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Calculating Pressure Drops Across Positive Displacement Motors In Air Drilling Systems

by

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Abstract

This research program was designed to establish down hole power requirements for a positive displacement motor (PDM) utilizing air as a drilling fluid. There are two key variables that are not well defined for calculating power requirements for air drilling. These variables are fluid viscosity and the friction factor for mixtures. Though many authors have successfully approximated the minimum surface requirements for air drilling, none have approximated the power requirements for a PDM using air.

It is important that the power requirements be estimated prior to initiating a drilling program so that proper equipment can be located at the drilling site. This special equipment includes air compressors, injection pumps, and rotating head. Inadequate equipment can result in either the inability to initiate rotation in the PDM or a loss of lifting capacity during drilling, resulting in a stuck drilling string and possibly a loss of the bottom hole assembly. An over abundance of surface equipment obviously results in wasted moneys.

In predicting the power requirements for a PDM utilizing air, it was ascertained that no direct method for measuring the pressure drop across the motor exists while actively drilling. Therefore, a borehole was drilled in Fremont County, Colorado in March of 1989 in order to acquire data while drilling with a positive displacement motor. This borehole was drilled with air while measuring surface pressure, ambient temperature, and drilling fluid flow rates. Energy balance derived equations were used to calculate pressure drops along the borehole using wellbore and drill fluid parameters. The difference between the calculated pressure at the top of the motor and the pressure in the annulus at the bit was assumed to be the pressure loss across the PDM. This thesis demonstrates a method of calculating the pressure drops along the flow system and a method to determine the horse power consumed by the motor.

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Introduction

Air drilling refers to the drilling of a borehole using air, in part or as a whole, as the circulating fluid[1]. Air systems are divided into four categories: straight air, mist, foam, and aerated mud.

Straight air drilling, as the name implies, uses only compressed air free of liquids. Mist drilling uses small quantities of water and depending on chemical requirements, a foaming agent. In mist drilling, water is dispersed throughout the drill hole and is lifted out as droplets. Foam drilling is sub-divided into two classes: 1) if water is used with a foaming agent, then the resulting fluid is called a "foam" system, 2) if mud is used with a foaming agent, then the circulating fluid is called "stiff foam".

In aerated mud systems, the liquid phase is the primary circulating medium. Air is injected into the system, generally without a foaming agent. Aerated mud systems are also divided into two classes: 1) if water is the liquid phase, the result is an aerated water system, 2) if mud is the liquid phase, it is called an aerated mud system. These classes of circulating systems are shown in Figure 1.

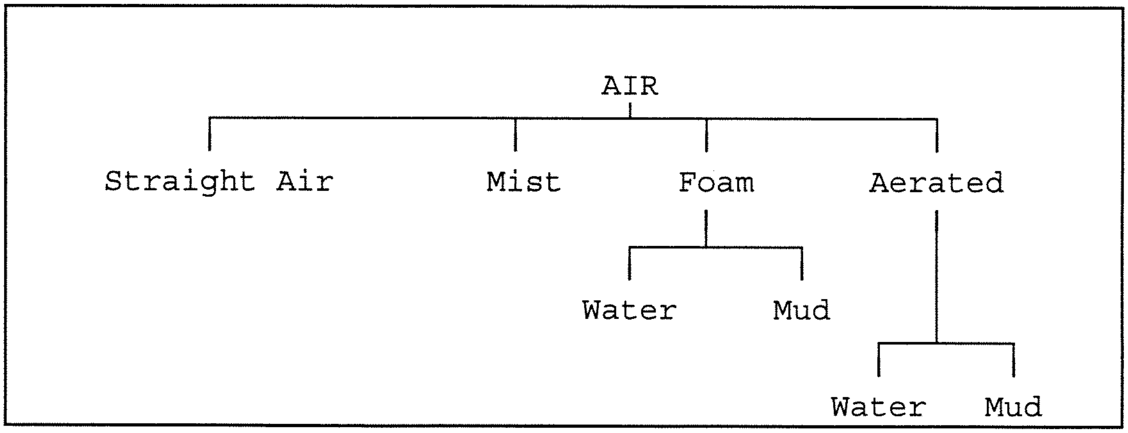

Figure 1 - Air/Gas Drilling System Types

The advantages of using air as the drilling fluid over the use of liquids are; 1) up to a tenfold increase in penetration rates can be realized[2], 2) extended bit life, 3) low risk of fishing, 4) fewer borehole problems, and 5) minimized formation damage of reservoirs such as low pressure, naturally fractured or coal-bed methane reservoirs.

Directional drilling refers to the drilling of a non-vertical hole such that the well is drilled at a predetermined inclination and direction. Two methods of deviating a well exist. The first consists of using a shovel shaped piece of equipment called a whipstock. The whipstock is set at the depth at which the deviation is to start, and a small pilot hole is drilled off the face of the whipstock. A larger bit is then used to ream the hole to gauge. In order to continue the build of the angle, the whipstock must be reset after each joint is drilled down, making the use of a whipstock time consuming.

The second method of directional drilling is performed by using a positive displacement downhole motor, referred to as a PDM or mud motor. The PDM utilizes a rotor and stator assembly which is in essence the same as a Moineau pump[3]. Generally, a liquid is forced into the stator chamber where it imparts a torque to the rotor converting the pressure of the fluid to the bit. This motor is attached to a bent sub that provides the motor with an inclination. The bent sub is lowered to the bottom of the hole and "pointed" in the desired direction.

Directional wells offer many advantages. Among them are the ability to reach targets inaccessible to vertical wells or to intersect the target such that reservoir exposure is maximized. The use of directional technology in off-shore drilling platforms, or for environmental considerations, greatly affects the economics of a drilling operation. Examples of these uses are the North Slope of Alaska, offshore Southern California, and the Gulf coast region.

