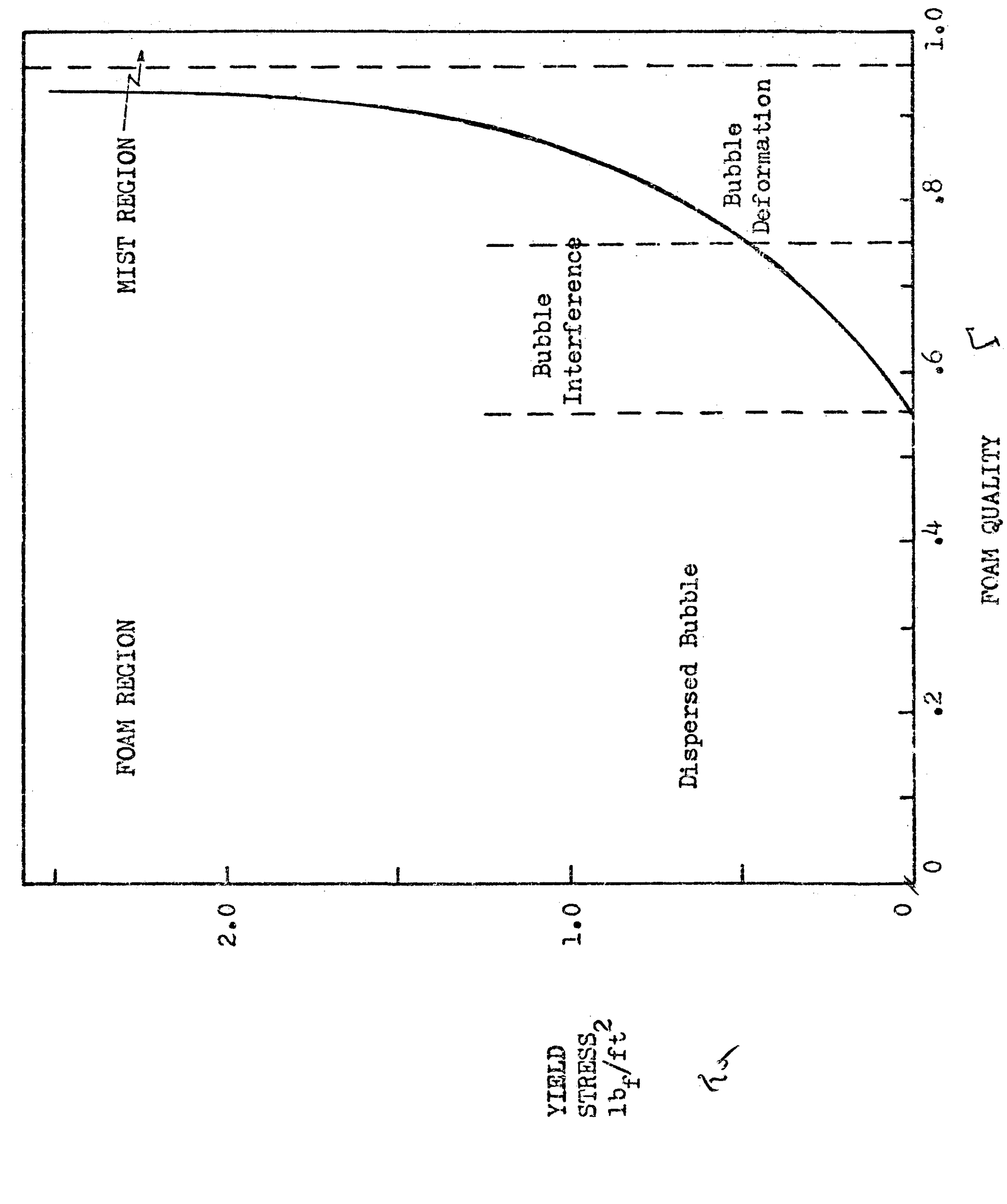


FIGURE: 2
YIELD STRESS vs. FOAM QUALITY
(Mitchell, 1970b)

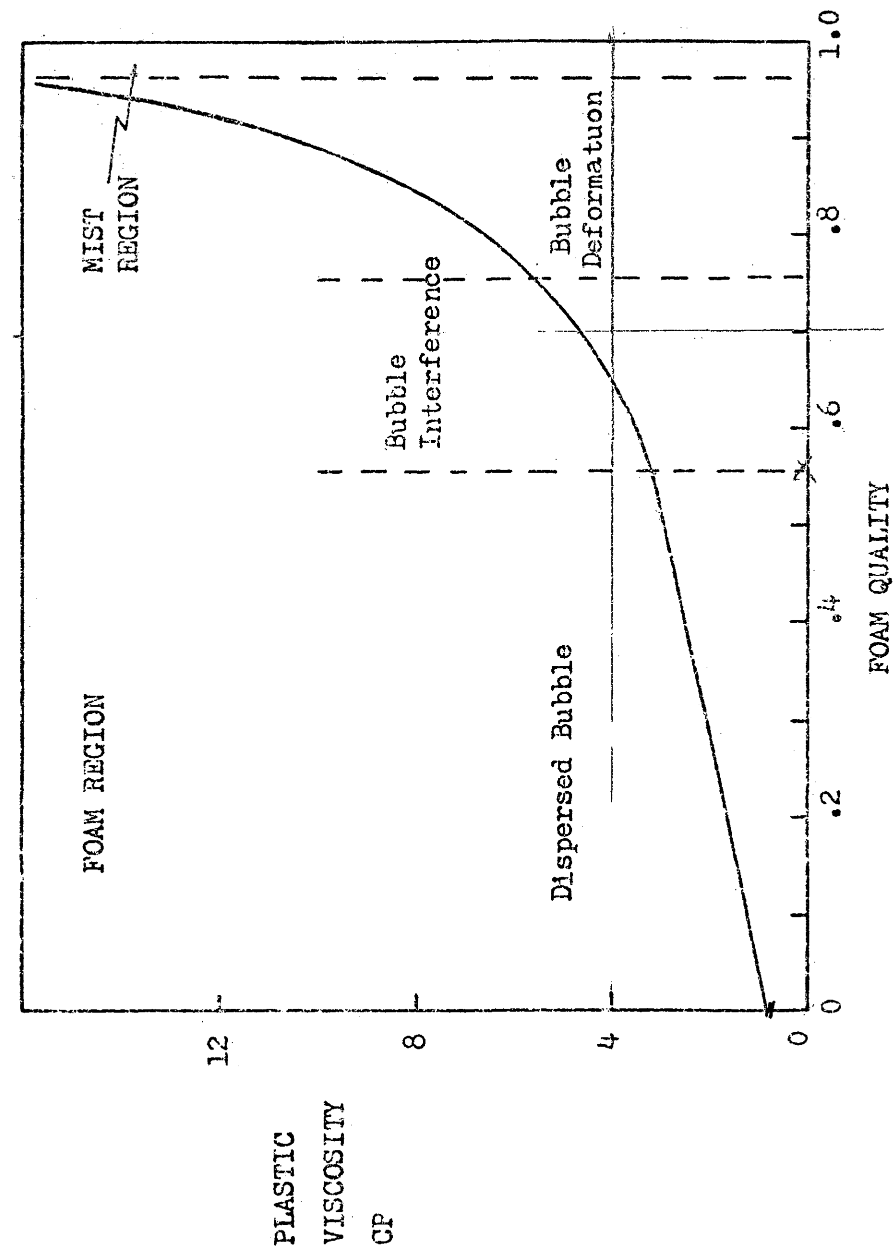


FIGURE: 3
PLASTIC VISCOSITY vs.
FOAM QUALITY
(Mitchell, 1970b)

Velocity Profile

The velocity profile for flow of foam in a circular pipe is based upon a Bingham model as shown by Figure 4. Three flow regimes are present: Laminar, transition, and plug. The pipe wall is assumed to be coated with a static, thin layer of the aqueous solution. The shear rate and shear stress have maximum values at the wall of the pipe and minimum values at the axis of the pipe. The flow parallel to the longitudinal axis of the pipe may be represented by concentric elemental thin cylinders. Each cylinder has an individual shear rate and shear stress. Laminar flow will exist in those cylinders which have shear rates greater than or equal to about 20,000 sec^{-1}. A transitional regime separates the laminar and plug flow regimes. The plug regime will include all cylinders having a shear rate equal to zero.

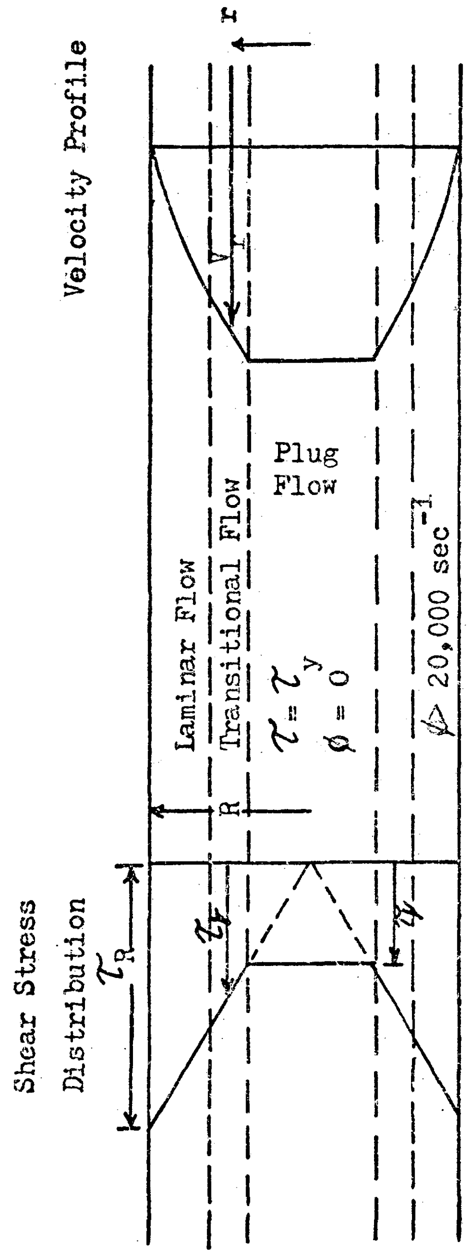


FIGURE: 4
FOAM SYSTEM IN DOWN PIPE

CHAPTER THREE

METHOD OF INVESTIGATION

Bingham Plastic Model

The Bingham plastic model is described by the following assumptions:

1. Isothermal, steady-state flow through a vertical circular pipe.
2. Rate of shear is proportional to the excess of the shear stress over a constant yield value, below which the material behaves as a continuous unit.
3. No slippage exists at the pipe wall.

Using these assumptions the Buckingham-Reiner equation may be developed. (See Figure 5 and Appendix B):

$$Q = \frac{\pi R^4 (P_0 - P_L)}{8 \mu_p L} \left[1 \quad \frac{4\tau_y}{3\tau_R} + \frac{1}{3} \left[\frac{\tau_y}{\tau_R} \right]^4 \right] \qquad 3$$

where Q = Volumetric flow rate

L = Flow length

R = Pipe radius

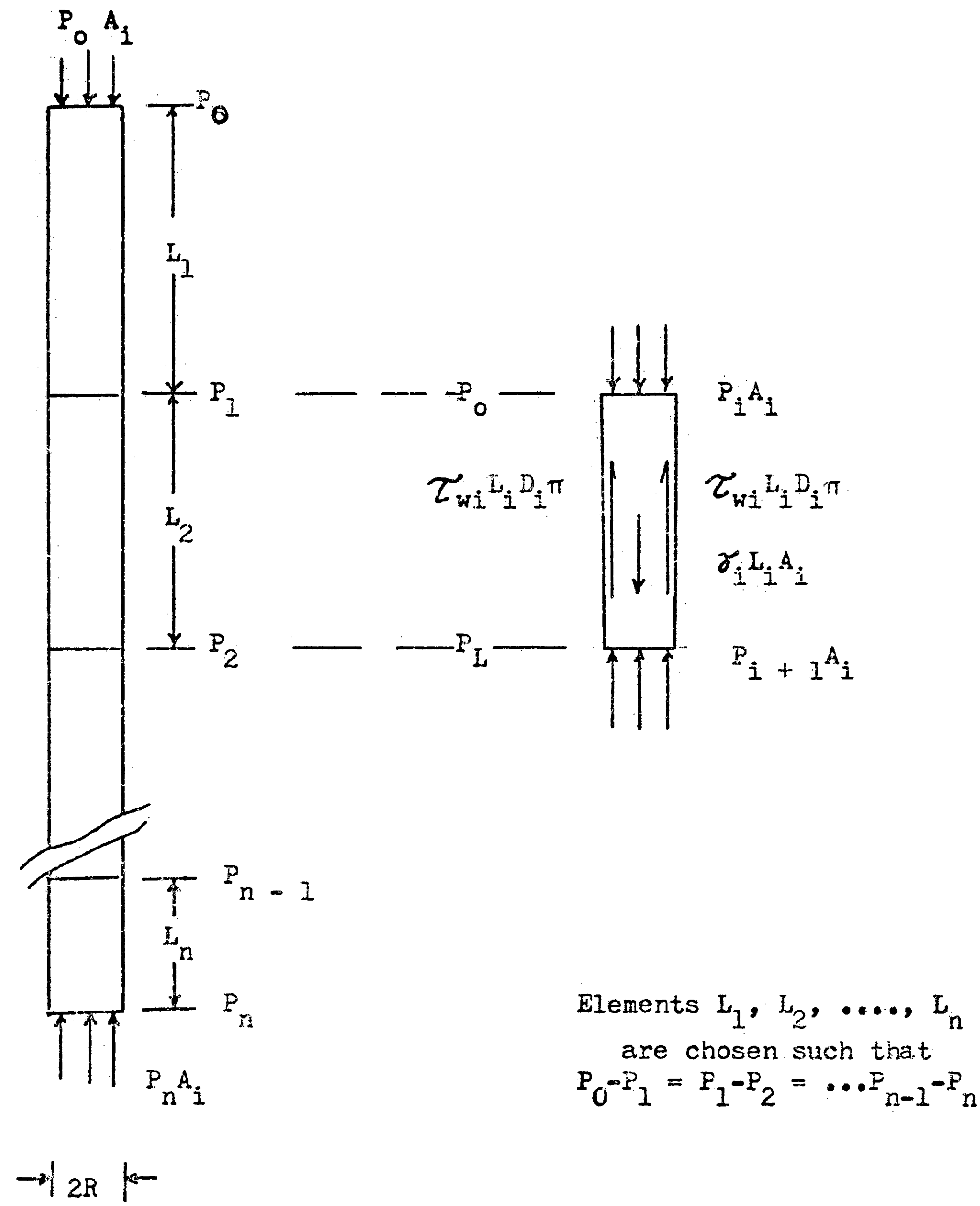
τ_R = Shear stress at the pipe wall

P = p $\quad \rho g L$

p = Pressure

g = Gravitational constant

ρ = Fluid density



a) Total Pipe Length

b) Segment of Pipe Length

FIGURE: 5
FORCES ACTING ON DOWNWARD
FLOW IN A PIPE

Comparison of Foam and Bingham Model

The assumptions used to derive the equation describing the Bingham plastic model may be applied to a flowing foam. The Bingham model assumes that the fluid has a constant temperature. However, in a foam drilling application, the fluid temperature will increase with depth. As an approximation to isothermal flow, the pipe and annulus are divided into incremental lengths and the temperature throughout each increment is assumed to be constant and equal to the formation temperature at any depth. A surface temperature of 60°F. and a geothermal gradient of 1.6°F./100 ft., as an accepted rule of thumb, have been used to determine the formation temperature for each incremental depth. No additional temperature correction has been made due to the compression or expansion of the air, or the friction of flow in the pipe or annulus.

A circular pipe and annulus are assumed. No correction has been attempted for an eccentric pipe-annulus arrangement. In actual practice, the drilled hole will not be truly circular and the pipe-annulus arrangement will not be concentric. Since the severity of eccentricity is not known, the ideal case has been used for computational purposes.

Mitchell (1970a, p. 60) found through laboratory experimentation that foam slippage at the pipe wall did not exist or was insignificant.

The foam viscosities and yield stresses have only been measured between 71°F. and 81°F (Mitchell, 1970a, p. 37). Temperature variations and its effect on the foam viscosity and yield stress have not been investigated. No attempt has therefore been made to include temperature-viscosity and temperature-yield stress relationships.

Numerical Integration Procedure

Flow Down the Pipe: The pressure-depth relationship for the flow of foam down the pipe is calculated by Eq. (3). The term $(\tau_y/\tau_R)^4$ is assumed to be relatively small, and is dropped from Eq. (3). Craft, et al. (1962, p. 38) state that the error is less than 2 per cent whenever τ_R exceeds 2.5 τ_y. The more convenient approximate expression describing the flow rate of a Bingham plastic fluid is then

$$Q = \frac{\pi\ R^4(P_0-P_L)}{8\mu_p L}\left[1 \quad \frac{4\tau_y}{3\tau_R}\right] \qquad 4$$

The volumetric flow rate (Q) is defined by

$$Q = \pi\ R^2 V \qquad 5$$

where V = Average fluid velocity.

Substituting Eq. (5) into Eq. (4) and solving for τ_R results in

$$\tau_R = \frac{4}{3}\left[\frac{\tau_y R^2(P_0-P_L)}{R^2(P_0-P_L) \quad 8\mu_p LV}\right] \qquad 6$$

The shear stress at the pipe wall (τ_R) is given by

$$\tau_R = \frac{(P_0-P_L)R}{2L} \qquad 7$$

Comparing Eq. (6) and Eq. (7) gives

$$\frac{R(P_0-P_L)}{2L} = \frac{4}{3}\left[\frac{\tau_y R^2(P_0-P_L)}{R^2(P_0-P_L) \quad 8\mu_p LV}\right] \qquad 8$$

and solving for the pipe length (L) results in

$$L = \frac{3R^2(P_0 - P_L)}{8\tau_y R + 24V\mu_p} \qquad 9$$

The statis pressure head is also expressed in terms of the pipe length (L) as

$$P_0 \quad P_L = p_0 - p_L + \rho g L \qquad 10$$

Substituting Eq. (10) into Eq. (9) and solving for L results in an explicit equation describing the pressure-depth relationship of a Bingham plastic fluid:

$$L = (p_0 - p_L) \Big/ \left[\frac{8\tau_y}{3R} + \frac{8\mu_p V}{R^2} \quad \rho g \right] \qquad 11$$

In order to apply Eq. (11) to foam, which is a compressible fluid, the pressure dependent variables, flowing density (ρ), yield stress (τ_y), and plastic viscosity (μ_p), must be maintained at nearly constant values. The pressure change ($p_0 - p_L$) will be maintained at a small constant value of 5 psi and the incremental pipe length will be calculated. Solution of Eq. (11) with constant pressure differentials of 2.5, 5.0, 7.5, and 10 psi showed that the pressure dependent variables did not vary significantly for this range. Five psi was therefore used for the calculations. Writing Eq. (11) in an iteration form and summing from the surface to the bottom of the pipe, the total pressure-depth relationship for foam flow down a vertical pipe is determined:

$$\sum_{i=1}^{n} L_i = \sum_{i=1}^{n} \frac{p_{i+1} - p_i}{\chi \rho_i g - \frac{8\tau_{yi}}{3R} \quad \frac{8 V_i \mu_{pi}}{R^2}} \qquad 12$$

The following discussion explains the evaluation of the secondary variables for each iteration of Eq. (12).