It has been surmised that the combination of air drilling and directional drilling technologies would be beneficial where the formation is sensitive to damage and maximum reservoir exposure to the drill hole is desired. This thesis provides the basic analysis for approximating the pressure drop across a PDM during a drilling operation of this type. Knowledge of the surface lines, drill string and drill hole parameters can help in finding the pressure required to power the motor. By knowing the configuration of the circulating system, the pressure along the path of air flow can be calculated. Once all change of pressure is accounted for, any excess pressure will be considered to be the pressure drop across the PDM.

The problem of drilling a directional borehole with an air system was tackled by Future Drilling Co. and Slanovich Petroleum Corporation in March of 1989. A drilling site was found in Fremont County, Colorado just south of the town of Florence. The well was drilled into the Pierre Shale formation. The Pierre is a very uniform shale, oil bearing, fractured formation. Because of the sensitivity of this formation to liquids and a low reservoir pressure along with natural fractures, this formation is considered ideal for drilling a directional borehole with air as the primary drilling fluid. The location of the drill site is within the known boundaries of the Florence Oil Field.

The borehole was drilled vertically to 1500 feet without a downhole motor. The hole was then deviated using a PDM and a bent sub. The build rate for this hole was approximately 3°/100 feet. Two compressors were used while the PDM was in the borehole. During drilling operations, orifice meter run measurements along with barometric pressure and ambient temperatures were recorded.

Equipment

The equipment required to provide pressure and temperature data for this analysis is simple. Measurements of flowrates were directly determined using an orifice meter. A two-inch orifice meter run (2.067-inch nominal I.D.) was used to measure the flowing pressure and temperature of air from the compressors and a record was made of the differential and downstream pressures at the meter run. Testing and calibration of the recorder was performed by the distributor (The Meter and Valve Co. Denver, CO) one week prior to the start of drilling and was found to be accurate to within 1 percent of full scale. The charts used for recording the data were an American Meter type M-500-H. The chart recorder measured line pressures to a maximum of 500 psig with a maximum differential pressure of 100 inches of water. Copies of the charts used for this experiment are shown in Appendix A.

Circulating and outside air temperatures were measured using mercury thermometers. Circulating temperature measurements were made at the orifice meter run.

Injection of the foam solution to cool and lubricate the mud motor was performed using a Gardner-Denver P-172 Triplex pump with a $2^{3}/_{16}$ inch diameter piston and a 2 inch stroke length. This type of pump displaces fluid only on one side of the piston, as opposed to a duplex pump that uses both sides of the piston for pumping fluid. The pump was powered by a 353 cubic inch Detroit diesel. The power train was a Ford Motor Company 4 speed manual transmission.

Two compressors were used to drill the test well: an Ingersoll-Rand XHP-950/350 (950 C.F.M./350 psig) two stage screw type compressor powered by a 12V71N Detroit Diesel engine; and a Gardner-Denver SKQVE-900/350 (900 C.F.M/350 psig) two stage screw type compressor powered by a Detroit 12V71T. Both compressor ratings are based on standard conditions.

Atmospheric pressures were measured using a mercury barometer constructed at the drilling site and a tape measure. The barometer consisted of a length of transparent teflon tubing capped at one end. It was filled with mercury and the open end immersed into a mercury filled reservoir. Values were recorded using a tape measure accurate to $^1/_{16}$ of an inch.

A Wedco two pen Geolograph was used to record the penetration rate, drill hole depths, and the weights applied to the bit.

The PDM used for drilling the borehole was a Baker-Hughes "Oncor" ½ lobe profile motor with an outside diameter of 4¾ inches. The overall length of the motor was 21 feet and the connections at both ends were standard API 3½ inch internal flush threads. For comparison, performance data by the manufacturer was obtained for the motor with full liquid flow. The manufacturers published flowrates ranged from 120 to 275 gallons per minute resulting in a rotational bit speed of 120 to 549 revolutions per minute. Maximum motor pressure drops was 375 psi for the Oncor[4]. This table of performance data is included in Appendix B. Although rotation can not be practically measured while drilling, the fluid rate at the motor can be calculated along with an approximate pressure drop. The comparison between the manufacturers liquid flow data and the data obtained in this experiment will be presented in the Conclusion Section.

The drill bit employed was a 6¼ inch REED HP-11 tricone jet bit with all of the jets removed. The resulting diameter of each of the three opening was ¾ of an inch.

An 8¾ inch surface hole was drilled and 200 feet of 7 inch J-55 23#/ft (internal diameter = 6.366 inches) surface casing was set and cemented. A 6¼ inch hole was drilled out from under surface and drilled vertically to a depth of 1500 feet before the well was drilled directionally. The directional hole measured depths were taken from the geolograph and were recorded on geolograph charts. True vertical depths were not used in the final analysis since the maximum drill hole inclination with the motor in the hole was measured at 10°. The small angle was found to have little affect on the overall solution in this particular case since the difference between the true vertical depth and the measured depth was small. However, high angles of inclination and long departure distances could result in significant differences in calculated pressures along the borehole.

The planned bottom hole assembly (BHA) consisted of 325 feet of 4¾ inch drill collars (2¼ inch bore), one 29 foot 4¾ inch Monel Non-magnetic collar (2¼ inch bore), and the positive displacement motor. The drill pipe used was 3½ inch 13.30#/ft internal flush drill pipe with an internal diameter of 2.764 inches.

Data Acquisition

In preparing for the acquisition of data, all surface line internal diameters and lengths running from the meter-run to the pin of the kelly were measured. In addition, all fittings such as elbows, swages, valves, and unions were listed and converted to equivalent lengths of straight pipe of a given diameter[5]. All of the dimensions for the fittings mentioned above can be found in Table 1. Table 2 summarizes the total equivalent length of pipe for each equivalent diameter of pipe listed in Table 1. The layout of the surface lines and positions of the various equipment used for this project can be found in Figures 2 and 3.

Manual entries for the pressure and temperature at the meter run were made in addition to the recording of the associated depth. Outside air temperature and barometric pressure were also recorded coinciding with the meter run observations.

A 1½ inch orifice plate was used in the orifice meter run throughout the experiment and was checked periodically for wear. At the conclusion of the experiment, no wear was observed. Measurements of the injection fluid rates were made coincidental with meter run measurements by observing the time required for the injection pump to stroke or cycle twenty times. A water based solution of potassium chloride and Ecco-Foam (a commercial surfactant) was mixed. The solution was to cool and lubricate the motor during operations and to stabilize the borehole. The average specific gravity of the mixture was 1.12 gms/cc from measurements made at a later date in the laboratory using a 10 ml specific gravity bottle.

Penetration rates were calculated by observing the time, as shown by geolograph charts, required to drill the 25 feet prior to meter run measurements. The weight on the bit was recorded manually by the driller and varied between 2000 and 4000 pounds while drilling with the motor.

Attempts made to measure the flowrate at the blooey line exit with a critical flow prover were not fruitful. This could be an area of future research.

Table 1 - Surface Line Configuration

Type of Pipe	Actual Length [ft]	Equivalent Dia. [in]	Equivalent Length [ft]
4.5" 11.6# csg	24.500	4.000	24.500
4.5" Long Rad. Elbow		4.000	4.500
4.5" 11.6# csg	0.400	4.000	0.400
4" x 3" Swage	0.596	3.000	1.750
3" Cameron Gate	0.708	3.000	3.320
4" x 3" Swage	0.596	3.000	4.500
4.5" 11.6# csg	36.500	4.000	36.500
4" Tee [Side Exit]		4.000	20.100
3.5" 13.3# Drill	0.650	2.764	0.650
4" Tee [Side Exit]		4.000	20.100
4" sch120 Pipe	0.450	3.626	0.450
Kelly Hose	45.000	3.125	45.000
3" Tee [Side Exit]		3.000	15.400
3.5" 13.3# Drill	1.000	2.764	1.000
3" Tee [Side Exit]		3.000	15.400
Swivel	4.630	2.750	4.630
Subs	3.000	2.250	3.000
Kelly & Subs	30.700	2.406	30.700
Blooey Line	40.000	3.000	40.000

Table 2 - Summary of Table 1

Equivalent Pipe Diameter [in]	Summation of Equivalent Length [feet]
2.25	3.000
2.40625	30.70
2.75	4.630
2.764	1.650
3	80.37
3.125	45.00
3.626	0.450
4	106.1