The volume flow rate for water at a depth z, Q_{wz}, is equal to the volume flow rate for water at standard conditions s, Q_{ws}.

$$Q_{wz} = Q_{ws} \qquad 13$$

The volume flow rate for air at a depth z, Q_{az}, is determined with the ideal gas law. The ideal gas law mathematically expresses that the pressure-volume-temperature ratio at state 1, $(\frac{P\ Vol}{T})_1$, is equal to the pressure-volume-temperature ratio at state 2, $(\frac{P\ Vol}{T})_2$:

$$(\frac{P\ Vol}{T})_1 = (\frac{P\ Vol}{T})_2 \qquad 14$$

where Vol = Volume of gas

T = Temperature

If the expansion or compression of a gas from state 1 to state 2 does not fulfill the relationship of Eq. (14), the gas is considered to be non-ideal. Joule and Thompson have measured the non-ideality of gases (Barrows, 1966, p. 138-140) and expressed it by

$$\mu_{JT} = (\frac{\partial T}{\partial P})_H \qquad 15$$

where μ_{JT} = Joule-Thompson coefficient

$(\frac{\partial T}{\partial P})_H$ = Change of temperature with respect to a change of pressure at constant enthalpy

H = Enthalpy

For the expected pressures and temperatures of a drilling operation, the Joule-Thompson coefficient for air is close to zero. Air will therefore be assumed to behave as an ideal gas and follow the mathematical relationship of Eq. (14). Hence

$$Q_{az} = Q_{as}(P/T)_s(T/P)_z \quad 16$$

The total volume flow rate at a depth z, Q_{tz}, is

$$Q_{tz} = Q_{wz} + Q_{az} \quad 17$$

At a depth z, the mass flow rate of air (M_{az}), water (M_{wz}), and the total (M_{tz}) are

$$M_{az} = Q_{az}\rho_{az} \quad 18$$

$$M_{wz} = Q_{wz}\rho_{wz} \quad 19$$

$$M_{tz} = M_{az} + M_{wz} \quad 20$$

The density (ρ) of flowing foam at a depth z is

$$\rho_z = (M_{tz}) / (Q_{tz}) \quad 21$$

In order to determine the pressure change attributable to friction, the plastic viscosity, yield stress, and velocity must be known. The foam quality at z must first be determined in order to evaluate the yield stress and plastic viscosity.

Foam quality (Γ) is defined as

$$\Gamma = \frac{\text{air volume}}{\text{air volume + water volume}} \quad 22$$

The foam quality at z may be found by the following calculation:

$$\Gamma_z = \frac{Q_{az}}{Q_{tz}} \quad 23$$

Once the quality is known, the yield stress and plastic viscosity may be determined from Figures 2 and 3.

The velocity of foam at z is

$$V_z = \frac{Q_{tz}}{A_i} \quad 24$$

where A_i = Pipe flow area.

In order to solve Eq. (12) this procedure must be followed: 1) the volume flow rate at z for water (Q_{wz}), air (Q_{az}), and total (Q_{tz}) are calculated with Eqs. (13), (16), and (17): 2) the mass flow rate at z for air ($\dot{M}_{az}$), water ($\dot{M}_{wz}$), and total ($\dot{M}_{tz}$) are calculated with Eqs. (18), (19), and (20): 3) the foam flowing density (ρ_z) is calculated with Eq. (21): 4) the quality at z, Γ_z, is calculated with Eq. (23): 5) the yield stress at z, τ_{yz}, and plastic viscosity at z, μ_{pz}, are evaluated from Figures 2 and 3 with the use of the quality at z: 6) the velocity at z, V_z, is calculated with Eq. (24). All the variables in Eq. (12) are now known and the incremental length for foam flow down the pipe may be determined for one iteration.

Flow Up the Annulus: Melrose, et al. (1958, p. 316-324) have shown that the flow equation for the isothermal, laminar flow of a Bingham plastic fluid in a concentric pipe-annulus arrangement could be approximated with good precision by the equation which describes laminar flow through a narrow slot. The flow equation can be written as

$$Q = \frac{EW^2\tau_w}{6\mu_p}\left[1 - \frac{3\tau_y}{2\tau_w} + \frac{1}{2}\left(\frac{\tau_y}{\tau_w}\right)^3\right] \qquad 25$$

Where E = Lateral extent of the slot

= Mean annular circumference, $\pi \frac{D_o + D_i}{2}$

W = Width of slot

= Annular width, $\frac{1}{2}(D_o - D_i)$

D_o = Annulus outside diameter

D_i = Annulus inside diameter

τ_w = Shear stress at the slot wall

For the derivation of Eq. (25), refer to Appendix C.

The pressure-depth relationship for the flow of a Bingham plastic fluid in a pipe-annulus arrangement is calculated with the use of Eq. (25). The last term in Eq. (25), $(\tau_y/\tau_w)^3$, is assumed to be small and is dropped. Craft, et al. (1962, p. 43) state that the error is less than 7 per cent whenever τ_w exceeds 2.5 τ_y. The approximate equation describing the annular flow rate, Q, is

$$Q = \frac{EW^2\tau_w}{6\mu_p}\left[1 \quad \frac{3\tau_y}{2\tau_w}\right] \qquad 26$$

The volumetric flow rate, Q, is

$$Q = EWV \qquad 27$$

Thus

$$V = \frac{W\tau_w}{6\mu_p}\left[1 - \frac{3\tau_y}{2\tau_w}\right] \tag{28}$$

Solving Eq. (28) for the shear stress at the slot wall (τ_w)

$$2\tau_w = \frac{12V\mu_p}{W} + 3\tau_y \tag{29}$$

The shear stress at the slot wall is

$$\tau_w = \frac{W(P_0-P_L)}{2L} \tag{30}$$

Comparing Eq. (29) and Eq. (30) gives

$$\frac{W(P_0-P_L)}{L} = \frac{12V\mu_p}{W} + 3\tau_y \tag{31}$$

and solving for the pipe length (L)

$$L = (P_0-P_L) \Big/ \left[\frac{12V\mu_p}{W^2} + \frac{3\tau_y}{W}\right] \tag{32}$$

The static pressure head, however, is also expressed in terms of the pipe length (L)

$$P_0 \quad P_L = p_0 \quad P_L \quad \rho g L \tag{33}$$

The slot width (W) is analogous to the annular width and is given by

$$W = \frac{1}{2}(D_o-D_i) \tag{34}$$

Substituting Eq. (33) and Eq. (34) into Eq. (32) and solving for L results in an explicit equation describing the pressure-depth relationship for the flow of a Bingham plastic fluid up a concentric annulus:

$$L = (p_0 - p_L) \Bigg/ \left[\frac{12V\mu_p}{\left(\frac{D_o - D_i}{2}\right)^2} + \frac{3\tau_y}{\frac{1}{2}(D_o - D_i)} + \rho g \right] \qquad 35$$

Eq. (35) is applied to foam, a compressible fluid, by maintaining the pressure-dependent variables, flowing density (ρ), yield stress (τ_y), and plastic viscosity (μ_p) at nearly constant values. The total pressure difference ($p_0 - p_L$) is maintained again at 5 psi and the incremental annulus length is calculated. Writing Eq. (35) in an iteration form and summing from the bottom of the pipe to the annulus surface, the total pressure-depth relationship for the flow of foam up a concentric annulus is calculated:

$$\sum_{i=1}^{n} L_i = \sum_{i=1}^{n} (p_{i+1} - p_i) \Bigg/ \left[\rho_i g + \frac{48V_i\mu_{pi}}{(D_o - D_i)^2} + \frac{6\tau_{yi}}{(D_o - D_i)} \right] \qquad 36$$

Because the particles are being lifted by the foam in the annulus, the flowing density, quality, and velocity calculations must be adjusted for the mass and volume of the sand cuttings. A constant drilling or cleaning rate will be assumed.

The density of foam flowing in an annulus at a depth z will become

$$\rho_z = \frac{M_{tz} + M_r}{(Q_{tz} + Q_r)} \qquad 37$$

where M_r = Mass rate of rock

Q_r = Volume flow rate of rock

The velocity of the foam and rock chips in the annulus is

$$V_{tz} = \frac{Q_{tz} + Q_r}{A} \qquad 38$$

where A = Annular flow area.

Since the calculation of foam quality requires the knowledge of the air and water volumes, a correction must be made for the rock chip volume in the annulus. Writing a volume balance on a section of the annulus:

$$Vol_{az} + Vol_{wz} = Vol_{ann} \quad Vol_{rock} \qquad 39$$

where Vol_{az} = Volume of air at z

Vol_{wz} = Volume of water at z

Vol_{ann} = Volume of annulus

Vol_{rock} = Volume of rock

The annular volume for a unit length is

$$Vol_{ann} = \frac{\pi(D_o^2 - D_i^2)l}{4} \qquad 40$$

Assuming that rock particle slippage does not occur, then the rock volume flowing in a unit length of annular volume is

$$Vol_{rock} = \frac{(Vol_{ann})Q_r}{Q_{tz} + Q_r} \qquad 41$$

Substitution of Eq. (40) and Eq. (41) into Eq. (39(gives the air and water volumes in a unit length of the annulus:

$$Vol_{az} + Vol_{wz} = \frac{\pi}{4}(D_o^2 - D_i^2)\, l \left(1 - \frac{Q_r}{Q_{tz} + Q_r}\right) \qquad 42$$

The volume of air at a depth z in the unit length of the annulus is

$$Vol_{az} = \frac{Q_{az} Vol_{ann}}{Q_{tz} + Q_r} \qquad 43$$

The quality at z is

$$\Gamma_z = \frac{Vol_{az}}{Vol_{az} + Vol_{wz}} \qquad 44$$

In order to solve Eq. (36) this procedure must be followed: 1) the density, ρ_z, of flowing foam at z is calculated with Eq. (37): 2) the velocity in the annulus, V_z, is calculated with Eq. (38): 3) in order to evaluate the quality, Γ_z, at z, Eqs. (42) and (43) must be solved and substituted into Eq. (44): 4) the yield stress at z, τ_{yz}, and plastic viscosity at z, μ_{pz}, are evaluated from Figures 2 and 3 with the use of the quality at z. All the variables in Eq. (36) are now known and the incremental length for foam flow up the annulus may be determined for one iteration.

Two differential equations result from the mathematical model describing the flow of foam in a drilling operation: one for the pipe flow and one for the annular flow. The differential equations are explicitly expressed in terms of pressure and depth and are numerically integrated over the full length of the pipe with a constant pressure increment. An iteration process develops because at the bottom of the pipe the pressure within the pipe must equal the pressure within the annulus. Further boundary conditions are: 1) a minimum annular velocity at the bottom of the pipe: 2) a maximum foam quality at the surface in the annulus. At the bottom of the pipe, foam velocity will be the controlling quantity for removal of cuttings. The foam velocity must be kept at a minimal value in order to reduce the enlargement of the hole. Foam quality should be a maximum at the annulus surface. The viscosity of foam does reach a maximum value at the beginning of the mist region. (See Figure 3). If the quality is allowed to enter the mist region, the viscosity will approach that of air. This annular boundary condition at the surface will therefore control the maximum quality which is desirable for the most efficient cutting removal.

In order to maintain good hole properties, a bottom-hole annular velocity of 1.5 fps (Wolke, 1970), and a foam quality of 0.96 in the annulus at the surface will be imposed upon the system as boundary conditions. Field experience indicates that a bottom-hole velocity of 1.5 fps will clean the hole of all solid particles while using foam. If the quality becomes greater than 0.96, the foam viscosity will decrease to that of mist and the solid particles will perhaps not be carried from the annulus. With the stipulated boundary conditions, the required air volume, aqueous volume, and the annulus choke-pressure are determined.

CHAPTER FOUR

RESULTS

With the use of the Colorado School of Mines PDP-10 computer, the Bingham plastic model was applied to a foam drilling system. Various pipe and hole sizes were used in the drilling simulation. Surface injection pressures of 200, 300, and 400 psi, depths of 1,000, 2,000, 3,000, and 4,000 ft., and drilling rates of 0.0, 0.5, 1.0, and 1.5 fps were run on each pipe and hole combination. The tabulated results are listed in the Tables section of this paper. The surface injection pressure, hole size, and tubing size determine which of the tables should be used for foam drilling. After the proper table is selected, the required air volume rate, water volume rate, and surface annulus pressure for various depths and drilling rates are read for a stable foam drilling operation. The engineer may match the output of the on-site equipment with the tabulated results of foam theory and thereby ensure a stable foam drilling operation.

Figures 6 and 7 represent a typical application of the tabulated results. Prior to drilling a hole with foam, the hole and drillpipe size have been selected, and the surface injection pressure is usually dictated by the source of the gas: i.e., field gas or compressor. With the use of the proper tables, the gas and liquid volume rates and surface-annulus pressures are plotted as shown by the data in Figure 6. Table 20 shows that as the depth increases, the air and liquid volume rates must be increased while the surface-annulus pressure must be

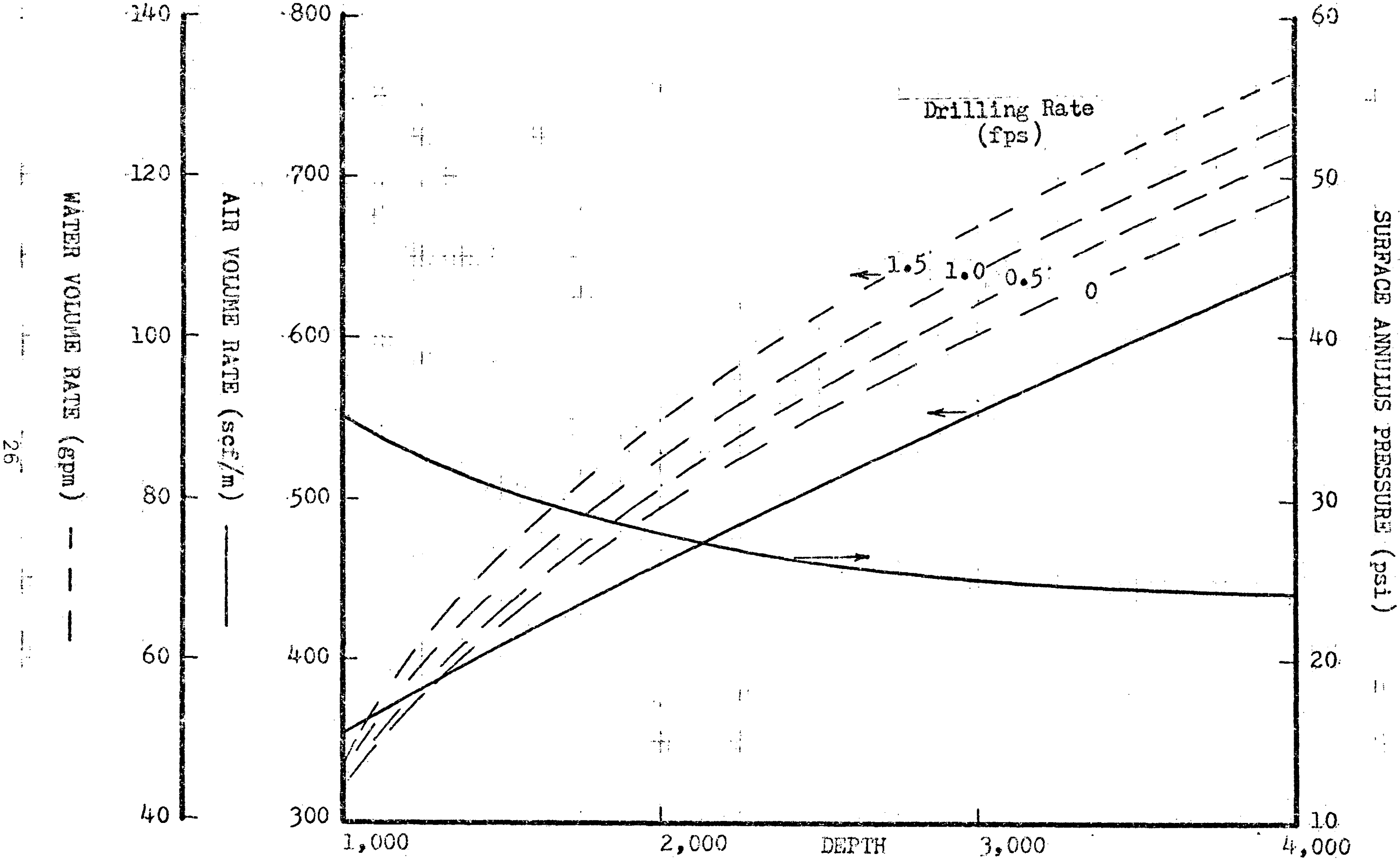


FIGURE: 6

Air And Liquid Requirements For Foam Drilling
Hole Size 9.00 in   Pipe Size 4.50in
Injection Pressure 200 psi