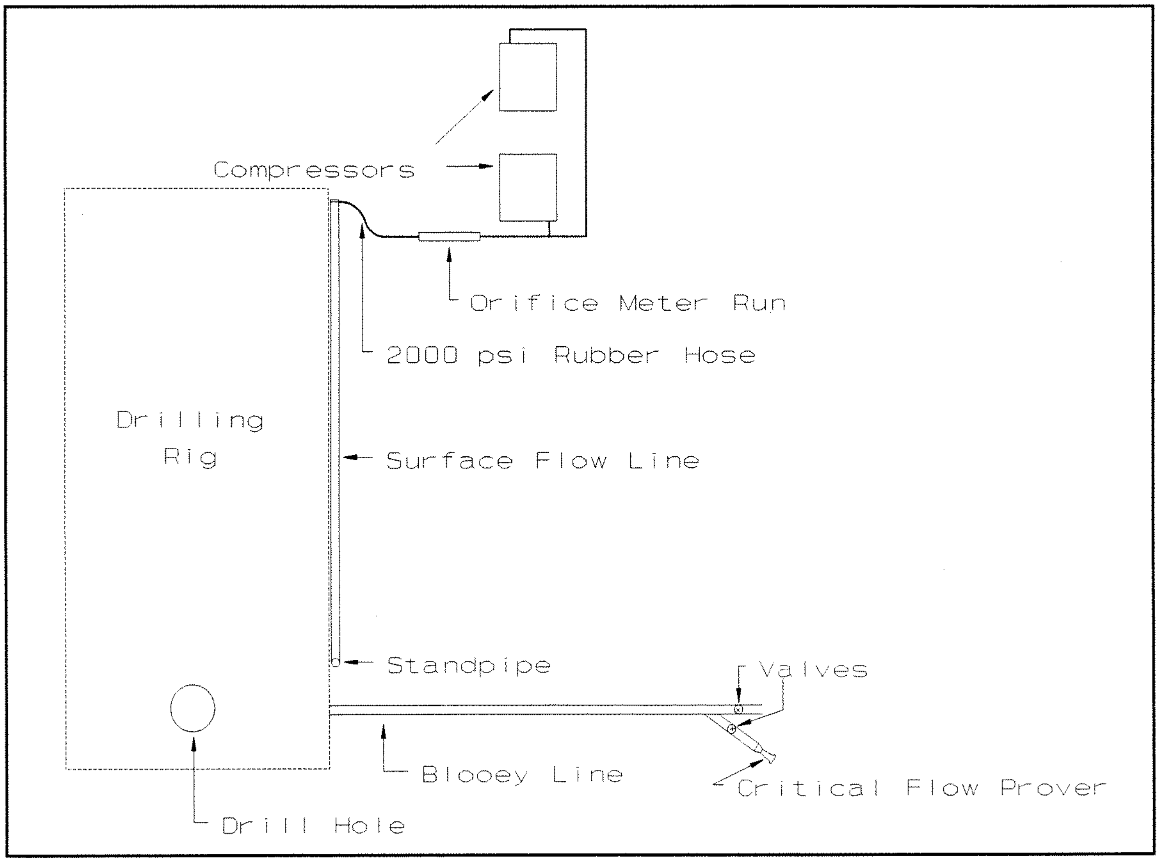

Figure 2 - Top View of Surface Lines and Equipment

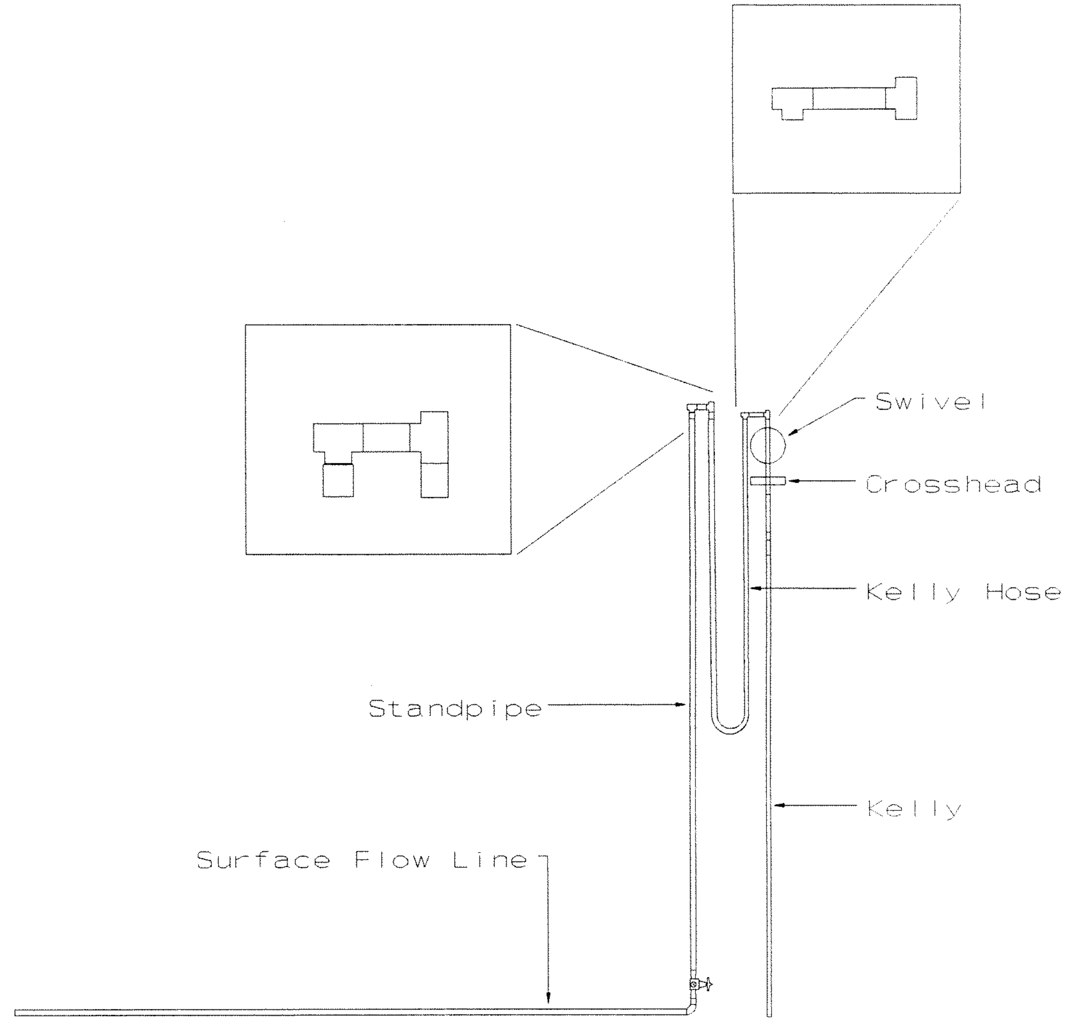

Figure 3 - Side View of Surface Lines.

Calculations

In choosing the equations and correlations for the computation of downhole pressure, temperature, and circulation rates, the following assumptions were made:

1. The drilling fluid is incompressible after the air attains its compressed state[6].
2. Rotational effects of the drill string on air pressure losses are negligible.
3. The circulating fluid is considered homogeneous.
4. The viscosity of the drilling fluid can be approximated using the weighted average viscosity of each component of the fluid[7].
5. Solid spherical particles are suspended homogeneously throughout the annulus.
6. No particle slip occurs.
7. The drill string and the drill hole are concentric.
8. The pressure drop through the openings of the bit are negligible.

9. The acceleration pressure losses/gains are negligible.
10. Loss of circulation into the formation does not occur.

The chosen equations were combined to form one consistent model, hereafter referred to as the "Bard model", for the computations of the state of flow in the system. The following explains the methodology used in calculating all pressure changes along the flow system using the Bard model. A finite element of one foot in length was used to ascertain the state of flow along the circulating path. The Bard model calculated these states of flow using aqcuired flow data and published correlations.

The Bard model consists of a main module and four supporting routines written in American National Standard Institute (ANSI) C. Two of the four routines (**zfactor** and **critical**) were obtained from the Colorado School of Mines Petroleum Library and converted from Fortran 77 to C. The remaining two routines (**visc_gas** and **visc_wat**) were written by the author.

The main calculation module **(cal_dril)** was written in two sections. The first section computes the pressure differences within the drill string from the surface down to the top of the motor. The second section computes the pressure differences in the annulus from the surface down to the drill bit. Further, each of these sections were partitioned based on whether the hole contained drillpipe or bottom hole assembly.

The reason for calculating both segments from the surface downward is that the motor is located in the middle of the flow path. After the pressures at both ends of the motor are computed, the pressure loss through the motor is calculated by taking the difference between absolute pressure at the bottom of the drill string and the absolute pressure at the bottom of the annulus. A complete listing of the program which is based upon the Bard model is in Appendix C.

The flow data for the model consisted of the following:

1. Current measured depth (ft)
2. Surface injection air flowrate (SCFM)
3. Surface injection pressure (psig)
4. Surface injection temperature (F)
5. Surface liquid injection rate (CFM)
6. Barometric pressure (psia)
7. Drill pipe inside diameter (in)
8. Drill pipe outside diameter (in)
9. Drill collar inside diameter (in)
10. Drill collar outside diameter (in)
11. Length of the drill collars (ft)

12. Hole size / bit size (in)
13. Average rate of penetration (FPM)
14. Average cutting diameter (ft)
15. Calculated surface pressure losses (psig)

Data obtained during drilling operations can be found in Appendix D, columns 1 through 3, 5 through 10, 21, and 24. The barometric pressure in psia, column 4, was calculated using the following:

$$P_{barometric\ (psia)} = P_{barometric\ (in.HG)} \left(\frac{14.7_{psia}}{29.92_{(in.HG)}} \right)$$

Using the data obtained at the drill site, the flowrate of air passing through the circulating system were calculated with the orifice meter run equation[8]:

$$Q = \frac{C' \sqrt{h_w p_f}}{60}$$

where:

Q = Flow measured at base temperature and pressure, standard cu. ft / min.

h_w = Pressure differential across the orifice, inches of water at 60°F.

p_f = Line pressure at orifice meter run, psia

C' = $F_b\ F_{pb}\ F_{tb}\ F_g\ F_{tf}\ F_r\ Y\ F_{pv}\ F_m$

such that:

F_b = Basic Orifice Factor, 542.26.

F_{pb} = Pressure Base Factor, 1.00 for a base of 14.7 psia.

F_{tb} = Temperature Base Factor, 1.00 for a base of 60°F.

F_g = Specific Gravity Factor, 1.00 for air

F_{tf} = Flowing Temperature Factor

$$F_{tf} = \sqrt{\frac{520}{460 + T_{1c}}}$$

where:

T_{1c} = Flowing temperature in meter run, °F

F_r = Reynolds Number Factor

$$F_r = 1 + \frac{b}{\sqrt{h_w\, p_f}}$$

such that:

$b = 0.0773$

Y = Expansion Factor, based on h_w, p_f and β

such that:

$$\beta = \frac{d_{orifice}}{D_{meter\ run}} = 0.7257$$

where:

$d_{orifice}$ = diameter of orifice opening, in.

$D_{meter\ run}$ = nominal inside diameter of orifice meter run

F_{pv} = Supercompressibility Factor

$$F_{pv} = \sqrt{\frac{1}{z_{1c}}}$$

where:

Z_{1c} = Compressibility factor at line conditions.

F_m = Manometer Factor, not used

Since the units for this flowrate is based on standard conditions, it is necessary to reduce the resulting volume of air to its compressed state as observed by the meter run. This was performed by using the real gas equations of state.

The equations of state are as follows:

$$Q_{1c} = Q_{sc}\left(\frac{P_{sc}}{P_{1c}}\right)\left(\frac{T_{1c}}{T_{sc}}\right)\left(\frac{Z_{1c}}{Z_{sc}}\right)$$

such that:

P_{1c} = Pressure at line conditions, psia.

P_{sc} = Pressure at base conditions, psia.

T_{1c} = Temperature at line conditions, °R.

T_{sc} = Temperature at base conditions, °R.

Z_{1c} = Compressibility factor at line conditions.

Z_{sc} = Compressibility factor at base conditions.

$$\rho_{1c_{air}} = \frac{MW_{air}\ (P_{1c} + P_{barometric}\ )}{Z_{1c}\ \ R\ (460+T_{1c})}$$

where:

R = Universal gas constant, 10.73 (psia·cu ft)/°R.

MW_{air} = Molecular Weight of air, 28.97 lbm / mole.

Values for the compressibility factor of air were determined by using the Hall - Yarborough method[9]. It is now possible to calculate the state of flow for this system using correlations and fluid dynamic equations.

The mass flowrate of each phase was also calculated in order to provide a way of estimating the viscosity and density of the combined air/liquid flow system. The mass flowrate calculation proves to be significant in understanding the requirements for maintaining motor rotation. The equations used for air, liquid, and solids are in consecutive order:

$$w_{air} = Q_{lc_{air}} \; \rho_{lc_{air}}$$

$$w_{liquid} = Q_{lc_{liquid}} \; \rho_{lc_{liquid}}$$

$$w_s = \frac{R_p \, A_h \, \rho_s}{3600}$$

where:

Q = Flowrate of selected phase.

R_p = Rate of penetration (ft/hr).

A_h = Area of the hole (ft^2).

ρ = Density of the selected phase (lbm/ft^3).

The resulting mass flowrate units are in mass pounds per second.

Hydraulic analysis of the drilling fluid was then performed in its compressed state as if the solution were an incompressible Newtonian fluid[10]. Several authors have noted that if the circulating fluid is considered incompressible, the Reynolds number relationship is identical to that of a single phase fluid. Therefore, the following relationship for the Reynolds number holds true:

$$N_R = 1488 \left(\frac{d \ v \ \rho}{\mu} \right)$$

such that:

d = diameter, ft

v = velocity, ft/sec

μ = viscosity, lbm·sec/ft^2

The viscosity for the combined phases (air and injection liquid) was estimated to be the weighted average of each phase.

Ikoku, Machado and Okpobiri[10,11] have derived equations for friction factors based on foam and mist flowing systems. Their methodology was chosen because it not only handled friction for the air/liquid phase but also included the friction due to solids being present within the borehole annulus. The affect of the frictional pressure losses associated with drill cuttings was modeled using a procedure published by Machado and Ikoku[11]. They experimentally determined particle friction factors for sandstone, limestone, and shale. Linear regression performed by them on the experimental data yielded four equations; one for sandstone, one for limestone, one for shale particles, and an equation for a mixture of all three. Since the borehole was drilled into a shale formation, the shale equation was used in this analysis. Machado concluded that his equation for shale exhibited a maximum error of 6.10 percent in all flow regimes.

$$f_s = 110.0 \left(g_c \frac{d_s}{v_g^2} \right)^{0.985} \left(\frac{w_s}{w_g} \right)^{1.088}$$

where:

f_s = solids friction factor

g_c = gravitational constant, 32.174 ft/sec^2

d_s = average diameter of cuttings, ft

v_g = velocity of air stream, ft/sec

w_s = mass flowrate of the cuttings, lbm/sec

w_g = mass flowrate of the air, lbm/sec

Liquid injection volumes were calculated using the following equation:

$$Q_{inj} = \frac{1.636\ d_p^2\ L_{st}}{t}$$

such that:

Q_{inj} = injection flowrate, ft^3/minute.

d_p = diameter of the triplex piston, inches.