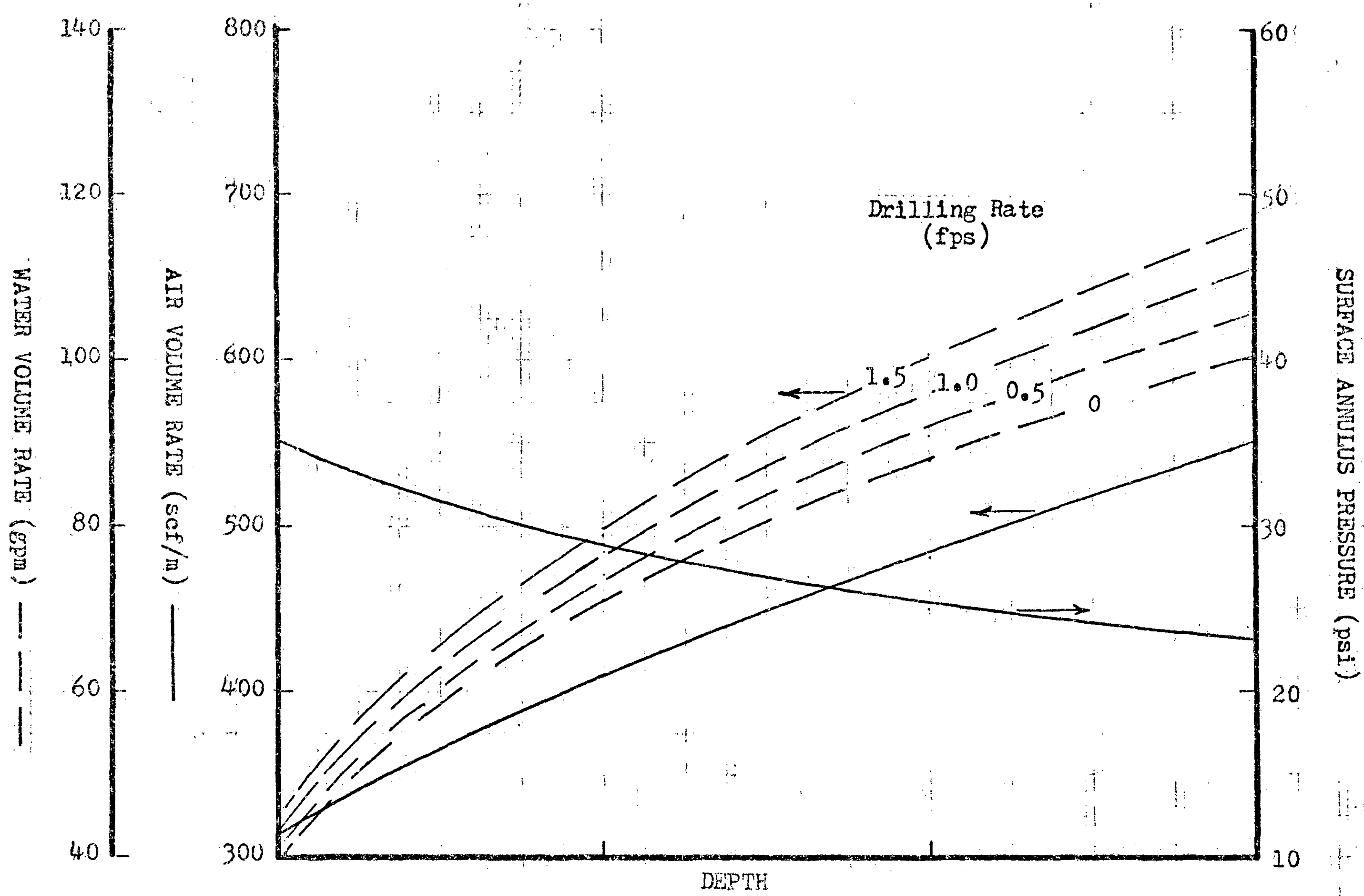


FIGURE: 7
Air And Liquid Requirements For Foam Drilling
Hole Size 9.00 in Pipe Size 5.50 in
Injection Pressure 200 psi

decreased. As the drilling rate increases, the air and liquid volume rates must be increased, and the surface-annulus pressure must be decreased. By displaying the volume and pressure requirements in graphical form, the adjustments in the field equipment may be determined easily and quickly for the changing depth and drilling rate. The air volume rate in Figures 6 and 7 represent a confidence interval for the drilling rates. The air volume rate is changing with depth and drilling rate, but the amount of change is too small to be seen on the figures.

Calculations show that the minimum hydraulic horsepower for foam drilling will be attained when the lowest available surface injection pressure and the largest drillpipe applicable to a hole is used. At higher surface injection pressures, more air is required; therefore the hydraulic horsepower is increased. The use of the largest drillpipe will minimize the hydraulic horsepower since the large drillpipe has less frictional losses than small pipe and will therefore require less horsepower. In order to minimize hydraulic horsepower in a foam drilling operation, the minimum surface injection pressure and the largest drillpipe should be used.

The range of the maximum Reynolds number in the pipe is 609 to 104,000 for the various pipe and hole combinations. The range of the maximum Reynolds number in the annulus is 1 to 22,000. The maximum Reynolds number for the pipe and annulus is at the bottom of the pipe. At this point, the effective foam viscosity is at a minimum, the density is at a maximum, and the velocity is at a minimum. The effective viscosity is extremely low and is the controlling number in the Reynolds calculation. The Reynolds number at this point is therefore a maximum. It should be noted that the majority of the Reynolds numbers are less than 2,000 and the flow is assumed to be in the laminar flow regime. The equation which was used to calculate the Reynolds number in the pipe is

$$Re = \frac{D_i V\rho}{\mu_e} \qquad 45$$

$$\text{where } \mu_e = \mu_p + \frac{\tau_y D_i}{6V}$$

and in the annulus is

$$Re = \frac{2WV\rho}{\mu_e} \qquad 46$$

$$\text{where } \mu_e = \mu_p + \frac{\tau_y W}{4V}$$

It should be noted that a Reynolds number criteria of 2,000 for defining turbulent flow of foam has not been verified by experimental work.

CHAPTER FIVE

DISCUSSION OF RESULTS

The data show that for an increase in depth, the water and air volumes must be increased while the surface annulus pressure must be decreased if the boundary conditions of 0.96 surface-annular quality and 1.5 fps bottom-hole velocity are to be maintained for the various depths. As the depth increases, the bottom-hole pressure will also increase while the gas volume will decrease. The velocity will therefore decrease. In order to maintain a velocity of 1.5 fps at the bottom of the pipe, the quantity of air must be increased. With the increase of air volume, there must be an associated increase of water volume if the surface quality is to be 0.96. The annulus surface pressure also affects the foam velocity and quality. If the annular pressure is not decreased with an increase in depth, larger water and air volumes will be required if the imposed boundary conditions are to be satisfied. The reported surface-annular pressures are the minimum pressures required if minimal air and water volumes are to be used in a foam drilling system.

For a specific depth, as the drilling rate is increased, the air and water volume rates must be increased and the annulus surface pressure must be decreased if the boundary conditions are to be met. As the rock chips are picked up and carried out of the annulus, they will add to the foam's density and increase the bottom-hole pressure. For higher drilling rates, the bottom-hole pressure will be larger; larger volumes of air and water will be required. As was stated in the last paragraph, the required air and water volumes are minimal volumes based upon the minimum annulus surface pressure for each group of data.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to present a mathematical model and its solution for the application of foam in a drilling system. The mathematical model of foam is the Bingham plastic fluid model applied to a compressible fluid. The Bingham model has been written in an iterative form and solved with a constant pressure iteration for a concentric vertical hole-annulus arrangement. Two equations have been written: one describing flow down the pipe and one describing flow up the annulus. The following conclusions may be stated about the mathematical model for foam:

1. The foam plastic viscosity is defined for a range of 1 to 14.7 cp for all qualities from 0 to 0.96.
2. The foam yield stress is defined for a range of 0 to 359 cp for all qualities from 0.584 to 0.96.
3. Foam plastic viscosity and yield stress are undefined in the mist region.
4. Maximum annular foam quality should not exceed 0.96.
5. All bottom-hole annular velocities may be used in the model, but computer time increases with higher velocities.
6. As the velocity increases, the foam properties will change such that smaller pipe lengths are required for the same change in pressure.
7. The optimum bottom-hole velocity has not been determined.

8. Temperature effects on foam stability have not been investigated.
9. Rock chip volume and mass have been accounted for in the quality calculation.
10. Solutions for pipe sizes of 2.87 to 4.50 in O.D. in hole sizes of 6.75 to 15.0 inches have been calculated.

Since the results of this study are based upon ideal drilling and hole conditions, the best test of the results would be an actual drilling application. It is recommended that the following items be investigated:

1. The bottom-hole velocity of 1.5 fps should be checked to determine if the velocity is sufficient to clean the rock chips from the bottom of the hole.
2. The actual pressure drop in the system should be checked against the theoretical calculated pressure change. In this manner, the Reynolds number for foam may be calculated and its effect upon the plastic viscosity and yield strength be determined.
3. Since the slip velocity in foam was assumed not to exist, a laboratory investigation should be made to verify this assumption.

TABLE 2

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 2ØØ. PSIA

PIPE SIZE OD 2.87 IN HOLE SIZE 6.75 IN
ID 2.45 IN

DEPTH FT		Ø.ØØ FT/MIN		Ø.5Ø FT/MIN		1.ØØ FT/MIN		1.5Ø FT/MIN
				DRILLING RATE				
1ØØØ.Ø	QG =	2Ø3.4	QG =	2Ø4.8	QG =	2Ø6.2	QG =	2Ø7.3
	QP =	32.2	QP =	33.2	QP =	34.4	QP =	35.7
	PA =	33.5	PA =	31.4	PA =	3Ø.7	PA =	29.6
	PB =	221.9	PB =	225.7	PB =	229.7	PB =	233.6
2ØØØ.Ø	QG =	26Ø.8	QG =	263.5	QG =	266.7	QG =	268.8
	QP =	57.3	QP =	58.8	QP =	6Ø.7	QP =	62.1
	PA =	25.4	PA =	22.8	PA =	25.4	PA =	25.4
	PB =	383.8	PB =	394.6	PB =	4Ø9.Ø	PB =	419.6
3ØØØ.Ø	QG =	319.8	QG =	322.4	QG =	323.9	QG =	325.2
	QP =	7Ø.9	QP =	73.3	QP =	75.1	QP =	77.3
	PA =	19.3	PA =	25.1	PA =	2Ø.5	PA =	23.4
	PB =	578.9	PB =	6Ø4.6	PB =	624.9	PB =	649.6
4ØØØ.Ø	QG =	366.8	QG =	367.1	QG =	366.4	QG =	365.1
	QP =	82.4	QP =	84.6	QP =	87.Ø	QP =	88.9
	PA =	27.4	PA =	24.5	PA =	28.2	PA =	22.3
	PB =	82Ø.8	PB =	853.8	PB =	892.1	PB =	922.8

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 3

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 2.87 IN HOLE SIZE 6.75 IN
ID 2.45 IN

DEPTH FT	DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	313.8	QG =	313.8	QG =	313.8	QG =	313.8
	QP =	25.0	QP =	25.0	QP =	25.0	QP =	25.0
	PA =	98.3	PA =	84.6	PA =	70.7	PA =	56.3
	PB =	305.0	PB =	305.0	PB =	305.0	PB =	345.0
2000.0	QG =	324.5	QG =	326.4	QG =	328.5	QG =	330.6
	QP =	41.2	QP =	43.1	QP =	45.1	QP =	47.0
	PA =	41.8	PA =	37.9	PA =	36.6	PA =	35.5
	PB =	394.9	PB =	405.5	PB =	417.1	PB =	428.6
3000.0	QG =	383.5	QG =	387.7	QG =	391.5	QG =	394.9
	QP =	56.8	QP =	58.3	QP =	59.7	QP =	61.1
	PA =	40.9	PA =	38.6	PA =	35.6	PA =	32.1
	PB =	573.8	PB =	590.5	PB =	607.2	PB =	623.7
4000.0	QG =	442.2	QG =	446.3	QG =	449.0	QG =	451.9
	QP =	66.1	QP =	68.0	QP =	69.5	QP =	71.3
	PA =	44.3	PA =	44.1	PA =	30.0	PA =	28.6
	PB =	764.5	PB =	793.1	PB =	814.2	PB =	841.9

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 4

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 4ØØ. PSIA

PIPE SIZE OD 2.87 IN HOLE SIZE 6.75 IN
ID 2.45 IN

DEPTH FT		DRILLING RATE Ø.ØØ FT/MIN		Ø.5Ø FT/MIN		1.ØØ FT/MIN		1.5Ø FT/MIN
1ØØØ.Ø	QG =	434.8	QG =	434.8	QG =	434.8	QG =	434.8
	QP =	21.2	QP =	21.2	QP =	21.2	QP =	21.2
	PA =	178.7	PA =	167.3	PA =	156.Ø	PA =	144.8
	PB =	4Ø5.Ø	PB =	4Ø5.Ø	PB =	4Ø5.Ø	PB =	4Ø5.Ø
2ØØØ.Ø	QG =	397.4	QG =	4ØØ.8	QG =	4Ø3.4	QG =	4Ø5.9
	QP =	31.3	QP =	32.3	QP =	33.4	QP =	34.6
	PA =	63.3	PA =	6Ø.6	PA =	55.6	PA =	54.7
	PB =	438.8	PB =	446.8	PB =	454.Ø	PB =	462.2
3ØØØ.Ø	QG =	442.3	QG =	446.1	QG =	45Ø.Ø	QG =	454.7
	QP =	45.6	QP =	47.6	QP =	49.5	QP =	51.5
	PA =	48.5	PA =	45.Ø	PA =	42.9	PA =	5Ø.2
	PB =	577.9	PB =	596.3	PB =	614.5	PB =	636.1
4ØØØ.Ø	QG =	5ØØ.9	QG =	5Ø6.6	QG =	511.9	QG =	516.7
	QP =	56.2	QP =	57.7	QP =	59.2	QP =	6Ø.6
	PA =	51.9	PA =	5Ø.2	PA =	48.2	PA =	45.2
	PB =	761.5	PB =	784.5	PB =	8Ø7.3	PB =	829.9

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 5

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200, PSIA

PIPE SIZE OD 3,50 IN HOLE SIZE 6,75 IN
ID 3,08 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	194,4	QG =	195,5	QG =	196,4	QG =	197,1
	QP =	29,7	QP =	30,7	QP =	32,[illegible]	QP =	33,2
	PA =	32,6	PA =	30,6	PA =	30,3	PA =	28,8
	PB =	239,7	PB =	243,8	PB =	243,2	PB =	252,3
2000,0	QG =	247,4	QG =	249,3	QG =	250,9	QG =	252,5
	QP =	51,4	QP =	52,9	QP =	54,3	QP =	56,0
	PA =	28,8	PA =	25,8	PA =	21,9	PA =	25,2
	PB =	408,3	PB =	419,6	PB =	430,9	PB =	444,7
3000,0	QG =	301,1	QG =	302,2	QG =	302,5	QG =	302,4
	QP =	62,9	QP =	65,1	QP =	67,1	QP =	69,1
	PA =	29,4	PA =	28,2	PA =	22,9	PA =	22,2
	PB =	605,9	PB =	630,0	PB =	654,2	PB =	677,6
4000,0	QG =	344,2	QG =	343,1	QG =	340,7	QG =	337,4
	QP =	72,2	QP =	74,5	QP =	77,0	QP =	79,4
	PA =	27,3	PA =	22,9	PA =	24,8	PA =	23,4
	PB =	838,0	PB =	874,7	PB =	915,0	PB =	954,8

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 6

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 6.75 IN
ID 3.08 IN

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
				DRILLING RATE				
1000.0	QG =	265.9	QG =	267.7	QG =	268.3	QG =	271.0
	QP =	22.5	QP =	23.0	QP =	23.4	QP =	24.2
	PA =	62.6	PA =	55.6	PA =	52.9	PA =	58.1
	PB =	305.1	PB =	307.2	PB =	310.4	PB =	314.8
2000.0	QG =	310.2	QG =	311.8	QG =	312.9	QG =	314.2
	QP =	37.3	QP =	39.7	QP =	41.4	QP =	43.3
	PA =	36.7	PA =	41.1	PA =	36.1	PA =	35.8
	PB =	425.8	PB =	439.7	PB =	450.9	PB =	463.4
3000.0	QG =	363.4	QG =	366.4	QG =	369.6	QG =	371.7
	QP =	50.8	QP =	52.3	QP =	54.1	QP =	55.5
	PA =	39.7	PA =	37.1	PA =	44.9	PA =	39.3
	PB =	608.6	PB =	626.0	PB =	647.6	PB =	664.7
4000.0	QG =	416.3	QG =	418.7	QG =	420.5	QG =	421.8
	QP =	58.5	QP =	60.4	QP =	62.2	QP =	64.2
	PA =	45.9	PA =	39.7	PA =	32.2	PA =	35.5
	PB =	799.2	PB =	827.3	PB =	854.8	PB =	887.4

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 7

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 6.75 IN
ID 3.08 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	382.4	QG =	382.4	QG =	382.4	QG =	382.4
	QP =	20.2	QP =	20.2	QP =	20.2	QP =	20.2
	PA =	153.6	PA =	139.0	PA =	124.5	PA =	109.9
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	380.2	QG =	382.8	QG =	384.9	QG =	386.4
	QP =	28.9	QP =	29.9	QP =	31.2	QP =	32.4
	PA =	60.7	PA =	58.2	PA =	59.3	PA =	57.3
	PB =	474.6	PB =	483.1	PB =	492.2	PB =	500.7
3000.0	QG =	422.8	QG =	425.3	QG =	428.3	QG =	430.5
	QP =	41.4	QP =	43.3	QP =	45.4	QP =	46.8
	PA =	49.2	PA =	44.2	PA =	51.4	PA =	41.7
	PB =	623.8	PB =	643.0	PB =	665.0	PB =	681.0
4000.0	QG =	474.6	QG =	478.7	QG =	482.5	QG =	486.4
	QP =	50.2	QP =	51.7	QP =	53.2	QP =	54.9
	PA =	46.3	PA =	44.7	PA =	41.5	PA =	52.7
	PB =	807.4	PB =	831.1	PB =	854.7	PB =	883.9

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 8

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200, PSIA

PIPE SIZE OD 2,87 IN HOLE SIZE 7,87 IN
ID 2,44 IN

DRILLING RATE

DEPTH FT		0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	278,0	QG =	282,3	QG =	285,3	QG =	288,2
	QP =	40,8	QP =	42,5	QP =	43,9	QP =	45,3
	PA =	31,9	PA =	30,8	PA =	30,1	PA =	30,9
	PB =	205,5	PB =	209,0	PB =	212,9	PB =	217,2
2000,0	QG =	360,5	QG =	365,3	QG =	369,3	QG =	374,7
	QP =	76,9	QP =	79,4	QP =	81,5	QP =	84,4
	PA =	22,1	PA =	22,3	PA =	20,1	PA =	26,4
	PB =	351,5	PB =	364,1	PB =	374,7	PB =	389,6
3000,0	QG =	447,9	QG =	453,5	QG =	456,2	QG =	459,2
	QP =	97,7	QP =	101,5	QP =	103,6	QP =	106,4
	PA =	21,4	PA =	29,1	PA =	21,1	PA =	20,5
	PB =	540,7	PB =	567,9	PB =	584,4	PB =	605,0
4000,0	QG =	518,2	QG =	520,5	QG =	521,4	QG =	521,3
	QP =	114,9	QP =	118,3	QP =	121,5	QP =	123,9
	PA =	22,8	PA =	25,3	PA =	26,3	PA =	19,8
	PB =	771,4	PB =	807,0	PB =	841,6	PB =	868,6