L_{st} = length of piston stroke, inches.

t = time for 20 strokes, seconds.

The density of the injection liquid was calculated measuring the weight of the fluid for a known volume. This was performed in the laboratory by filling a 10 ml gravity bottle and weighing the liquid. The equation for the mass flowrate of the injection liquid is:

$$w_{inj} = \rho_w \, SG_{inj} \, Q_{inj}$$

such that:

ρ = Density of water (lbm/ft^3).

SG_{inj} = Specific gravity of injection fluid, gm/cc.

This equation yields the mass flowrate in lbs per second. The density of the two-phase fluid was then calculated from the ratio of mass flowrate and volumetric flowrate using:

$$\rho_{mist} = \frac{w_{air} + w_{inj}}{Q_{lc} + Q_{inj}}$$

Friction for the fluid system was calculated using Ikoku's methodology[12]. The equations depend on whether the flow is laminar or turbulent. For a Reynolds number of less than 10000, the flow is laminar. The equation for this condition is:

$$f_{fluid} = \frac{0.0701}{Re_{fluid}^{0.25}}$$

The equation for turbulent flow is as follows:

$$f_{fluid} = 0.0008+\left(\frac{0.0552}{Re_{fluid}^{0.237}}\right)$$

The total friction factor f_T, is nothing more that the sum of all calculated friction factor contributed by the air/mist fluid system and the cuttings. Friction losses caused by solids were determined using the Ikoku, et. al. model mentioned above.

Velocities for each segment were calculated by taking the two phase flowrate and dividing it by the cross sectional area of the segment. All required calculations prior to pressure loss or gain determinations have been performed. Now the pressure changes for each part of the borehole depends on the physical characteristics of the hole. For pipe flow, the pressure change calculation for a segment is as follows[13]:

$$\Delta p = \frac{\rho_{fluid}\,\Delta L}{144} - \frac{f_{fluid}\,\rho_{fluid}\,v_{fluid}^{2}\,\Delta L}{72\,g_c\,d_{dp}}$$

such that:

d_{dp} = inside pipe diameter, ft

Ikoku concluded that for annular flow the following equation should be used:

$$\Delta p = \frac{\rho_{mist}\,\Delta L}{144} + \frac{f_m\,\rho_{mist}\,\Delta L\,v_{mist}^{2}}{72\,g_c\,d_H}$$

such that:

d_H = hydraulic diameter, ft

Once the model has been used to determine the state of flow for the circulating system, the horsepower consumed by the PDM is the difference between the available horsepower at the inlet of the motor and the available horsepower at the bit in the annulus. The equation for horsepower calculations is as follows:

$$H.P. = \frac{144\,P\,Q}{550}$$

such that:

P = Pressure at point of interest, psia.

Q = Flowrate at the point of interest, ft^3/sec.

Discussion

A summary of the precision of the results are presented in Tables 3, 4, and 5. The statistical results for the portion of the hole drilled without the motor are presented in Table 3. The average pressure difference of 0.54 psia presented in table 3 indicates that bottom hole pressures as calculated with equations which apply to flow within the drill string and those calculated with equations which apply to flow within the annulus are precise and complete. This is the basis for believing that the Bard model created for this investigation is correct and reasonable.

The statistical results for the portion of the hole drilled with the motor are presented in Table 4. The average pressure difference of 259.96 psia presented in Table 4 is the pressure drop across the bottom hole motor. This value of 259.96 psia is the difference between drilling with a motor and drilling without a motor. All pressure were computed with the Bard model in both cases.

Horsepower consumption by the motor is resented in Table 5.

Table 3 - Statistics for 785 to 1100 feet

Motor NOT in hole.

Footage Drilled 785 - 1100 feet	Pressure Difference (psia)
Average Value	0.544532
Minimum Sample Value	-2.40999
Maximum Sample Value	3.18226
Standard Deviation	1.803409

Table 4 - Statistics for 1500 to 1836 Feet

Motor in the hole

Footage Drilled 1500 - 1836 feet	Pressure Difference (psia)
Average Value	259.9642
Minimum Sample Value	125.3461
Maximum Sample Value	309.6877
Standard Deviation	41.23178

Table 5 - Statistics for Horse Power Consumption by the PDM

1500 - 1836 feet	Horsepower Consumed by the PDM
Average Value	433.7474
Minimum Sample Value	207.5260
Maximum Sample Value	549.1219
Standard Deviation	9.540160

The pressure profiles in Appendix E show the pressures within the annulus and drill pipe versus depth. Noted in the profiles for the shallow depths without the motor in the hole (785 - 1100 feet) is the tendency for the curves to meet at the bottom of the hole. The meeting of the curves indicate that the calculated pressures along the flowing streams were accurate. The change in gradient approximately 325 feet from the bottom of the hole is due to a change in the physical dimensions of the drill string. It is here where the bottom hole assembly starts. Any curvature in either in the annulus curve or in the drill string curve is cause by the second order term in the friction loss equations and changes in the density of the flowing fluid.

The pressure profiles for hole depths where the PDM was in the hole (1500-1836 feet) illustrate the calculated differences in the pressures at the motor. The separation of the two curves at the bottom of curves is the pressure drop across the motor. It can also be seen that the change in density of the flowing fluid is more significant than the friction losses for flow within the pipe section of the drill string and less significant for flow in the bottom hole assembly. This results in an slight pressure gain in the drill pipe section rather than a pressure loss.

Additional observations at the wellsite indicated a reluctance for the motor to initially start unless a slug of injection fluid was introduced before the compressors were put on line. It was noted that if a preceding slug of fluid was not introduced into the system that air would pass through the motor without inducing rotation. It is surmised that by introducing this slug into the air stream that a "sealing" of the gaps between the rotor and stator took place, allowing sufficient pressure build-up within the stator chamber to initiate rotation.