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 9

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 2.87 IN HOLE SIZE 7.37 IN
ID 2.44 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG =	464.4	464.4	464.4	464.4
	QP =	32.4	32.4	32.4	32.4
	PA =	122.2	111.6	101.0	90.6
	PB =	305.0	305.0	305.0	305.0
2000.0	QG =	449.9	454.8	458.2	461.5
	QP =	51.4	54.1	56.4	59.1
	PA =	42.4	42.8	38.1	36.7
	PB =	360.9	371.4	380.2	392.3
3000.0	QG =	530.4	537.3	543.2	549.4
	QP =	76.2	78.8	80.8	83.0
	PA =	38.7	38.0	33.9	33.7
	PB =	526.2	544.9	560.9	578.0
4000.0	QG =	614.6	623.1	630.4	635.0
	QP =	89.8	92.9	95.9	98.1
	PA =	31.9	37.0	40.5	32.8
	PB =	704.5	734.5	764.3	786.3

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 10

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 2.87 IN HOLE SIZE 7.87 IN
ID 2.44 IN

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	636.0	QG =	636.0	QG =	636.0	QG =	636.0
	QP =	26.5	QP =	26.5	QP =	26.5	QP =	26.5
	PA =	198.4	PA =	188.6	PA =	179.1	PA =	169.7
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	545.2	QG =	552.1	QG =	558.7	QG =	563.3
	QP =	39.5	QP =	41.4	QP =	43.0	QP =	44.2
	PA =	68.5	PA =	63.9	PA =	65.3	PA =	61.5
	PB =	410.0	PB =	415.0	PB =	423.4	PB =	430.5
3000.0	QG =	613.0	QG =	619.4	QG =	624.9	QG =	630.9
	QP =	57.0	QP =	60.3	QP =	63.3	QP =	66.5
	PA =	50.6	PA =	49.6	PA =	46.5	PA =	48.3
	PB =	523.1	PB =	540.9	PB =	558.0	PB =	577.3
4000.0	QG =	691.9	QG =	700.8	QG =	710.9	QG =	719.3
	QP =	75.1	QP =	77.6	QP =	80.3	QP =	82.5
	PA =	48.1	PA =	44.8	PA =	51.0	PA =	50.9
	PB =	696.3	PB =	720.5	PB =	748.3	PB =	771.6

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 11

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 7.87 IN
ID 3.08 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	277.9	QG =	281.3	QG =	284.1	QG =	286.4
	QP =	38.2	QP =	39.6	QP =	41.0	QP =	42.4
	PA =	33.7	PA =	35.4	PA =	35.5	PA =	35.0
	PB =	221.0	PB =	225.7	PB =	229.8	PB =	233.9
2000.0	QG =	357.1	QG =	360.8	QG =	364.5	QG =	367.6
	QP =	69.2	QP =	72.1	QP =	74.7	QP =	76.8
	PA =	25.7	PA =	26.7	PA =	28.0	PA =	27.0
	PB =	368.9	PB =	382.7	PB =	395.7	PB =	407.1
3000.0	QG =	440.9	QG =	444.1	QG =	446.5	QG =	448.2
	QP =	87.6	QP =	90.5	QP =	93.3	QP =	96.0
	PA =	29.9	PA =	27.0	PA =	23.9	PA =	20.1
	PB =	556.6	PB =	577.7	PB =	598.6	PB =	619.2
4000.0	QG =	510.2	QG =	511.0	QG =	510.5	QG =	508.6
	QP =	101.9	QP =	105.1	QP =	108.8	QP =	112.2
	PA =	27.0	PA =	23.5	PA =	25.9	PA =	26.1
	PB =	774.2	PB =	807.5	PB =	845.0	PB =	882.3

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 12

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 7.87 IN
ID 3.08 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG =	423.8	423.8	423.8	423.8
	QP =	31.3	31.3	31.3	31.3
	PA =	106.5	93.7	80.9	67.8
	PB =	305.0	305.0	305.0	305.0
2000.0	QG =	449.5	453.4	456.8	459.3
	QP =	47.0	49.1	51.5	53.9
	PA =	48.1	44.2	42.6	39.6
	PB =	387.7	397.0	407.1	416.7
3000.0	QG =	524.5	530.0	535.1	539.7
	QP =	68.3	71.1	73.6	75.8
	PA =	39.7	38.9	38.6	36.4
	PB =	550.0	569.9	588.9	605.8
4000.0	QG =	605.6	612.0	616.2	620.5
	QP =	81.0	83.9	86.2	89.0
	PA =	44.6	46.7	37.1	37.3
	PB =	732.3	761.4	784.3	812.7

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 13

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 7.87 IN
ID 3.08 IN

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	583.0	QG =	583.0	QG =	583.0	QG =	583.0
	QP =	25.8	QP =	25.8	QP =	25.8	QP =	25.8
	PA =	181.7	PA =	170.5	PA =	159.4	PA =	148.6
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	544.1	QG =	549.5	QG =	555.4	QG =	559.5
	QP =	37.5	QP =	38.7	QP =	40.1	QP =	41.2
	PA =	70.9	PA =	67.7	PA =	70.0	PA =	63.8
	PB =	438.9	PB =	446.7	PB =	455.7	PB =	462.3
3000.0	QG =	612.6	QG =	617.8	QG =	622.5	QG =	625.9
	QP =	51.3	QP =	54.2	QP =	57.4	QP =	60.0
	PA =	55.7	PA =	52.7	PA =	54.2	PA =	48.4
	PB =	558.5	PB =	575.4	PB =	594.4	PB =	610.6
4000.0	QG =	684.6	QG =	691.6	QG =	699.6	QG =	705.4
	QP =	67.3	QP =	70.1	QP =	73.0	QP =	75.1
	PA =	50.1	PA =	45.8	PA =	54.0	PA =	49.5
	PB =	728.4	PB =	754.1	PB =	783.7	PB =	806.1

DRILLING RATE applies to the column headings.

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 14

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 7.87 IN
ID 3.76 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	250.0	QG =	251.8	QG =	253.3	QG =	254.4
	QP =	35.2	QP =	36.6	QP =	38.1	QP =	39.6
	PA =	34.6	PA =	32.8	PA =	32.8	PA =	31.5
	PB =	242.5	PB =	246.8	PB =	251.4	PB =	255.8
2000.0	QG =	317.4	QG =	319.6	QG =	321.6	QG =	323.5
	QP =	61.9	QP =	63.9	QP =	65.9	QP =	68.3
	PA =	30.6	PA =	26.5	PA =	24.1	PA =	27.5
	PB =	406.6	PB =	418.5	PB =	430.5	PB =	445.0
3000.0	QG =	386.6	QG =	387.8	QG =	388.1	QG =	387.3
	QP =	75.8	QP =	78.7	QP =	81.6	QP =	84.7
	PA =	32.2	PA =	29.4	PA =	25.1	PA =	26.2
	PB =	597.5	PB =	622.5	PB =	647.2	PB =	675.0
4000.0	QG =	443.7	QG =	441.5	QG =	438.3	QG =	432.9
	QP =	86.8	QP =	90.8	QP =	93.8	QP =	97.4
	PA =	23.8	PA =	31.4	PA =	21.1	PA =	22.0
	PB =	817.3	PB =	864.2	PB =	900.8	PB =	945.0

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 15

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 7.87 IN
ID 3.76 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	358.9	QG =	343.5	QG =	345.0	QG =	347.3
	QP =	28.4	QP =	27.7	QP =	28.3	QP =	29.0
	PA =	59.2	PA =	61.0	PA =	56.6	PA =	56.1
	PB =	306.2	PB =	312.5	PB =	315.6	PB =	319.2
2000.0	QG =	401.2	QG =	403.2	QG =	404.7	QG =	435.7
	QP =	43.5	QP =	45.9	QP =	48.7	QP =	51.3
	PA =	43.6	PA =	40.4	PA =	41.3	PA =	40.2
	PB =	427.0	PB =	438.7	PB =	451.9	PB =	464.6
3000.0	QG =	465.9	QG =	469.5	QG =	472.8	QG =	476.0
	QP =	60.7	QP =	63.1	QP =	65.1	QP =	67.5
	PA =	35.0	PA =	36.3	PA =	34.3	PA =	41.0
	PB =	603.2	PB =	623.9	PB =	642.6	PB =	664.7
4000.0	QG =	533.7	QG =	536.7	QG =	539.0	QG =	539.9
	QP =	70.4	QP =	73.0	QP =	75.9	QP =	78.3
	PA =	48.7	PA =	42.4	PA =	44.8	PA =	34.9
	PB =	790.7	PB =	820.0	PB =	853.8	PB =	882.4

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 16

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 4ØØ, PSIA

PIPE SIZE OD 4,5Ø IN HOLE SIZE 7,87 IN
ID 3,76 IN

DRILLING RATE

DEPTH FT	Ø,ØØ FT/MIN	Ø,5Ø FT/MIN	1,ØØ FT/MIN	1,5Ø FT/MIN
1ØØØ,Ø	QG = 479,8	QG = 479,8	QG = 479,8	QG = 479,8
	QP = 24,6	QP = 24,6	QP = 24,6	QP = 24,6
	PA = 154,1	PA = 138,5	PA = 123,Ø	PA = 1Ø7,4
	PB = 4Ø5,Ø	PB = 4Ø5,Ø	PB = 4Ø5,Ø	PB = 4Ø5,Ø
2ØØØ,Ø	QG = 489,3	QG = 493,Ø	QG = 496,3	QG = 498,4
	QP = 34,5	QP = 35,8	QP = 37,3	QP = 38,6
	PA = 7Ø,4	PA = 67,5	PA = 63,5	PA = 6Ø,8
	PB = 481,4	PB = 49Ø,3	PB = 499,8	PB = 5Ø7,4
3ØØØ,Ø	QG = 546,3	QG = 549,1	QG = 551,4	QG = 553,9
	QP = 47,9	QP = 5Ø,9	QP = 53,4	QP = 56,2
	PA = 56,1	PA = 53,9	PA = 46,3	PA = 48,3
	PB = 62Ø,4	PB = 641,6	PB = 66Ø,6	PB = 652,2
4ØØØ,Ø	QG = 6Ø9,5	QG = 613,5	QG = 618,8	QG = 622,5
	QP = 6Ø,4	QP = 62,4	QP = 64,8	QP = 66,9
	PA = 58,6	PA = 43,5	PA = 56,4	PA = 52,8
	PB = 8Ø5,4	PB = 828,2	PB = 858,3	PB = 883,4

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 17

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200, PSIA

PIPE SIZE OD 3,50 IN HOLE SIZE 9,00 IN
ID 3,08 IN

DEPTH FT	DRILLING RATE 0,00 FT/MIN	0,50 FT/MIN	1,00 FT/MIN	1,50 FT/MIN
1000,0	QG = 370,7	QG = 374,9	QG = 378,6	QG = 382,2
	QP = 48,5	QP = 49,8	QP = 51,3	QP = 52,5
	PA = 40,3	PA = 38,3	PA = 38,5	PA = 34,5
	PB = 208,3	PB = 212,0	PB = 216,2	PB = 219,0
2000,0	QG = 479,9	QG = 484,9	QG = 489,7	QG = 494,9
	QP = 86,8	QP = 90,8	QP = 94,5	QP = 98,4
	PA = 29,9	PA = 26,4	PA = 23,2	PA = 23,9
	PB = 338,9	PB = 351,0	PB = 362,6	PB = 375,8
3000,0	QG = 596,9	QG = 602,2	QG = 607,7	QG = 612,0
	QP = 114,9	QP = 118,3	QP = 122,3	QP = 126,3
	PA = 31,0	PA = 24,6	PA = 24,7	PA = 23,9
	PB = 527,0	PB = 537,7	PB = 559,2	PB = 580,5
4000,0	QG = 697,0	QG = 700,3	QG = 702,3	QG = 702,7
	QP = 135,2	QP = 139,2	QP = 143,9	QP = 148,3
	PA = 28,4	PA = 22,3	PA = 22,2	PA = 21,2
	PB = 728,0	PB = 756,9	PB = 790,9	PB = 824,3

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 18

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 3ØØ. PSIA

PIPE SIZE OD 3.5Ø IN HOLE SIZE 9.ØØ IN
ID 3.Ø8 IN

DRILLING RATE

DEPTH FT	Ø.ØØ FT/MIN		Ø.5Ø FT/MIN		1.ØØ FT/MIN		1.5Ø FT/MIN	
1ØØØ.Ø	QG =	599.Ø	QG =	599.Ø	QG =	599.Ø	QG =	599.Ø
	QP =	39.6	QP =	39.6	QP =	39.6	QP =	39.6
	PA =	129.3	PA =	119.Ø	PA =	1Ø8.8	PA =	98.8
	PB =	3Ø5.Ø	PB =	3Ø5.Ø	PB =	3Ø5.Ø	PB =	3Ø5.Ø
2ØØØ.Ø	QG =	598.9	QG =	6Ø6.4	QG =	613.8	QG =	619.6
	QP =	58.1	QP =	6Ø.3	QP =	62.9	QP =	65.4
	PA =	5Ø.4	PA =	46.4	PA =	45.5	PA =	42.5
	PB =	36Ø.9	PB =	369.2	PB =	378.5	PB =	387.1
3ØØØ.Ø	QG =	7Ø3.3	QG =	711.5	QG =	72Ø.5	QG =	726.8
	QP =	84.6	QP =	89.Ø	QP =	93.6	QP =	97.Ø
	PA =	4Ø.2	PA =	37.3	PA =	4Ø.8	PA =	35.1
	PB =	5Ø1.4	PB =	521.1	PB =	543.6	PB =	559.8
4ØØØ.Ø	QG =	814.5	QG =	824.2	QG =	834.7	QG =	841.9
	QP =	1Ø5.2	QP =	1Ø8.6	QP =	112.7	QP =	116.Ø
	PA =	39.2	PA =	35.2	PA =	4Ø.2	PA =	35.Ø
	PB =	679.5	PB =	7Ø3.3	PB =	733.Ø	PB =	756.4

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 19

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400, PSIA

PIPE SIZE OD 3,50 IN   HOLE SIZE 9,00 IN
ID 3,08 IN

DRILLING RATE

DEPTH FT		0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	819,3	QG =	819,3	QG =	819,3	QG =	819,3
	QP =	32,5	QP =	32,5	QP =	32,5	QP =	32,5
	PA =	208,1	PA =	198,5	PA =	189,1	PA =	179,9
	PB =	405,0	PB =	405,0	PB =	405,0	PB =	405,0
2000,0	QG =	723,2	QG =	730,8	QG =	737,6	QG =	748,4
	QP =	47,1	QP =	48,5	QP =	49,7	QP =	51,7
	PA =	73,9	PA =	73,5	PA =	68,0	PA =	74,6
	PB =	411,1	PB =	419,2	PB =	425,8	PB =	436,1
3000,0	QG =	820,4	QG =	829,7	QG =	839,5	QG =	846,9
	QP =	63,3	QP =	65,9	QP =	69,4	QP =	72,9
	PA =	66,7	PA =	58,6	PA =	58,5	PA =	55,5
	PB =	519,2	PB =	532,3	PB =	548,4	PB =	563,7
4000,0	QG =	917,7	QG =	929,5	QG =	939,5	QG =	950,8
	QP =	83,0	QP =	87,9	QP =	92,1	QP =	96,5
	PA =	52,2	PA =	52,0	PA =	48,3	PA =	53,0
	PB =	663,5	PB =	692,2	PB =	717,7	PB =	747,1

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 20

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 9.00 IN
ID 3.76 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	349.7	QG =	354.0	QG =	357.1	QG =	360.3
	QP =	44.6	QP =	46.3	QP =	47.6	QP =	49.3
	PA =	35.1	PA =	36.8	PA =	34.1	PA =	33.9
	PB =	224.4	PB =	229.2	PB =	232.8	PB =	237.0
2000.0	QG =	450.2	QG =	454.1	QG =	457.8	QG =	461.8
	QP =	79.0	QP =	82.9	QP =	86.6	QP =	90.5
	PA =	29.5	PA =	26.2	PA =	24.6	PA =	28.5
	PB =	365.0	PB =	378.6	PB =	391.9	PB =	406.9
3000.0	QG =	553.5	QG =	557.9	QG =	561.5	QG =	563.6
	QP =	101.5	QP =	105.4	QP =	109.8	QP =	114.2
	PA =	25.7	PA =	23.6	PA =	26.8	PA =	28.5
	PB =	544.9	PB =	567.1	PB =	592.6	PB =	617.8
4000.0	QG =	643.8	QG =	645.1	QG =	644.3	QG =	641.0
	QP =	118.7	QP =	123.7	QP =	128.0	QP =	133.2
	PA =	27.6	PA =	29.4	PA =	23.1	PA =	26.9
	PB =	754.1	PB =	793.3	PB =	826.9	PB =	869.3

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 21

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 3ØØ, PSIA

PIPE SIZE OD 4,5Ø IN HOLE SIZE 9,ØØ IN
ID 3,76 IN

DRILLING RATE

DEPTH FT		Ø,ØØ FT/MIN		Ø,5Ø FT/MIN		1,ØØ FT/MIN		1,5Ø FT/MIN
1ØØØ,Ø	QG =	515,6	QG =	516,6	QG =	515,6	QG =	516,6
	QP =	38,3	QP =	38,3	QP =	38,3	QP =	38,3
	PA =	113,9	PA =	1ØØ,8	PA =	87,6	PA =	74,3
	PB =	3Ø5,Ø	PB =	3Ø5,Ø	PB =	3Ø5,Ø	PB =	375,Ø
2ØØØ,Ø	QG =	566,Ø	QG =	572,3	QG =	577,9	QG =	581,9
	QP =	53,8	QP =	56,3	QP =	59,2	QP =	62,Ø
	PA =	48,9	PA =	47,7	PA =	46,1	PA =	45,8
	PB =	39Ø,8	PB =	4Ø1,Ø	PB =	411,6	PB =	421,5
3ØØØ,Ø	QG =	661,Ø	QG =	667,3	QG =	672,6	QG =	677,6
	QP =	77,5	QP =	81,8	QP =	85,4	QP =	[illegible]8,6
	PA =	42,4	PA =	4Ø,8	PA =	36,1	PA =	32,7
	PB =	542,7	PB =	564,6	PB =	584,Ø	PB =	6[illegible]2,6
4ØØØ,Ø	QG =	759,1	QG =	767,4	QG =	774,1	QG =	779,2
	QP =	93,8	QP =	97,7	QP =	1Ø1,5	QP =	1Ø5,3
	PA =	37,Ø	PA =	41,7	PA =	43,5	PA =	43,3
	PB =	72Ø,Ø	PB =	75Ø,4	PB =	78Ø,Ø	PB =	8Ø9,8

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 22

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 4ØØ, PSIA

PIPE SIZE OD 4,5Ø IN HOLE SIZE 9,ØØ IN
ID 3,76 IN

DEPTH FT		Ø,ØØ FT/MIN		Ø,5Ø FT/MIN		1,ØØ FT/MIN		1,5Ø FT/MIN
1ØØØ,Ø	QG =	714,5	QG =	714,5	QG =	714,5	QG =	714,5
	QP =	32,2	QP =	32,2	QP =	32,2	QP =	32,2
	PA =	193,3	PA =	181,7	PA =	17Ø,3	PA =	159,1
	PB =	4Ø5,Ø	PB =	4Ø5,Ø	PB =	4Ø5,Ø	PB =	4Ø5,Ø
2ØØØ,Ø	QG =	683,3	QG =	692,1	QG =	698,4	QG =	7Ø5,Ø
	QP =	43,7	QP =	45,4	QP =	46,7	QP =	48,3
	PA =	71,5	PA =	75,1	PA =	69,7	PA =	69,9
	PB =	445,4	PB =	455,Ø	PB =	462,4	PB =	471,Ø
3ØØØ,Ø	QG =	774,3	QG =	781,8	QG =	788,Ø	QG =	792,7
	QP =	58,6	QP =	61,6	QP =	64,9	QP =	68,3
	PA =	67,5	PA =	6Ø,8	PA =	57,4	PA =	51,8
	PB =	563,Ø	PB =	578,6	PB =	595,3	PB =	611,7
4ØØØ,Ø	QG =	863,1	QG =	871,2	QG =	879,1	QG =	886,7
	QP =	76,3	QP =	8Ø,5	QP =	84,6	QP =	88,3
	PA =	56,8	PA =	51,9	PA =	51,1	PA =	53,9
	PB =	719,7	PB =	748,1	PB =	776,9	PB =	8Ø5,7

DRILLING RATE applies to the four rate columns.

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 23

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200, PSIA

PIPE SIZE OD 5,50 IN HOLE SIZE 9,00 IN
ID 4,78 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	312,8	QG =	315,1	QG =	317,2	QG =	318,9
	QP =	47,9	QP =	42,5	QP =	44,3	QP =	46,3
	PA =	38,5	PA =	35,8	PA =	35,6	PA =	36,8
	PB =	245,8	PB =	250,0	PB =	254,8	PB =	259,8
2000,0	QG =	396,6	QG =	399,4	QG =	401,6	QG =	403,3
	QP =	71,0	QP =	74,8	QP =	77,9	QP =	80,6
	PA =	27,1	PA =	30,0	PA =	30,7	PA =	27,7
	PB =	401,5	PB =	417,8	PB =	432,[illegible]	PB =	444,6
3000,0	QG =	482,6	QG =	484,2	QG =	484,3	QG =	482,8
	QP =	86,1	QP =	91,9	QP =	96,2	QP =	100,3
	PA =	23,2	PA =	24,2	PA =	25,3	PA =	23,8
	PB =	586,7	PB =	612,1	PB =	640,[illegible]	PB =	668,3
4000,0	QG =	556,1	QG =	553,2	QG =	547,7	QG =	540,0
	QP =	101,5	QP =	106,7	QP =	111,6	QP =	116,3
	PA =	27,0	PA =	29,7	PA =	28,4	PA =	23,8
	PB =	800,5	PB =	847,1	PB =	892,6	PB =	937,1

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 24

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300, PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 9.00 IN
ID 4.78 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	455.4	QG =	429.7	QG =	432.4	QG =	434.6
	QP =	34.2	QP =	32.5	QP =	33.4	QP =	34.3
	PA =	78.7	PA =	67.1	PA =	65.6	PA =	63.8
	PB =	316.7	PB =	318.5	PB =	322.2	PB =	325.8
2000.0	QG =	503.6	QG =	506.9	QG =	508.9	QG =	517.1
	QP =	49.7	QP =	52.6	QP =	55.5	QP =	58.8
	PA =	52.6	PA =	50.0	PA =	44.9	PA =	43.3
	PB =	429.9	PB =	441.8	PB =	453.2	PB =	465.9
3000.0	QG =	582.9	QG =	586.8	QG =	590.6	QG =	593.3
	QP =	69.9	QP =	73.6	QP =	77.1	QP =	79.8
	PA =	38.4	PA =	39.1	PA =	46.2	PA =	42.6
	PB =	597.8	PB =	621.5	PB =	645.4	PB =	664.6
4000.0	QG =	665.7	QG =	669.4	QG =	671.9	QG =	672.5
	QP =	91.9	QP =	85.3	QP =	89.1	QP =	92.8
	PA =	42.5	PA =	36.3	PA =	37.7	PA =	35.8
	PB =	779.7	PB =	809.8	PB =	843.8	PB =	877.5

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 25

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 9.00 IN
ID 4.78 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	596.6	QG =	596.6	QG =	596.6	QG =	596.6
	QP =	30.7	QP =	30.7	QP =	30.7	QP =	30.7
	PA =	167.5	PA =	151.9	PA =	136.4	PA =	121.0
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	612.2	QG =	617.0	QG =	620.9	QG =	624.4
	QP =	40.0	QP =	41.6	QP =	43.1	QP =	44.9
	PA =	77.5	PA =	73.5	PA =	67.3	PA =	65.7
	PB =	488.2	PB =	497.0	PB =	505.3	PB =	514.4
3000.0	QG =	686.3	QG =	690.1	QG =	692.9	QG =	694.8
	QP =	54.0	QP =	57.3	QP =	61.1	QP =	64.7
	PA =	62.9	PA =	55.0	PA =	54.4	PA =	52.1
	PB =	619.1	PB =	638.5	PB =	660.0	PB =	681.6
4000.0	QG =	761.7	QG =	767.3	QG =	771.7	QG =	775.6
	QP =	69.0	QP =	73.1	QP =	76.1	QP =	78.8
	PA =	51.8	PA =	59.5	PA =	54.7	PA =	50.5
	PB =	793.9	PB =	828.5	PB =	856.1	PB =	881.9

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 26

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 9.87 IN
ID 3.07 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	464.7	QG =	460.2	QG =	456.7	QG =	461.0
	QP =	53.9	QP =	56.4	QP =	59.7	QP =	61.5
	PA =	40.8	PA =	36.7	PA =	38.0	PA =	38.7
	PB =	205.0	PB =	205.0	PB =	206.9	PB =	211.3
2000.0	QG =	581.1	QG =	588.2	QG =	594.4	QG =	601.1
	QP =	100.0	QP =	105.3	QP =	110.2	QP =	115.4
	PA =	30.6	PA =	27.5	PA =	24.2	PA =	24.0
	PB =	319.7	PB =	331.8	PB =	343.4	PB =	356.4
3000.0	QG =	723.5	QG =	733.5	QG =	742.1	QG =	749.0
	QP =	136.3	QP =	141.7	QP =	147.0	QP =	152.1
	PA =	23.1	PA =	25.1	PA =	26.0	PA =	26.5
	PB =	492.4	PB =	514.5	PB =	536.5	PB =	558.2
4000.0	QG =	852.6	QG =	859.4	QG =	863.0	QG =	865.3
	QP =	163.1	QP =	169.4	QP =	174.4	QP =	180.2
	PA =	26.8	PA =	29.0	PA =	25.0	PA =	25.6
	PB =	698.6	PB =	734.2	PB =	763.3	PB =	797.7

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 27

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 3.50 IN HOLE SIZE 9.87 IN
ID 3.07 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	750.6	QG =	750.6	QG =	750.6	QG =	750.6
	QP =	45.7	QP =	45.7	QP =	45.7	QP =	45.7
	PA =	139.9	PA =	130.6	PA =	121.3	PA =	112.3
	PB =	305.0	PB =	305.0	PB =	305.0	PB =	305.0
2000.0	QG =	720.3	QG =	732.5	QG =	742.7	QG =	751.1
	QP =	67.6	QP =	70.5	QP =	73.3	QP =	76.0
	PA =	51.6	PA =	52.2	PA =	50.6	PA =	47.5
	PB =	344.5	PB =	354.2	PB =	363.0	PB =	371.1
3000.0	QG =	852.2	QG =	862.6	QG =	872.8	QG =	883.7
	QP =	97.7	QP =	102.9	QP =	108.3	QP =	114.2
	PA =	44.9	PA =	39.0	PA =	36.6	PA =	38.8
	PB =	474.4	PB =	492.0	PB =	511.1	PB =	532.8
4000.0	QG =	987.7	QG =	1003.1	QG =	1015.3	QG =	1026.1
	QP =	125.2	QP =	130.4	QP =	134.6	QP =	138.8
	PA =	38.6	PA =	42.0	PA =	39.1	PA =	36.2
	PB =	647.1	PB =	676.0	PB =	700.0	PB =	724.1

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 28

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400, PSIA

PIPE SIZE OD 3,50 IN HOLE SIZE 9,87 IN
ID 3,07 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	1023,3	QG =	1023,3	QG =	1023,3	QG =	1023,3
	QP =	39,4	QP =	39,4	QP =	39,4	QP =	39,4
	PA =	228,7	PA =	219,8	PA =	211,2	PA =	202,7
	PB =	405,0	PB =	405,0	PB =	405,0	PB =	405,0
2000,0	QG =	903,7	QG =	893,6	QG =	897,8	QG =	901,3
	QP =	52,9	QP =	55,6	QP =	57,7	QP =	60,0
	PA =	80,4	PA =	75,3	PA =	71,3	PA =	72,9
	PB =	405,0	PB =	405,0	PB =	410,0	PB =	416,9
3000,0	QG =	985,9	QG =	1002,4	QG =	1015,6	QG =	1027,8
	QP =	72,9	QP =	76,4	QP =	79,7	QP =	83,6
	PA =	63,7	PA =	63,1	PA =	59,1	PA =	57,4
	PB =	492,9	PB =	508,0	PB =	521,8	PB =	536,5
4000,0	QG =	1110,4	QG =	1127,4	QG =	1140,6	QG =	1154,7
	QP =	95,4	QP =	101,8	QP =	107,1	QP =	112,9
	PA =	55,6	PA =	56,3	PA =	51,5	PA =	53,2
	PB =	626,1	PB =	654,7	PB =	679,7	PB =	707,9

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 29

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 9.87 IN
ID 3.75 IN

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
				DRILLING RATE				
1000.0	QG =	431.9	QG =	437.6	QG =	441.7	QG =	446.3
	QP =	52.9	QP =	54.7	QP =	56.1	QP =	57.8
	PA =	41.2	PA =	41.5	PA =	38.0	PA =	37.1
	PB =	214.8	PB =	219.3	PB =	222.6	PB =	226.5
2000.0	QG =	560.4	QG =	566.9	QG =	571.9	QG =	577.0
	QP =	91.3	QP =	97.0	QP =	101.9	QP =	107.0
	PA =	32.5	PA =	31.7	PA =	28.4	PA =	28.6
	PB =	341.2	PB =	355.6	PB =	368.2	PB =	382.2
3000.0	QG =	691.9	QG =	699.7	QG =	705.7	QG =	710.2
	QP =	122.7	QP =	127.9	QP =	132.9	QP =	137.6
	PA =	27.1	PA =	27.9	PA =	27.9	PA =	26.7
	PB =	516.2	PB =	538.7	PB =	561.[illegible]	PB =	583.1
4000.0	QG =	810.7	QG =	815.1	QG =	817.0	QG =	816.3
	QP =	144.5	QP =	150.4	QP =	156.9	QP =	162.3
	PA =	26.6	PA =	26.0	PA =	29.4	PA =	26.3
	PB =	714.7	PB =	750.0	PB =	789.5	PB =	823.4

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 30

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 9.87 IN
ID 3.75 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	671.0	QG =	671.0	QG =	671.0	QG =	671.0
	QP =	45.4	QP =	45.4	QP =	45.4	QP =	45.4
	PA =	129.4	PA =	118.3	PA =	107.3	PA =	96.5
	PB =	305.0	PB =	305.0	PB =	305.0	PB =	305.0
2000.0	QG =	698.2	QG =	708.9	QG =	717.6	QG =	725.6
	QP =	62.8	QP =	65.7	QP =	68.5	QP =	71.7
	PA =	51.2	PA =	52.6	PA =	51.3	PA =	51.8
	PB =	370.6	PB =	381.0	PB =	390.4	PB =	400.5
3000.0	QG =	821.7	QG =	831.3	QG =	839.3	QG =	846.7
	QP =	88.9	QP =	94.5	QP =	99.8	QP =	104.7
	PA =	44.7	PA =	42.4	PA =	39.6	PA =	38.0
	PB =	525.4	PB =	526.4	PB =	540.7	PB =	566.8
4000.0	QG =	946.9	QG =	958.9	QG =	968.5	QG =	976.6
	QP =	113.1	QP =	118.0	QP =	122.2	QP =	126.4
	PA =	43.0	PA =	45.1	PA =	41.7	PA =	37.7
	PB =	682.3	PB =	711.5	PB =	736.9	PB =	762.1

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 31

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400, PSIA

PIPE SIZE OD 4,50 IN HOLE SIZE 9,87 IN
ID 3,75 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	917,6	QG =	917,6	QG =	917,6	QG =	917,6
	QP =	37,9	QP =	37,9	QP =	37,9	QP =	37,9
	PA =	210,9	PA =	200,6	PA =	190,5	PA =	180,7
	PB =	405,0	PB =	405,0	PB =	405,0	PB =	405,0
2000,0	QG =	841,9	QG =	853,2	QG =	861,0	QG =	872,8
	QP =	51,5	QP =	53,3	QP =	54,6	QP =	56,7
	PA =	79,5	PA =	79,1	PA =	71,6	PA =	76,9
	PB =	425,2	PB =	433,8	PB =	440,2	PB =	450,2
3000,0	QG =	957,9	QG =	969,7	QG =	982,1	QG =	990,4
	QP =	68,1	QP =	71,0	QP =	74,9	QP =	76,2
	PA =	72,3	PA =	64,7	PA =	65,3	PA =	55,4
	PB =	532,9	PB =	546,6	PB =	563,3	PB =	577,0
4000,0	QG =	1072,4	QG =	1085,0	QG =	1096,6	QG =	1106,1
	QP =	87,2	QP =	92,8	QP =	98,6	QP =	103,5
	PA =	59,1	PA =	54,7	PA =	54,8	PA =	50,8
	PB =	669,6	PB =	697,0	PB =	726,5	PB =	752,7

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 32

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 9.87 IN
ID 4.78 IN

	DRILLING RATE			
DEPTH FT	0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG = 402.4	QG = 406.5	QG = 409.9	QG = 413.1
	QP = 48.6	QP = 50.3	QP = 52.0	QP = 53.8
	PA = 39.4	PA = 38.7	PA = 37.2	PA = 34.9
	PB = 232.5	PB = 236.8	PB = 240.9	PB = 244.7
2000.0	QG = 516.3	QG = 520.7	QG = 524.1	QG = 527.3
	QP = 63.3	QP = 88.7	QP = 93.4	QP = 97.8
	PA = 30.4	PA = 29.7	PA = 27.6	PA = 27.1
	PB = 369.1	PB = 384.9	PB = 399.2	PB = 413.4
3000.0	QG = 632.0	QG = 636.8	QG = 639.4	QG = 640.6
	QP = 108.9	QP = 114.2	QP = 118.7	QP = 123.8
	PA = 29.4	PA = 32.1	PA = 27.3	PA = 26.6
	PB = 548.8	PB = 574.6	PB = 597.0	PB = 622.3
4000.0	QG = 734.9	QG = 735.5	QG = 733.2	QG = 728.0
	QP = 127.2	QP = 133.1	QP = 138.8	QP = 144.8
	PA = 32.6	PA = 30.2	PA = 26.1	PA = 25.2
	PB = 752.1	PB = 791.1	PB = 829.5	PB = 871.4

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 33

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 9.87 IN
ID 4.78 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG =	575.3	551.9	556.2	559.0
	QP =	39.8	38.6	39.4	40.4
	PA =	78.1	69.1	66.4	65.0
	PB =	300.8	302.5	305.9	309.1
2000.0	QG =	649.9	656.8	662.9	667.8
	QP =	58.0	60.7	63.7	67.1
	PA =	53.3	49.8	48.7	48.8
	PB =	402.5	412.4	422.9	434.0
3000.0	QG =	758.6	765.1	770.6	775.2
	QP =	81.8	87.1	92.3	96.6
	PA =	47.5	44.4	44.0	41.5
	PB =	550.0	573.1	596.4	617.2
4000.0	QG =	867.2	875.5	881.9	886.3
	QP =	100.6	105.1	109.7	114.1
	PA =	38.5	41.3	41.9	40.2
	PB =	727.2	757.5	787.8	817.9

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 34

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 4ØØ, PSIA

PIPE SIZE OD 5,5Ø IN   HOLE SIZE 9,87 IN
ID 4,78 IN

DEPTH FT		DRILLING RATE Ø,ØØ FT/MIN		Ø,5Ø FT/MIN		1,ØØ FT/MIN		1,5Ø FT/MIN
1ØØØ,Ø	QG =	789,2	QG =	789,2	QG =	789,2	QG =	789,2
	QP =	35,2	QP =	35,2	QP =	35,2	QP =	35,2
	PA =	183,4	PA =	17Ø,4	PA =	157,7	PA =	145,2
	PB =	4Ø5,Ø	PB =	4Ø5,Ø	PB =	4Ø5,Ø	PB =	4Ø5,Ø
2ØØØ,Ø	QG =	785,7	QG =	794,3	QG =	8Ø1,9	QG =	8Ø9,6
	QP =	47,4	QP =	49,2	QP =	5Ø,9	QP =	52,9
	PA =	76,5	PA =	75,6	PA =	73,6	PA =	76,2
	PB =	46Ø,9	PB =	469,7	PB =	478,2	PB =	487,7
3ØØØ,Ø	QG =	888,5	QG =	898,1	QG =	9Ø5,1	QG =	911,Ø
	QP =	62,6	QP =	66,2	QP =	69,8	QP =	74,2
	PA =	7Ø,5	PA =	68,1	PA =	61,9	PA =	63,2
	PB =	577,3	PB =	594,8	PB =	611,3	PB =	63Ø,7
4ØØØ,Ø	QG =	99Ø,2	QG =	998,7	QG =	1ØØ6,8	QG =	1Ø12,7
	QP =	8Ø,2	QP =	85,4	QP =	91,Ø	QP =	95,2
	PA =	59,7	PA =	53,4	PA =	56,8	PA =	5Ø,8
	PB =	727,9	PB =	757,9	PB =	791,Ø	PB =	818,1