While drilling with the PDM, a higher rate than normal of liquid must be injected in order permit continuous rotation of the motor. This can be seen in Figure 4. This figure indicates that even though the mass flowrate of air and solid does not appreciably increase, the liquid mass flowrate, which is represented by the plus symbol, is substantially higher while the PDM is in operation; i.e. below depth of 1500 feet.

It was also noted that removal of the dump valve in the motor is critical since the dump valve can require pressures of roughly 350 psi[14] to open. In this case, the extra pressure required to open the dump valve is approximately equivalent to the maximum compressor rating.

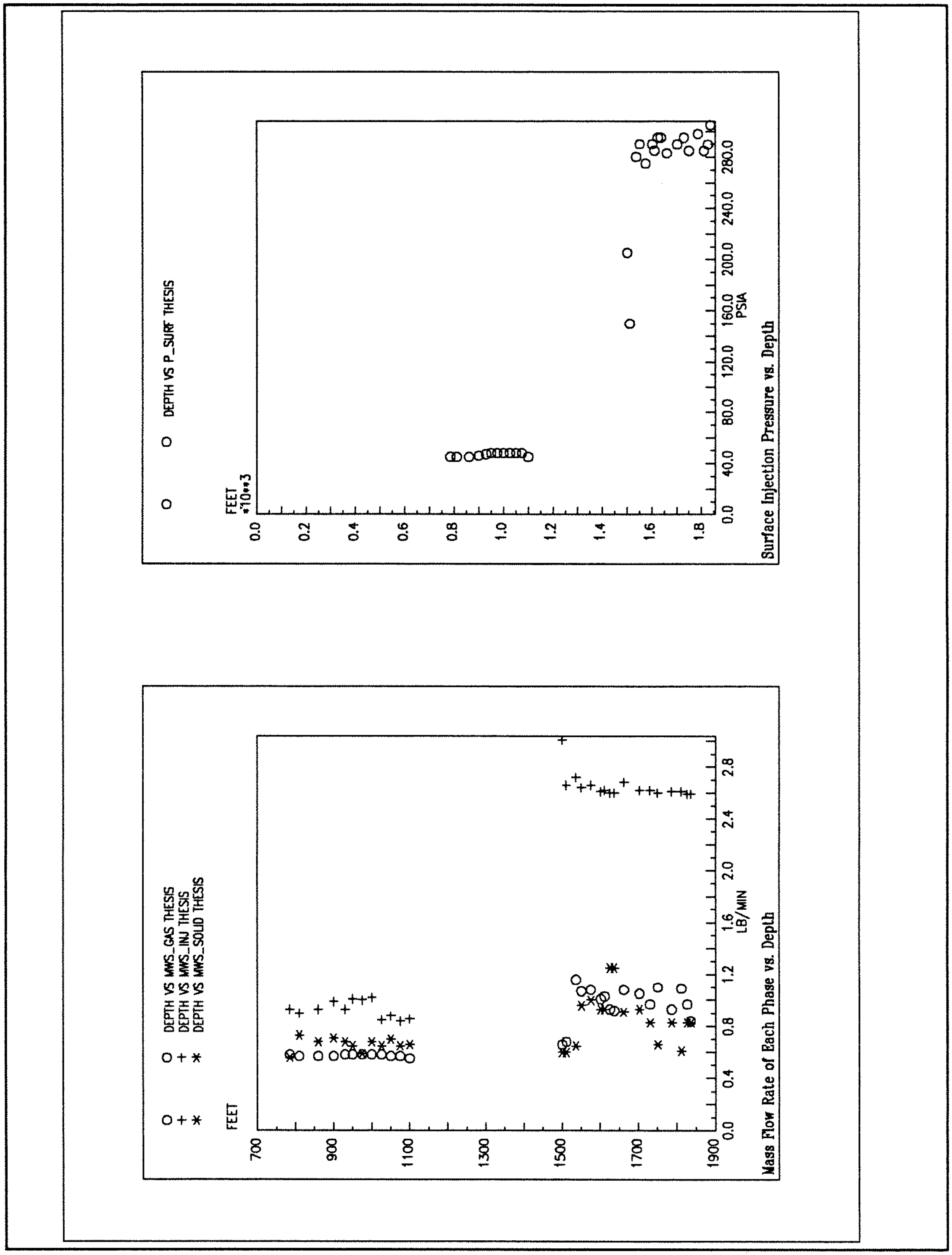

Figure 4 - Mass Flow Rate and Injection Pressure vs. Depth

Conclusion

1. Comparisons of pressures at the bit with and without the motor substantiate the validity of the research of this thesis. The pressure profiles plotted for the range of depths without and with the use of the motor (785 through 1100 feet and 1500 through 1836 feet, respectively) in Appendix E show that pressures and circulating volume rates can reasonably be calculated using the Bard model. The converging pressure profiles for drilling of the borehole without the motor (785 through 1100 feet) support this conclusion.

2. Calculated pressure consumption by the PDM ranged from 72 percent to 83.5 percent of the pressure available at the motor. The average pressure drop was found to be 260 psi or 81.3 percent of the available pressure.

3. The average flowrate at the top of the motor was found to be 42.494 cubic feet per second. This equates to 340.8 gallons per minute which is approximately 26 percent greater than the maximum flowrate at 100

percent liquid flow. It is hypothesized that this is due to slippage of air through the rotor and stator of the PDM.

4. The maximum calculated pressure drop of 309 psi is within the manufacturer specifications. It is surmised that the maximum pressure loss for the PDM is probably because of the physical makeup of the stator. Since the stator is a flexible compound, increasing pressure causes a deformation of the stator, allowing air to pass.