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 35

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 12.50 IN
ID 3.75 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	774.5	QG =	762.0	QG =	752.1	QG =	746.0
	QP =	74.6	QP =	74.9	QP =	80.4	QP =	83.9
	PA =	53.6	PA =	45.5	PA =	45.2	PA =	40.6
	PB =	205.0	PB =	205.0	PB =	205.0	PB =	205.0
2000.0	QG =	922.9	QG =	940.4	QG =	959.5	QG =	968.7
	QP =	129.9	QP =	137.0	QP =	147.0	QP =	152.9
	PA =	33.3	PA =	31.1	PA =	34.3	PA =	27.9
	PB =	293.1	PB =	304.1	PB =	318.7	PB =	327.1
3000.0	QG =	1160.2	QG =	1180.6	QG =	1195.9	QG =	1209.4
	QP =	191.5	QP =	201.8	QP =	209.6	QP =	217.3
	PA =	29.5	PA =	31.3	PA =	28.9	PA =	27.3
	PB =	452.1	PB =	475.9	PB =	494.9	PB =	514.1
4000.0	QG =	1383.0	QG =	1399.5	QG =	1411.8	QG =	1420.3
	QP =	233.0	QP =	243.0	QP =	252.5	QP =	261.8
	PA =	31.8	PA =	30.9	PA =	29.2	PA =	27.3
	PB =	637.4	PB =	669.3	PB =	700.7	PB =	731.6

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 36

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 12.50 IN
ID 3.75 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	1216.9	QG =	1216.9	QG =	1216.9	QG =	1216.9
	QP =	65.2	QP =	65.2	QP =	65.2	QP =	65.2
	PA =	155.5	PA =	146.7	PA =	138.2	PA =	129.9
	PB =	305.0	PB =	305.0	PB =	305.0	PB =	305.0
2000.0	QG =	1136.3	QG =	1158.8	QG =	1179.1	QG =	1196.9
	QP =	93.9	QP =	97.7	QP =	101.4	QP =	105.0
	PA =	59.3	PA =	59.2	PA =	58.1	PA =	56.0
	PB =	329.1	PB =	338.5	PB =	347.5	PB =	355.8
3000.0	QG =	1352.5	QG =	1382.8	QG =	1403.5	QG =	1422.5
	QP =	127.3	QP =	135.4	QP =	142.3	QP =	150.1
	PA =	55.3	PA =	51.6	PA =	46.1	PA =	42.7
	PB =	436.3	PB =	455.4	PB =	470.8	PB =	487.5
4000.0	QG =	1574.2	QG =	1606.1	QG =	1628.3	QG =	1651.7
	QP =	167.8	QP =	180.0	QP =	189.0	QP =	198.5
	PA =	43.2	PA =	46.1	PA =	42.0	PA =	43.7
	PB =	582.6	PB =	616.7	PB =	643.3	PB =	673.3

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 37

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 12.50 IN
ID 3.75 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG = 1649.6	QG = 1649.6	QG = 1649.6	QG = 1649.6
	QP = 56.8	QP = 56.8	QP = 56.8	QP = 56.8
	PA = 247.5	PA = 239.0	PA = 230.7	PA = 222.6
	PB = 405.0	PB = 405.0	PB = 405.0	PB = 405.0
2000.0	QG = 1491.8	QG = 1480.1	QG = 1465.7	QG = 1449.4
	QP = 74.3	QP = 73.7	QP = 77.9	QP = 82.6
	PA = 98.3	PA = 90.8	PA = 85.5	PA = 80.7
	PB = 405.0	PB = 405.0	PB = 405.4	PB = 405.0
3000.0	QG = 1555.1	QG = 1591.7	QG = 1616.7	QG = 1643.8
	QP = 100.3	QP = 105.3	QP = 109.1	QP = 113.7
	PA = 74.1	PA = 77.2	PA = 71.1	PA = 69.5
	PB = 462.5	PB = 484.9	PB = 497.4	PB = 511.0
4000.0	QG = 1763.0	QG = 1799.3	QG = 1831.7	QG = 1857.1
	QP = 125.1	QP = 132.2	QP = 140.0	QP = 147.8
	PA = 67.1	PA = 64.0	PA = 62.0	PA = 57.3
	PB = 578.6	PB = 601.3	PB = 624.9	PB = 647.1

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 38

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 12.50 IN
ID 4.76 IN

DRILLING RATE

DEPTH FT	0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN	
1000.0	QG =	698.7	QG =	705.7	QG =	714.4	QG =	724.2
	QP =	74.5	QP =	76.7	QP =	78.9	QP =	81.5
	PA =	47.9	PA =	45.8	PA =	44.1	PA =	44.4
	PB =	206.2	PB =	209.6	PB =	213.4	PB =	217.8
2000.0	QG =	908.6	QG =	925.4	QG =	939.8	QG =	951.0
	QP =	119.4	QP =	126.6	QP =	134.4	QP =	142.3
	PA =	35.9	PA =	34.8	PA =	34.2	PA =	32.5
	PB =	310.3	PB =	322.4	PB =	334.9	PB =	347.0
3000.0	QG =	1134.2	QG =	1150.1	QG =	1162.0	QG =	1173.5
	QP =	173.1	QP =	182.7	QP =	190.2	QP =	197.9
	PA =	34.2	PA =	32.8	PA =	28.0	PA =	26.2
	PB =	469.2	PB =	492.0	PB =	510.7	PB =	530.5
4000.0	QG =	1342.1	QG =	1356.6	QG =	1366.6	QG =	1373.2
	QP =	208.2	QP =	217.9	QP =	227.3	QP =	237.7
	PA =	32.0	PA =	30.1	PA =	27.3	PA =	27.8
	PB =	646.8	PB =	679.0	PB =	710.7	PB =	746.4

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 39

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 12.50 IN
ID 4.78 IN

DRILLING RATE

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	1118.4	QG =	1118.4	QG =	1118.4	QG =	1118.4
	QP =	65.8	QP =	65.8	QP =	65.8	QP =	65.8
	PA =	143.9	PA =	139.2	PA =	129.6	PA =	120.4
	PB =	305.0	PB =	305.0	PB =	305.0	PB =	305.0
2000.0	QG =	1128.9	QG =	1145.9	QG =	1161.7	QG =	1178.9
	QP =	88.2	QP =	91.4	QP =	94.5	QP =	98.3
	PA =	65.9	PA =	62.0	PA =	57.3	PA =	56.8
	PB =	353.5	PB =	361.7	PB =	369.5	PB =	378.6
3000.0	QG =	1329.8	QG =	1356.0	QG =	1376.3	QG =	1394.1
	QP =	116.5	QP =	123.7	QP =	130.6	QP =	138.4
	PA =	51.0	PA =	50.5	PA =	46.7	PA =	44.5
	PB =	460.7	PB =	479.1	PB =	496.2	PB =	514.3
4000.0	QG =	1541.6	QG =	1566.9	QG =	1589.5	QG =	1607.1
	QP =	151.1	QP =	161.5	QP =	172.2	QP =	181.2
	PA =	47.2	PA =	44.1	PA =	45.6	PA =	44.0
	PB =	606.9	PB =	637.5	PB =	670.3	PB =	699.3

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 40

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 5.50 IN　　HOLE SIZE 12.50 IN
ID 4.78 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
1000.0	QG =	1520.6	QG =	1520.6	QG =	1520.6	QG =	1520.6
	QP =	55.0	QP =	55.0	QP =	55.0	QP =	55.0
	PA =	234.6	PA =	225.2	PA =	216.0	PA =	207.1
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	1350.6	QG =	1374.7	QG =	1388.7	QG =	1408.1
	QP =	70.7	QP =	74.5	QP =	76.4	QP =	79.0
	PA =	92.7	PA =	88.9	PA =	81.9	PA =	81.9
	PB =	410.0	PB =	415.1	PB =	421.0	PB =	429.3
3000.0	QG =	1541.5	QG =	1569.7	QG =	1594.0	QG =	1618.7
	QP =	93.7	QP =	97.8	QP =	101.8	QP =	106.6
	PA =	80.2	PA =	78.2	PA =	73.9	PA =	73.7
	PB =	501.4	PB =	515.9	PB =	529.3	PB =	544.2
4000.0	QG =	1736.1	QG =	1769.8	QG =	1800.0	QG =	1823.1
	QP =	114.9	QP =	121.9	QP =	129.6	QP =	137.3
	PA =	69.4	PA =	69.1	PA =	69.0	PA =	65.1
	PB =	612.0	PB =	636.8	PB =	662.2	PB =	686.2

QG　AIR VOLUME　SCF/MIN
QP　LIQUID VOLUME　GAL/MIN
PA　SURFACE ANNULUS PRESSURE　PSIA
PB　BOTTOM HOLE PRESSURE　PSIA

TABLE 41

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200. PSIA

PIPE SIZE OD 4.50 IN HOLE SIZE 15.00 IN
ID 3.75 IN

DEPTH FT	DRILLING RATE 0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG = 1195.5	QG = 1195.5	QG = 1195.5	QG = 1195.5
	QP = 112.3	QP = 112.3	QP = 112.3	QP = 112.3
	PA = 83.6	PA = 75.5	PA = 67.5	PA = 59.8
	PB = 205.0	PB = 205.0	PB = 205.0	PB = 205.0
2000.0	QG = 1329.5	QG = 1339.4	QG = 1373.1	QG = 1396.3
	QP = 175.3	QP = 183.8	QP = 195.1	QP = 204.5
	PA = 36.0	PA = 33.5	PA = 34.6	PA = 31.8
	PB = 267.3	PB = 277.1	PB = 289.4	PB = 299.0
3000.0	QG = 1666.4	QG = 1745.9	QG = 1732.3	QG = 1754.9
	QP = 260.4	QP = 278.6	QP = 291.7	QP = 323.0
	PA = 30.0	PA = 31.5	PA = 28.4	PA = 24.9
	PB = 407.1	PB = 432.8	PB = 451.7	PB = 469.1
4000.0	QG = 2014.7	QG = 2044.0	QG = 2068.2	QG = 2094.3
	QP = 332.3	QP = 345.6	QP = 358.5	QP = 375.9
	PA = 34.1	PA = 30.8	PA = 27.5	PA = 30.8
	PB = 593.6	PB = 618.1	PB = 645.0	PB = 682.9

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 42

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 4.50 IN · ID 3.75 IN — HOLE SIZE 15.00 IN

DEPTH FT		0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
		DRILLING RATE			
1000.0	QG =	1856.8	1856.8	1856.8	1856.8
	QP =	90.3	90.3	90.3	90.3
	PA =	176.9	169.1	161.4	154.0
	PB =	305.0	305.0	305.0	305.0
2000.0	QG =	1644.0	1633.6	1668.8	1703.4
	QP =	122.7	131.4	137.0	142.6
	PA =	60.4	59.8	58.4	59.2
	PB =	305.0	310.3	318.6	328.3
3000.0	QG =	1910.3	1965.6	2010.0	2046.0
	QP =	170.7	181.0	190.7	200.0
	PA =	50.9	52.3	50.6	46.9
	PB =	395.8	413.8	429.9	444.6
4000.0	QG =	2253.0	2306.8	2348.3	2392.2
	QP =	224.6	240.6	254.9	271.6
	PA =	48.6	46.6	42.2	43.4
	PB =	525.0	553.9	579.8	611.0

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 43

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400, PSIA

PIPE SIZE OD 4,50 IN   HOLE SIZE 15,00 IN
ID 3,75 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN		0,50 FT/MIN		1,00 FT/MIN		1,50 FT/MIN
1000,0	QG =	2505,6	QG =	2505,6	QG =	2505,6	QG =	2505,6
	QP =	78,7	QP =	78,7	QP =	78,7	QP =	78,7
	PA =	270,9	PA =	263,0	PA =	255,4	PA =	247,9
	PB =	405,0	PB =	405,0	PB =	405,0	PB =	405,0
2000,0	QG =	2318,0	QG =	2300,7	QG =	2288,2	QG =	2267,8
	QP =	85,0	QP =	90,0	QP =	93,6	QP =	99,5
	PA =	125,6	PA =	119,6	PA =	110,3	PA =	105,4
	PB =	405,0	PB =	405,0	PB =	405,0	PB =	405,0
3000,0	QG =	2184,4	QG =	2240,3	QG =	2292,6	QG =	2339,8
	QP =	135,2	QP =	141,4	QP =	147,7	QP =	153,7
	PA =	73,7	PA =	74,5	PA =	74,4	PA =	72,9
	PB =	426,9	PB =	441,9	PB =	456,5	PB =	470,0
4000,0	QG =	2499,5	QG =	2562,5	QG =	2611,4	QG =	2669,1
	QP =	169,2	QP =	177,7	QP =	185,0	QP =	196,7
	PA =	73,7	PA =	69,2	PA =	62,4	PA =	62,7
	PB =	528,5	PB =	548,7	PB =	567,0	PB =	590,2

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 44

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 200, PSIA

PIPE SIZE OD 5,50 IN HOLE SIZE 15,00 IN
ID 4,78 IN

DEPTH FT		DRILLING RATE 0,00 FT/MIN	0,50 FT/MIN	1,00 FT/MIN	1,50 FT/MIN
1000,0	QG =	1127,8	1127,8	1127,8	1093,9
	QP =	106,8	106,8	106,8	105,7
	PA =	74,3	65,3	56,3	48,6
	PB =	205,0	205,0	205,0	205,0
2000,0	QG =	1323,9	1352,1	1384,6	1407,0
	QP =	161,7	169,3	179,6	188,0
	PA =	40,8	37,7	39,0	36,0
	PB =	281,4	291,0	303,2	312,8
3000,0	QG =	1667,8	1702,7	1736,4	1758,5
	QP =	229,6	245,2	262,9	275,7
	PA =	33,4	31,3	33,2	29,9
	PB =	412,2	434,4	460,0	479,3
4000,0	QG =	2006,4	2036,1	2063,9	2086,8
	QP =	294,8	308,5	321,9	337,0
	PA =	34,4	32,2	29,3	29,4
	PB =	586,5	615,4	643,6	676,3

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

TABLE 45

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 300. PSIA

PIPE SIZE OD 5.50 IN HOLE SIZE 15.00 IN
ID 4.78 IN

DEPTH FT		DRILLING RATE 0.00 FT/MIN	0.50 FT/MIN	1.00 FT/MIN	1.50 FT/MIN
1000.0	QG =	1756.2	1756.2	1756.2	1756.2
	QP =	88.2	88.2	88.2	88.2
	PA =	169.3	160.9	152.7	144.7
	PB =	305.0	305.0	305.0	305.0
2000.0	QG =	1628.8	1664.6	1690.3	1720.9
	QP =	119.5	124.6	128.4	133.4
	PA =	67.8	67.9	62.6	62.3
	PB =	321.8	331.3	338.2	347.2
3000.0	QG =	1939.9	1982.5	2025.2	2060.3
	QP =	158.9	166.4	175.2	183.6
	PA =	62.0	57.5	55.8	51.9
	PB =	419.4	434.0	450.0	464.7
4000.0	QG =	2258.9	2315.0	2359.4	2400.2
	QP =	200.3	214.7	228.9	244.8
	PA =	53.7	52.8	49.7	49.7
	PB =	539.2	567.8	595.0	625.4

QG	AIR VOLUME	SCF/MIN
QP	LIQUID VOLUME	GAL/MIN
PA	SURFACE ANNULUS PRESSURE	PSIA
PB	BOTTOM HOLE PRESSURE	PSIA

TABLE 46

AIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING

SURFACE INJECTION PRESSURE 400. PSIA

PIPE SIZE OD 5.50 IN   HOLE SIZE 15.00 IN
ID 4.78 IN

DEPTH FT		0.00 FT/MIN		0.50 FT/MIN		1.00 FT/MIN		1.50 FT/MIN
				DRILLING RATE				
1000.0	QG =	2377.4	QG =	2377.4	QG =	2377.4	QG =	2377.4
	QP =	77.1	QP =	77.1	QP =	77.1	QP =	77.1
	PA =	262.8	PA =	254.4	PA =	246.3	PA =	238.3
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
2000.0	QG =	2181.0	QG =	2164.7	QG =	2147.7	QG =	2126.9
	QP =	87.7	QP =	92.4	QP =	97.3	QP =	103.4
	PA =	115.1	PA =	107.9	PA =	100.8	PA =	95.5
	PB =	405.0	PB =	405.0	PB =	405.0	PB =	405.0
3000.0	QG =	2220.3	QG =	2270.5	QG =	2316.8	QG =	2367.8
	QP =	126.6	QP =	132.1	QP =	137.5	QP =	144.0
	PA =	79.9	PA =	79.3	PA =	77.4	PA =	80.2
	PB =	453.9	PB =	468.3	PB =	481.9	PB =	497.7
4000.0	QG =	2524.5	QG =	2581.9	QG =	2639.4	QG =	2686.8
	QP =	155.9	QP =	163.5	QP =	172.2	QP =	180.6
	PA =	80.9	PA =	75.4	PA =	73.6	PA =	68.8
	PB =	555.7	PB =	575.5	PB =	597.1	PB =	616.8

QG AIR VOLUME SCF/MIN
QP LIQUID VOLUME GAL/MIN
PA SURFACE ANNULUS PRESSURE PSIA
PB BOTTOM HOLE PRESSURE PSIA

APPENDIX A

NOMENCLATURE

ENGLISH SYMBOLS

A	annular flow area, ft^2
A_i	pipe flow area, ft^2
d	differential calculus operator
D_i	inside annulus diameter, in
D_o	outside pipe diameter, in
E	slot lateral extent, in
g	gravitational constant $\frac{32.2\ Lbm\ ft}{Lbf\ sec^2}$
H	enthalpy
L	incremental pipe length, ft
M	mass rate of flow, Lbm/sec
n -	Bingham plastic fluid power coefficient
P	static pressure head, psi
p	pressure, psi
Q -	volume flow rate, ft^3/sec
R -	inside radius of pipe, in
Re	Reynolds number
r	point of differentiation and integration
V	average velocity of flow, ft/sec
Vol -	volume, ft^3
W	slot width extent, in

GREEK SYMBOLS

γ - specific weight, lb_f/ft^3

Γ - quality of foam

μ_e - effective viscosity, cps of lbm-ft/sec

μ_p dynamic plastic viscosity, cps of $\frac{\text{Lbm-ft}}{\text{sec}}$

ϕ - shear rate, sec^{-1}

ρ - flowing density, Lbm/ft^3

$\Phi(\tau)$ assumed function of shear stress

τ - shear stress, psi or lb_f/ft^2

τ_y yield shear stress, psi or lb_f/ft^2

θ angle of investigation

SUBSCRIPTS

a air

h lateral point in slot

i ith iteration

n - total number of iterations

r rock

s standard conditions: 14.7 psia and 60°F

t - total

w - water

x vertical point in slot

z - depth of the midpoint of the L_i iteration

APPENDIX B

BINGHAM PLASTIC MODEL - FLOW DOWN THE PIPE

The derivation of the Bingham Plastic fluid flow equation (Bird, et al., 1969, p. 48-50) is based upon the following assumptions:

1. Isothermal, steady-state, incompressible flow through a circular pipe.
2. Shear rate is proportional to the excess of the shearing stress (τ) over a certain constant yield value (τ_y), below which the material has a zero shear rate.
3. No slippage exists at the pipe wall.
4. Fluid is in laminar and plug flow.

Consider now the steady laminar flow of a constant fluid density (ρ) in very long tube of length (L) and inside radius of R. A very long tube is specified because no "end effects" will be considered.

A momentum balance is now written for a cylindrical shell of thickness Δr and length L (see Fig. 8). The various contributions to the momentum balance in the z-direction are

Rate of momentum in across cylindrical surface at r	$(2\pi r L \tau_{rz})\Big|_r$	1B-1
rate of momentum out across cylindrical surface at r+Δr	$-(2\pi r L \tau_{rz})\Big|_{r+\Delta r}$	1B-2
gravity force acting on cylindrical shell	$(2\pi r \Delta r L)\rho$	1B-3
pressure force acting on annular surface at z=0	$(2\pi r \Delta r)p_0$	1B-4

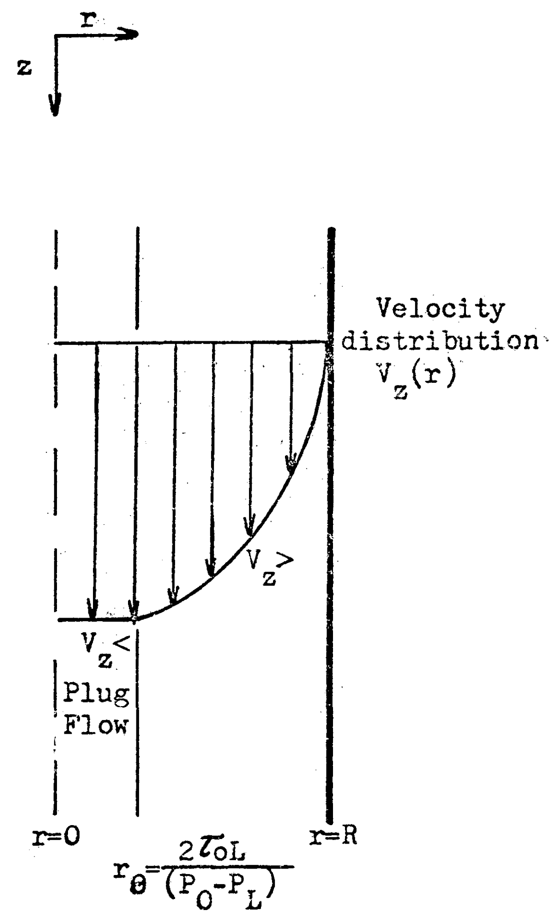


FIGURE: 8
FLOW OF A BINGHAM FLUID IN A CIRCULAR TUBE

(Bird, et al., 1964, p. 49)

pressure force acting on annular surface at z=L $\qquad -(2\pi r\Delta r)p_L \qquad$ 1B-5

where τ_{rz} = shear stress at depth z and at a pipe radius of r.

Now adding all contributions to the momentum balance

$$(2\pi rL\tau_{rz})\Big|_r \quad (2\pi rL\tau_{rz})\Big|_{r+\Delta r} + 2\pi r\Delta rL\rho g +$$

$$2\pi r\Delta rp_0 \quad 2\pi r\Delta rp_L = 0 \qquad \text{1B}$$

Dividing Eq. (1B) by $2\pi L\Delta r$ and taking the limit as Δr approaches zero results in

$$\lim_{\Delta r \to 0} \frac{(r\tau_{rz})\Big|_r \quad (r\tau_{rz})\Big|_{r+\Delta r}}{\Delta r} = \left[\frac{P_0 - P_L}{L} + \rho g\right] r \qquad \text{2B}$$

Since the left side is the definition of the first derivative, Eq. (2B) may be written as

$$\frac{d}{dr}(r\tau_{rz}) = \left[\frac{P_0 \quad P_L}{L}\right] r \qquad \text{3B}$$

where P represents the combined effect of the gravity force and the static pressure. ($P = p \quad \rho gz$) where z is measured positive downwards in the direction of gravity.

Eq. (3B) may be integrated to give

$$\tau_{rz} = \frac{(P_0 \quad P_L)r}{2L} + \frac{c_1}{r} \qquad \text{4B}$$

At r = 0, c_1 must equal zero if the shear stress is not to be infinite. The shear stress is therefore equal to

$$\tau_{rz} = \left[\frac{P_0 \quad P_L}{2L}\right] r \qquad \text{5B}$$

The shear stress for a Bingham plastic fluid is

$$\tau_y - \tau_{rz} = \frac{\mu_p dV_z}{dr} \qquad 6B$$

The velocity gradient is zero when the shear stress is less than the value τ_y. A "plug-flow" region in the central part of the tube exists. Outside the plug-flow region the shear stress and velocity gradient will be defined by Eq. (6B).

Substitution of Eq. (5B) into Eq. (6B) results in a first-order differential equation:

$$\tau_y \quad \frac{\mu_p dV_z}{dr} = \left[\frac{P_0 \quad P_L}{2L}\right] r \qquad 7B$$

Integrating Eq. (7B)

$$V_z = \frac{-(P_0 \quad P_L)r^2}{4\mu_p L} + \frac{\tau_y r}{\mu_p} + c_2 \qquad 8B$$

The constant c_2 is evaluated with the boundary conditions:

$V_z = 0$

at $r = R$

Eq. (8B) becomes

$$^{*} \; V_z^{>} = \left[\frac{P_0 \quad P_L}{4\mu_p L}\right] R^2 \left[1 \quad (\frac{r}{R})^2\right] \quad \frac{\tau_y R}{\mu_p} \quad \left[1 \quad \frac{r}{R}\right] \qquad 9B\text{-}1$$

for $r \geq r_o$

$$V_z^{<} = \left[\frac{P_0 \quad P_L}{4\mu_p L}\right] R^2 \left[1 \quad \frac{r_0}{R}\right]^2 \qquad 9B\text{-}2$$

*Following the nomenclature of Bird, et al.

for $r \leq r_0$

where V_z = velocity in laminar flow region

V_z = velocity in plug-flow region

where r_0 is the radius of the plug-flow region defined by

$$\tau_y = \left[\frac{P_0 \quad P_L}{2L}\right] r_0$$

The volume rate of flow Q may be calculated from

$$Q = \int_0^{2\pi} \int_0^R V_z r dr d\theta$$

where θ = angle of investigation

$$Q = 2\pi \int_0^{r_0} V_z^< \, dr + 2\pi \int_{r_0}^R V_z^> \, dr \qquad \text{10B}$$

Integrating Eq. (10B) results in

$$Q = 2\pi \left[\tfrac{1}{2} r^2 V_z \Big|_0^R \quad \tfrac{1}{2} \int_0^R \frac{dV_z}{dr} \quad r^2 dr \right] \qquad \text{11B}$$

$r^2 V_z$ is zero for both integration limits and the lower limit of the integral may be replaced by r_0 since $\frac{dV_z}{dr} = 0$ for $r \leq r_0$

Hence the volume rate of flow is, if $\tau_R > \tau_y$

$$Q = \pi \int_{r_0}^R \left[- \frac{dV_z^>}{dr} \right] r^2 dr \qquad \text{12B}$$

$$= \pi \int_{r_0}^{R} \left[\left[\frac{P_0 - P_L}{2\mu_p L} \right] r \quad \frac{\tau_y}{\mu_p} \right] r^2 dr \qquad \text{13B}$$

Performing the integration and using the symbol τ_R, for the shear stress at the pipe wall, $(P_0 \quad P_L)R$, Eq. (13B) becomes

$$Q = \pi \frac{(P_0 - P_L)R^4}{8\mu_p L} \left[1 \quad \frac{4}{3} \frac{\tau_y}{\tau_R} + \frac{1}{3} \left[\frac{\tau_y}{\tau_R} \right]^4 \right] \qquad \text{14B}$$

which is the Buckingham-Reiner equation for a Bingham plastic model.

Eq. (14B) is Eq. (3) in the text, chapter three, page 11.

APPENDIX C

BINGHAM PLASTIC MODEL FLOW UP THE ANNULUS

Melrose and his associates (1958, p. 316) have shown that isothermal, laminar flow of a Bingham model fluid within a concentric circular annulus could be approximated by the equation which applies to laminar flow in a narrow slot.

The same assumptions are used as in the derivation given in Appendix B for pipe flow. For the system shown in Figure 9, where the lateral extent, E, is assumed to be much greater than the width, W, (for the calculated pipe and hole combinations, E/W has a range of 6.66 to 20.8) the general flow equation for slot flow can be written as (Craft, et al., 1962, p. 42)

$$Q = \frac{EW^2}{2(\tau_w)^2} \int_0^{\tau_w} \Phi(\tau)\ \tau_{hx}\ d\ \tau_{hx} \qquad \text{1C}$$

where E = slot lateral extent

W = slot width extent

$\Phi(\tau)$ = assumed function of shear stress

τ_{hx} = shear stress at slot width of h and depth of x

Substituting VEW for the volumetric flow rate Q, the general equation becomes

$$\frac{V}{W} = \frac{1}{2(\tau_w)^2} \int_0^{\tau_w} \tau_{hx}\ \Phi(\tau)\ d\ \tau_{hx} \qquad \text{2C}$$

where τ_{hx} = shear stress in the slot at point hx.

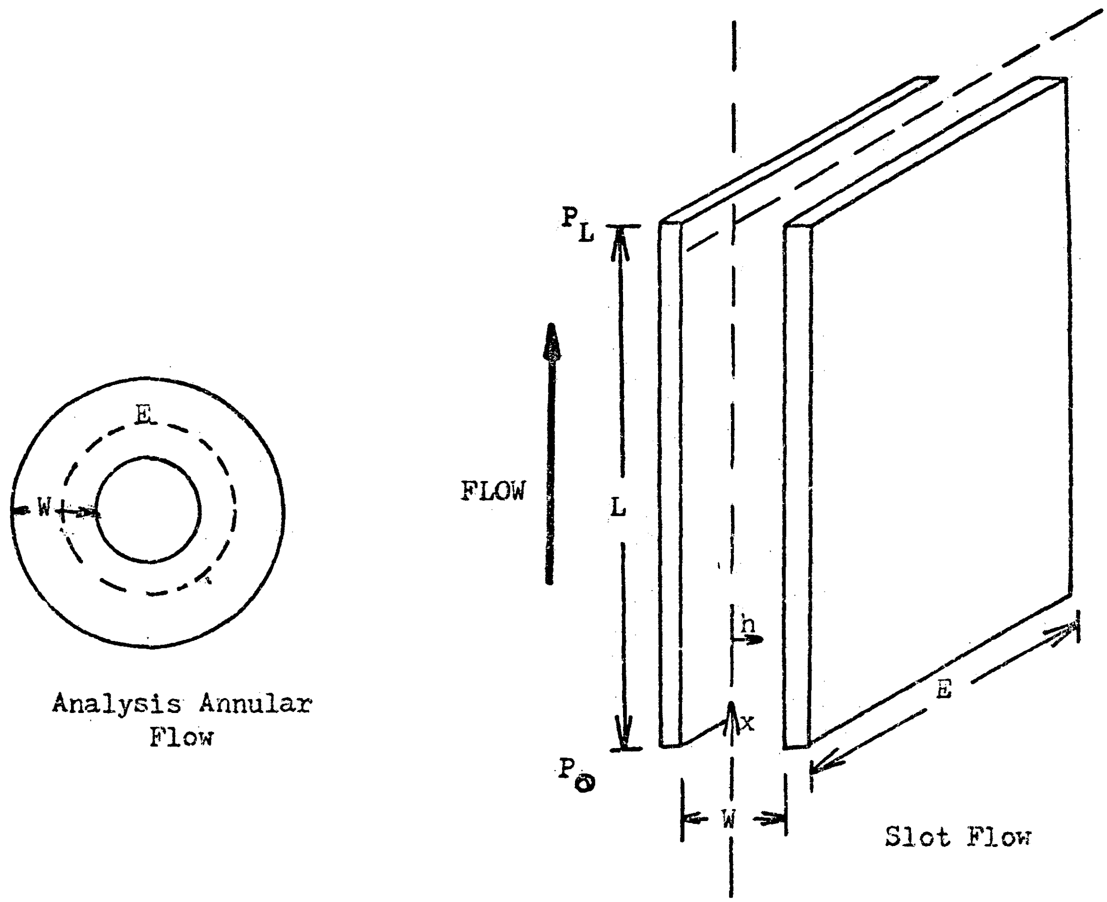


FIGURE: 9
RECTILINEAR FLOW BETWEEN FIXED
PARALLEL PLATES

(after Craft, et al., 1962, p. 42)

The shear stress at either wall of the slot is

$$\tau_w = \frac{(P_0 - P_L)W}{2L} \qquad 3C$$

where p = p + ρgL.

The functional dependence of shear rate upon shear stress, $\Phi(\tau)$, for a Bingham plastic fluid is

$$\Phi(\tau) = \frac{\tau \quad \tau_y}{\mu_p} \qquad 4C$$

Substituting Eqs. (3C) and (4C) into Eq. (2C) and integrating results in

$$\frac{6V}{W} = \frac{\tau_w}{\mu_p}\left[1 \quad \frac{3\tau_y}{2\tau_w} + \frac{1}{2}\left[\frac{\tau_y}{\tau_w}\right]^3\right] \qquad 5C$$

or in terms of a volumetric flow rate, Q,

$$Q = \frac{EW^2\,\tau_w}{6\mu_p}\left[1 \quad \frac{3\tau_y}{2\tau_w} + \frac{1}{2}\left[\frac{\tau_y}{\tau_w}\right]^3\right] \qquad 6C$$

Eq. (6C) is Eq. (25) in the text, Chapter three, page 19.

```
C
C
C
C                              APPENDIX D
C
C        PROGRAM "FOAM" CALCULATES THE REQUIRED
C        AIR AND LIQUID VOLUME RATES FOR A
C        FOAM DRILLING OPERATION
C
C
C
C        THIS PROGRAM BELONGS TO JACK A. KRUG
C
C        PETROLEUM ENGINEERING DEPARTMENT
C
C
C
$FTRAN MAIN
      COMMON VEL1(200),GAMMA1(200)
      COMMON KN,TAUY,Z2FLAG
      COMMON IDP,ODP,IDA,QG,PSPG,PSPP,DENL,DENG,DEPTH
      COMMON QGX,VM,MRATE,GAMMA,QT,X,DELPRF,PX,VEL,AREA,RE,F,Z
      COMMON K,FLAG,MUL,PXP,PXA
      COMMON QF,DEN,MU,PSA,ZFLAG
      COMMON L,DRLRTE,N,PB1(8,5),BP(200)
       COMMON QG1(8,5),QP1(8,5),PA1(8,5)
      REALMRATE,MU,IDP,ODP,IDA,L
      REAL MUL,MUTEMP,MROCK
C
C         NOMENCLATURE OF TERMS
C
C         AREA      FLOW AREA                                 INCHES**2
C         BP        BOTTOM HOLE PRESSURE                      PSIA
C         DELPRF    PRESSURE DROP DUE TO FRICTION             PSIA
C         DEN       DENSITY AT X                              LB/GAL
C         DRLRTE    DRILLING RATE                             FT/MIN
C         F         MOODY FRICTION FACTOR
C         GAMMA     QUALITY AT X
C         EMU       EFFECTIVE VISCOSITY                       CENTIPOISE
C         IDA       HOLE SIZE                                 IN**2
C         IDP       INSIDE DIAMETER OF PIPE                   IN
C         MRATE     MASS RATE OF FLOW                         LB/MIN
C         MU        PLASTIC VISCOSITY                         CENTIPOISE
C         MUL       LIQUID VISCOSITY                          CENTIPOISE
C         ODP       OUTSIDE DIAMETER OF PIPE                  IN
C         PSC       PRESSURE AT STANDARD CONDITIONS           PSIA
C         PX        PRESSURE AT X                             PSIA
C         PXA       ANNULUS PRESSURE AT X                     PSIA
C         PXP       PIPE PRESSURE AT X                        PSIA
C         QG        COMPRESSOR FLOW RATE(GAS)                 SCF/MIN
C         QGX       GAS FLOW RATE AT X                        SCF/MIN
C         QF        PUMP FLOW RATE(LIQUID)                    GPM
C         QT        TOTAL FLOW RATE AT X                      GPM
C         RE        REYNOLDS NUMBER
C         TAUY      BINGHAM YIELD STRESS                      LB/FT**2
C         TSC       TEMPERATURE AT STANDARD CONDITIONS        RANKINE
C         TX        TEMPERATURE AT X                          RANKINE
C         VM        VOLUME FLOW RATE AT X                     GPM
C         X         INCREMENTAL DISTANCE FROM THE TOP         FEET
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C * * READ ALL DATA
C * * PIPE DATA
C
      IDA=4,75
      ODP=2,87
      IDP=2,44
C
C * * COMPRESSOR OUTPUT(SCF/MIN) AND PRESSURE(PSIA)
C
C      COMPRESSOR AND PUMP VALUES ARE INITIALIZED FOR
C      FIRST TRIAL AND ERROR ITERATION
C        LIQUID DENSITY IS ASSUMED TO BE 1,0
C        GAS DENSITY IS ASSUMED TO BE 1,0
     DENL=1,0
     DENG=1,0
        QP=40,28
        QG=411,36
      DO 450 IPRESS=200,400,100
      DO 410 IDEP=1,4
       DO 410 IRTE=1,4
      DEPTH = FLOAT(IDEP)*1000,
      DPURTE = (FLOAT(IRTE)-1,)*,5
      PSPP = FLOAT(IPRESS)
     PSPG=PSPP
     K=1
     IFLAG=1
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C      TUBING PRESSURE CALCULATION       Z=1
C      ANNULUS PRESSURE CALCULATION      Z=2
50     CONTINUE
        FLAG=0,0
      PXA=5,0
     DELPRF = PXA
     Z2FLAG=1,0
     Z=1,
     F=0,
     ZFLAG=0,0
     CALL BHP
C
C      TRIAL AND ERROR SOLUTION FOR AIR AND WATER
C     QUANTITIES,.........CONDITIONS FOR CORRECT
C      SOLUTION
C        BOTTOM ANNULUS VELOCITY ...........      1,5 FPS
C        SURFACE ANNULUS QUALITY ...........       ,95
C
     IF(Z,GT,1,2)GO TO 70
     QP=QP*1,15
     GO TO 50
  70 CONTINUE
     IF(ABS(VEL1(1)-1,5),LE,0,1,AND,ABS(GAMMA1(KN)-
    10,945),LE,0,02)GO TO 400
     IF(IFLAG,GE,3)GO TO 120
     IF(FLAG,GE,0,99)GO TO 120
     IF(VEL1(1),LE,1.5,AND,GAMMA1(KN),LE,0,96)
    1GO TO 100
     IF(VEL1(1),GT,1.5,AND,GAMMA1(KN),LT,,96)
    1GO TO 100
```

```
      IF(VEL1(1).GT.1.5.AND.GAMMA1(KN).GT..96)
    1 GO TO 110
 80  QG=QG*1.5/VEL1(1)
     QP=QP*1.5/VEL1(1)
     GO TO 50
100  QP=QP*(1.5/VEL1(1))
     QG=QG*(1.5/VEL1(1))*(0.965/GAMMA1(KN))
     GO TO 50
110  QP=QP*(GAMMA1(KN)/0.955)
     QG=QG*(0.955/GAMMA1(KN))
     GO TO 50
120  IFLAG=4
     IF(GAMMA1(KN).GE.0.94)GO TO 140
      IF(ABS(1.50-VEL1(1)).LT.0.04)GO TO 160
      QP=QP/1.0005
      QP=QP*1.5/VEL1(1)
     QG=QG*1.5/VEL1(1)
      K=10

3      FORMAT(4F12.2)
     GO TO 50
140  IF(K.GE.5)GO TO 150
      QP=QP*1.005*(1.5/VEL1(1))
     QG=QG*1.5/VEL1(1)
     GO TO 50
150  QP=QP*1.0005
     GO TO 50
160  QP=QP/1.0001
     GO TO 50
C
C      PRINT THE ARRAY RESULTS
400  CONTINUE
     HHP=PSPG*(QG*7.48 + QP)/1714.
     PRINT 1,QP,QG,PSA,BP(1),DEPTH,DRLRTE,GAMMA1(KN),VEL1(1),HHP
```

```
       FORMAT(4F9.2,F7.0,3F7.3,F9.2)
           QG1(IDEP,IRTE)=QG
           PB1(IDEP,IRTE)=BP(1)
           QP1(IDEP,IRTE)=QP
           PA1(IDEP,IRTE)=PSA
 410  CONTINUE
      CALL OUTPUT
      DO 420 ID=1,8
      DO 420 IF=1,5
      QG1(ID,IF)=0.0
      QP1(ID,IF)=0.0
      PA1(ID,IF)=0.0
      PB1(ID,IF)=0.
 420  CONTINUE
 450  CONTINUE
 500  STOP
      END
$FTRAN BHP
      SUBROUTINE BHP
C
C      SUBROUTINE BHP CALCULATES THE BOTTOM-HOLE PRESSURE IN THE
C      TUBING AND ANNULUS ,...,IT USES AN ITERATIVE CELL TYPE
C      OF APPROACH
C
C               Z= 1       TUBING CALCULATION
C               Z= 2       ANNULUS CALCULATION
      COMMON VEL1(200),GAMMA1(200)
      COMMON KN,TAUY,Z2FLAG
      COMMON IDP,ODP,IDA,QG,PSPG,PSPP,DENL,DENG,DEPTH
      COMMON QGX,VM,MRATE,GAMMA,QT,X,DELPRF,PX,VEL,AREA,RE,F,Z
      COMMON K,FLAG,MUL,PXP,PXA
      COMMON QP,DEN,MU,PSA,ZFLAG
      COMMON L,DRLRTE,N,PB1(8,5),BP(200)
       COMMON QG1(8,5),QP1(8,5),PA1(8,5)
      REALMRATE,MU,IDP,ODP,IDA,L
      REAL MUL,MUTEMP,MROCK
C
C      ROCK MASS RATE CALCULATION POUND PER MINUTE,...THIS CALCULATION
C      ASSUMES THE ROCK TO HAVE A SPECIFIC GRAVITY OF 2,7 (WATER =1,)
C
      MROCK = (IDA**2)*DRLRTE*1,172
C
C      VOLUME RATE OF ROCK DISPLACED,  GALLON PER MINUTE
C
      VOLRCK = 0,0408*(IDA**2)*DRLRTE
      X=0.0
      PX=PSPP
      KN=0
  50  CONTINUE
      PSC=14.7
      TSC=520.
      Z2FLAG = 0.0
      DELPRF = PXA
C
C      TEMPERATURE GRADIENT  ASSUMING AN AMBIENT TEMPERATURE OF 60 F
 100  TX= 0.014*X+60.+460.
C      VOLUME FLOW RATE  GAL/MIN
      QGX=QG*(PSC/TSC)*(TX/(PX + DELPRF/2.))
      IF(Z.EQ.2.)
     1QGX=QG*(PSC/TSC)*(TX/(PX - DELPRF/2.))
```

$\frac{\pi \times di^2}{4 \times 144} \times ft \times 7.4805$

```
      IF(Z2FLAG.EQ.12.)
     1QGX=QG*(PSC/TSC)*(TX/PX)
      VM=QP+7.48*QGX
C
C * * MASS RATE OF FLOW,POUND PER MINUTE
C
      MRATE=8.33*DENL*QP +0.2764*DENG*QGX
C
C      DENSITY CALCULATION FOR AIR AND WATER ONLY  POUND PER GAL
      DEN=MRATE/VM
C
C      DENSITY CORRECTION FOR DRILLING CUTTINGS
      IF(Z.EQ.2.)
     1DEN=(MRATE+MROCK)/(VM+VOLRCK)
C
C      TOTAL VOLUME FLOW RATE  GAL/MIN
      QT=QGX*7.48+QP
C      CORRECTION FOR ROCK VOLUME
      IF(Z.NE.2.)GO TO 103
C
C      HOLE VOLUME   GALLONS
      VOLHOL = (IDA**2 - ODF**2)*0.0408
C
C      VOLUME RATE WITH CUTTINGS   GAL/MIN
      VM = VM + VOLRCK
C
C      AIR + WATER VOLUME RATE   GAL/MIN
      QT = (VOLHOL - (VOLHOL/VM)*VOLRCK)*(VM/VOLHOL)
C
C      QUALITY CALCULATION FOR AIR AND WATER
  103 GAMMA =(QGX*7.48)/QT
C
C      SUBROUTINE VISCTY CALCULATES THE PLASTIC VISCOSITY
C      AND THE YIELD STRESS FOR FOAM
C
      CALL VISCTY
      IF(FLAG.EQ.1..AND.Z.EQ.1.)GO TO 350
      IF(FLAG.EQ.1..AND.Z.EQ.2.)GO TO 405
C
C      SUBROUTINE FRCTN CALCULATES THE PRESSURE DROP AND
C      INCREMENTAL LENGTH
C
      CALL FRCTN
      IF(Z.EQ.1.)X = X + L
      IF(Z.EQ.2.) X = X - L
```

$\frac{\pi \times in^2}{4 \times 144} \times ft \times 7.4805$

```
      FORMAT(F1?,2,3F8,3,F8,?,2F8,2)
      IF(A,EQ,2,)GO TO 122
      PX = PX + DELPRF
      PXP=PX
      ZZ=DEPTH-X
      IF(ZZ)1?8,1?6,1?5
 1?5  IF(ZZ,GE,L)GO TO 10?
      IF(ZZ,GT,2,)GO TO 11?
 1?6  Z=2,
      IF(F,GE,97?,)
     1PRINT 1,X,DEN,GAMMA,VEL,RE,MU,TAUY
      GO TO 5?
 1?8  Z2FLAG=12.?
      X=X-L
      PX=PX-DELPRF
      L=DEPTH-X
      GO TO 12?
 11?  L=ZZ
      KZ=KZ-1
      Z2FLAG = 12,
      GO TO 12?
 12?  CONTINUE
      PX=PX-DELPRF
      PSA = PX
C
C      TRANSFER OF COEFFICIENTS
      KN=KN+1
      BP(KN)=PX+DELPRF
      GAMMA1(KN)=GAMMA
      VEL1(KN)=VEL
      IF(KN,EQ,1,AND,F,GE,97?,)
     1PRINT 1,X,DEN,GAMMA,VEL,RE,MU,TAUY
      IF(X)15?,2??,10?
C
C         RESELECT INITIAL COMPRESSOR AND PUMP VALUES
C         DENSITY MUST BE INCREASED
C         VELOCITY MUST BE DECREASED
 15?  IF(KN,NE,1)GO TO 16?
      GAMMA1(KN)=1,
      VEL1(KN)=1,?
      RETURN
 16?  Z2FLAG=12,
      X=X+L
      L=X
      PX=PX+DELPRF
      KN=KN-1
      GO TO 1?0
 2??  RETURN
 35?  CONTINUE
      KN=1
      GAMMA1(KN)=1,?
      VEL1(1)=2,?
      RETURN
 42?  RETURN
 4?5  GAMMA1(KN)=GAMMA
      VEL1(KN)=VEL
      VEL1(KN)=VEL
      RETURN
      END
SFTRAN OUTPUT
```

```
      SUBROUTINE OUTPUT
      COMMON VEL1(200),GAMMA1(200)
      COMMON KN,TAUY,Z2FLAG
      COMMON IDP,ODP,IDA,QG,PSPG,PSPP,DENL,DENG,DEPTH
      COMMON QGX,VM,MRATE,GAMMA,QT,X,DELPRF,PX,VEL,AREA,RE,F,Z
      COMMON K,FLAG,MUL,PXP,PXA
      COMMON QP,DEN,MU,PSA,ZFLAG
      COMMON L,DRLRTE,N,PB1(8,5),BP(200)
       COMMON QG1(8,5),QP1(8,5),PA1(8,5)
      REALMRATE,MU,IDP,ODP,IDA,L
      REAL MUL,MUTEMP,MROCK
      WRITE(6,10)PSPP,ODP,IDA,IDP
   10 FORMAT(1H1,//////////,41X,
     1 45HAIR AND LIQUID REQUIREMENTS FOR FOAM DRILLING,
     2 //,45X,26HSURFACE INJECTION PRESSURE,F5.0,5H PSIA,
     3 ///,39X,14HPIPE SIZE  OD ,F5.2,3H IN,10X,
     4 10HHOLE SIZE ,F5.2,3H IN,/,50X,3HID ,F5.2,3H IN,
     5 ///,66X,13HDRILLING RATE,/)
      WRITE(6,20)
   20 FORMAT(25X,10HDEPTH   FT,5X,12H 0.00 FT/MIN,5X,
     1 12H 0.50 FT/MIN,5X,12H 1.00 FT/MIN,5X,12H 1.50 FT/MIN)
      DO 100 IDEP=1,4,1
       DEPTH =FLOAT(IDEP)*1000.
       WRITE(6,30)DEPTH,QG1(IDEP,1),QG1(IDEP,2),QG1(IDEP,3),
     1 QG1(IDEP,4)
   30 FORMAT(/,25X,F10.1,4(10H      QG = ,F7.1))
      WRITE(6,40)QP1(IDEP,1),QP1(IDEP,2),QP1(IDEP,3),QP1(IDEP,4)
   40 FORMAT(35X,4(10H      QP = ,F7.1))
      WRITE(6,45)PA1(IDEP,1),PA1(IDEP,2),PA1(IDEP,3),
     1 PA1(IDEP,4)
   45 FORMAT(35X,4(10H      PA = ,F7.1))
      WRITE(6,47)PB1(IDEP,1),PB1(IDEP,2),PB1(IDEP,3),PB1(IDEP,4)
   47 FORMAT(35X,4(10H      PB = ,F7.1))
  100 CONTINUE
      WRITE(6,50)
   50 FORMAT(/,40X,15HQG   AIR VOLUME,17X,7HSCF/MIN,
     1 /,40X,18HQP   LIQUID VOLUME,14X,7HGAL/MIN,
     2 /,40X,29HPA   SURFACE ANNULUS PRESSURE,7H   PSIA,
     3 /,40X,25HPB   BOTTOM HOLE PRESSURE,11H       PSIA)
      RETURN
      END
$FTRAN FRCTN
      SUBROUTINE FRCTN
      COMMON VEL1(200),GAMMA1(200)
      COMMON KN,TAUY,Z2FLAG
      COMMON IDP,ODP,IDA,QG,PSPG,PSPP,DENL,DENG,DEPTH
      COMMON QGX,VM,MRATE,GAMMA,QT,X,DELPRF,PX,VEL,AREA,RE,F,Z
      COMMON K,FLAG,MUL,PXP,PXA
      COMMON QP,DEN,MU,PSA,ZFLAG
      COMMON L,DRLRTE,N,PB1(8,5),BP(200)
       COMMON QG1(8,5),QP1(8,5),PA1(8,5)
      REAL MUL,MUTEMP,MROCK
      REALMRATE,MU,IDP,ODP,IDA,L
C
C      THE CALCULATION PROCEDURE FOLLOWS CRAFT, HOLDEN, GRAVES,
C      WELL DESIGN, P. 34....., FOR A BINGHAM PLASTIC FLUID IN
C      LAMINAR FLOW.
C
C
C      VELOCITY CALCULATION   FT/SEC
```

```
      IF(Z.L  .2.)GO TO 5
      ARE  =( .1416/4.)*IDP**2
      VEL=(QT/AREA)*(144./448.86)
      GO TO 8
    5 ARE =(3.1416/4.)*(IDA**2.-ODP**2.)
      VEL = ((GGX*7.48 + QP + VOLRCK)/AREA)*(144./448.86)
    8 CONTINUE
C
C       VISCOSITY CORRECTION TO EFFECTIVE VISCOSITY FOR REYNOLDS
C        NUMBER CALCULATION
      EMU = MUp+ 6.649*TAUY*IDP/VEL
      IF(Z.EQ.2.)
     1EMU= MU + 4.987*TAUY*(IDA-ODP)/VEL
C
C * * REYNOLDS NUMBER CALCULATION
C
      RE=928.*IDP*VEL*DEN/EMU
      IF(Z.E  .2.)
     1RE=928.*(IDA-ODP)*VEL*DEN/EMU
      IF(  .E .0.AND.Z.EQ.2.)GO TO 125
C
C * * FRICTION FACTOR CALCULATION
C
   10 CONTINUE
   20 CONTINUE
C
C * * CALCULATION OF PRESSURE DROP DUE TO FRICTION, BINGHAM PLASTIC
C
      IF(Z2FLAG.NE.12.)GO TO 25
      IF(Z.EQ.2.)GO TO 22
      DELPRF = (MU*L*VEL)/(1500.*IDP**2) + (TAUY*L)/(225.*IDP)
      DELPRF = 0.0502*DEN*L-DELPRF
      IF(DELPRF.LT.0.0)DELPRF=5.
      GO TO 30
   22 DELPRF = (MU*L*VEL)/(1000.*(IDA-ODP)**2)+(TAUY*L)/(200.*(IDA-ODP))
      DELPRF = 0.0502*DEN*L + DELPRF
      GO TO 30
   25 IF(Z.NE.1.)GO TO 27
   26 L=DELPRF/(0.0502*DEN-VEL*MU/(1500.*IDP**2.)-TAUY/(225.*IDP))
      IF(L)40,30,30
      IF(Z.NE.2.)GO TO 30
   27 L = DELPRF/(0.0502*DEN+MU*VEL/(1000.*(IDA-ODP)**2.)+
     1          TAUY/(200.*(IDA-ODP)))
      IF(L)40,30,30
   30 RETURN
   40 Z2FLAG=12.0
      L=DEPTH
      GO TO 20
      RETURN
```

```
      FORMAT(7F10.2)
 125  L=0.
      RETURN
      END
$FTRAN VISCTY
      SUBROUTINE VISCTY
      COMMON VEL1(200),GAMMA1(200)
      COMMON XM,TAUY,Z2FLAG
      COMMON IDP,ODP,IDA,DG,PSPG,PSPP,DENL,DENG,DEPTH
      COMMON DGX,VM,MRATE,GAMMA,GT,X,DELPRF,PX,VEL,AREA,RE,F,Z
      COMMON  ,FLAG,MUL,PXP,PXA
      COMMON DP,DEN,MU,PSA,ZFLAG
      COMMON L,DRLRTE,N,PR1(8,5),SP(200)
      COMMON DG1(8,5),GP1(8,5),PA1(8,5)
      REAL MUL,MUTEMP,MROCK
      REALMRATE,MU,IDP,ODP,IDA,L
C
C      VISCTY DETERMINES THE BINGHAM PLASTIC VISCOSITY AND THE
C      YIELD STRESS
C
C      THE VISCOSITY OF WATER IS 1.023 CP
C
      MUL=1.0203
      FLAG=0.
      IF(GAMMA.GE..55)GO TO 20
      MU=MUL+3.95*GAMMA
      TAUY = 0.0
      RETURN
  20  IF(GAMMA.GT..96)GO TO 30
      MU =  14.3174         -  15.001417*GAMMA
     1                      - 400.232256*GAMMA**2.
     2                      +1528.444416*GAMMA**3.
     3                      -1974.331443*GAMMA**4.
     4                      + 873.408325*GAMMA**5.
      TAUY = 32.894268      - 266.23227*GAMMA
     1                      + 729.34306*GAMMA**2.
     2                      - 834.46553*GAMMA**3.
     3                      + 344.25674*GAMMA**4.
C
C       YIELD STRESS OF FOAM IS CALCULATED IN LBF/FT**2
C       A CONVERSION MUST BE MADE TO  LBF/100FT**2
      TAUY=100.*TAUY
      IF(GAMMA.LE.0.584)TAUY=0.0
      RETURN
  30  FLAG=1.0
      GAMMA=0.97
      RETURN
      END
$ENTRY
```

1.0203

0.55 < Γ < 0.96

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