Nomenclature

Q = Flowrate, SCFM.
h_w = Pressure differential, in. of water.
p = Pressure, psi.
d = Diameter, ft.
v = Velocity, ft/sec.
ρ = Density, lbm/ft^3.
μ = Viscosity, cp.
N_r = Reynold number
g_c = Gravitational constant, 32.174 ft/sec^2.
w = Mass flowrate, lbm/sec.
R_p = Rate of penetration, ft/hr.
A = Area, ft^2.
C' = Orifice plate coefficient
G = Gas gravity (Air = 1.00)
T = Temperature (°Rankine)
t = Time recorded for 20 strokes
R = Universal Gas Constant, 10.73 psia·ft^3/°R
MW = Molecular Weight, lbm/mole
f = Friction
g_c = Gravitaional Constant, 32.174 ft/sec^2
L = Length

Subscripts

w = Water

dp = Drill pipe

dc = Drill collars

g = Gas (Air)

f = Fluid

m = mixture

s = Solids

inj = Injection

lc = Line Conditions

sc = Standard Conditions

h = Hole

H = Hydraulic diameter

st = Stroke

Orifice Meter Equation Constants

F_b = Basic Orifice Factor, 542.26.

F_{pb} = Pressure Base Factor, 1.00 for a base of 14.7 psia.

F_{tb} = Temperature Base Factor, 1.00 for a base of 60°F.

F_g = Specific Gravity Factor, 1.00 for Air

F_{tf} = Flowing Temperature Factor

$$F_{tf} = \sqrt{\frac{520}{460 + T_{1c}}}$$

F_r = Reynolds Number Factor

$$F_r = 1 + \frac{b}{\sqrt{h_w\, p_f}}$$

$$b = 0.0773$$

Y = Expansion Factor, based on h_w, p_f and β, such that

$$\beta = \frac{d_{orifice}}{D_{meter\ run}} = 0.7257$$

F_{pv} = Supercompressibility Factor

$$F_{pv} = \sqrt{\frac{1}{Z_{1c}}}$$

F_m = Manometer Factor, not used

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13. Ingersoll-Rand, "Compressed Air and Gas Data", pg.26-8.

14. Bard, W.A., Personal conversations with the distributor of the downhole motor., March, 1989.

Appendix A

Orifice Meter Run Charts

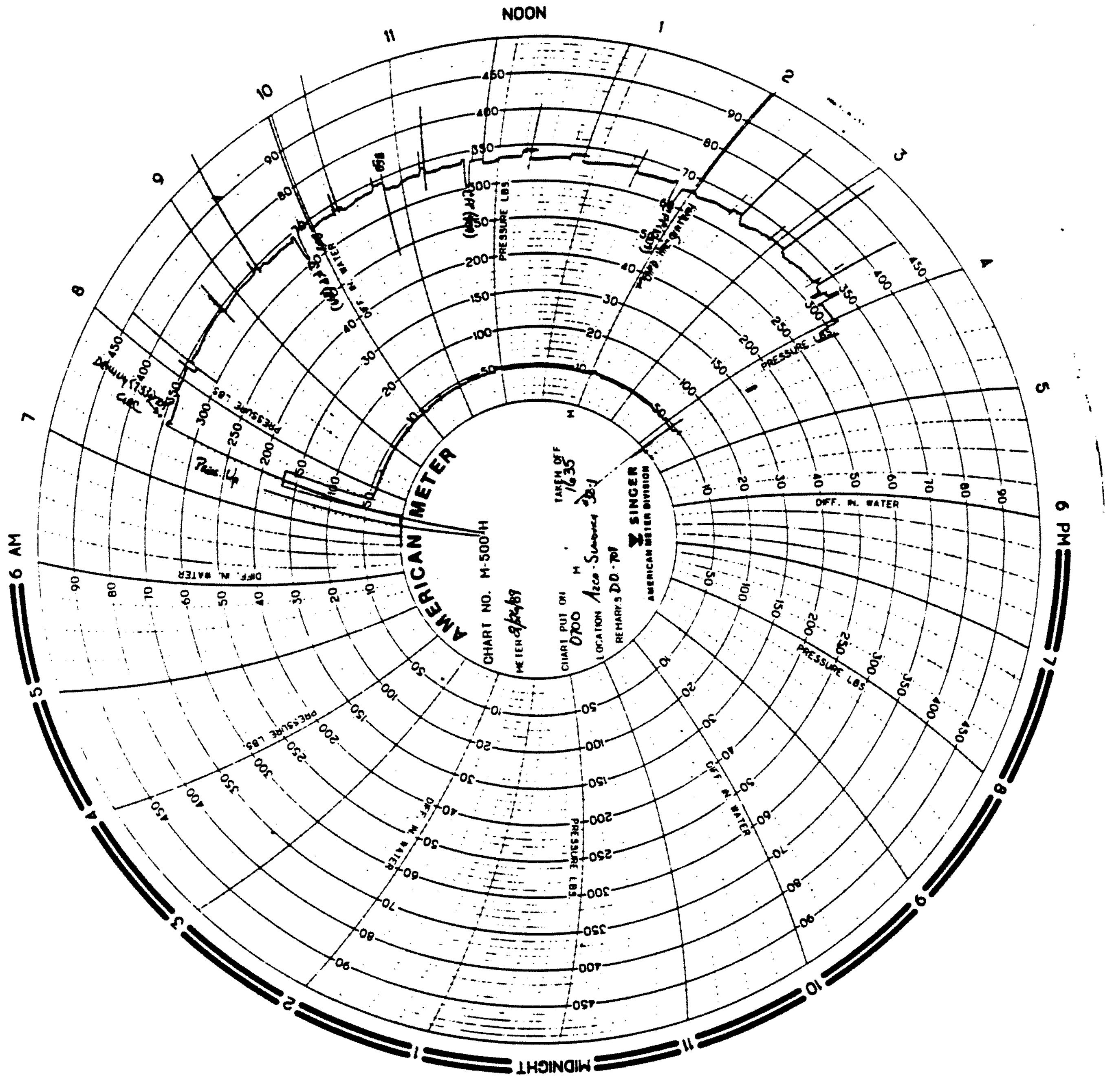


CHART NO. M-500-H

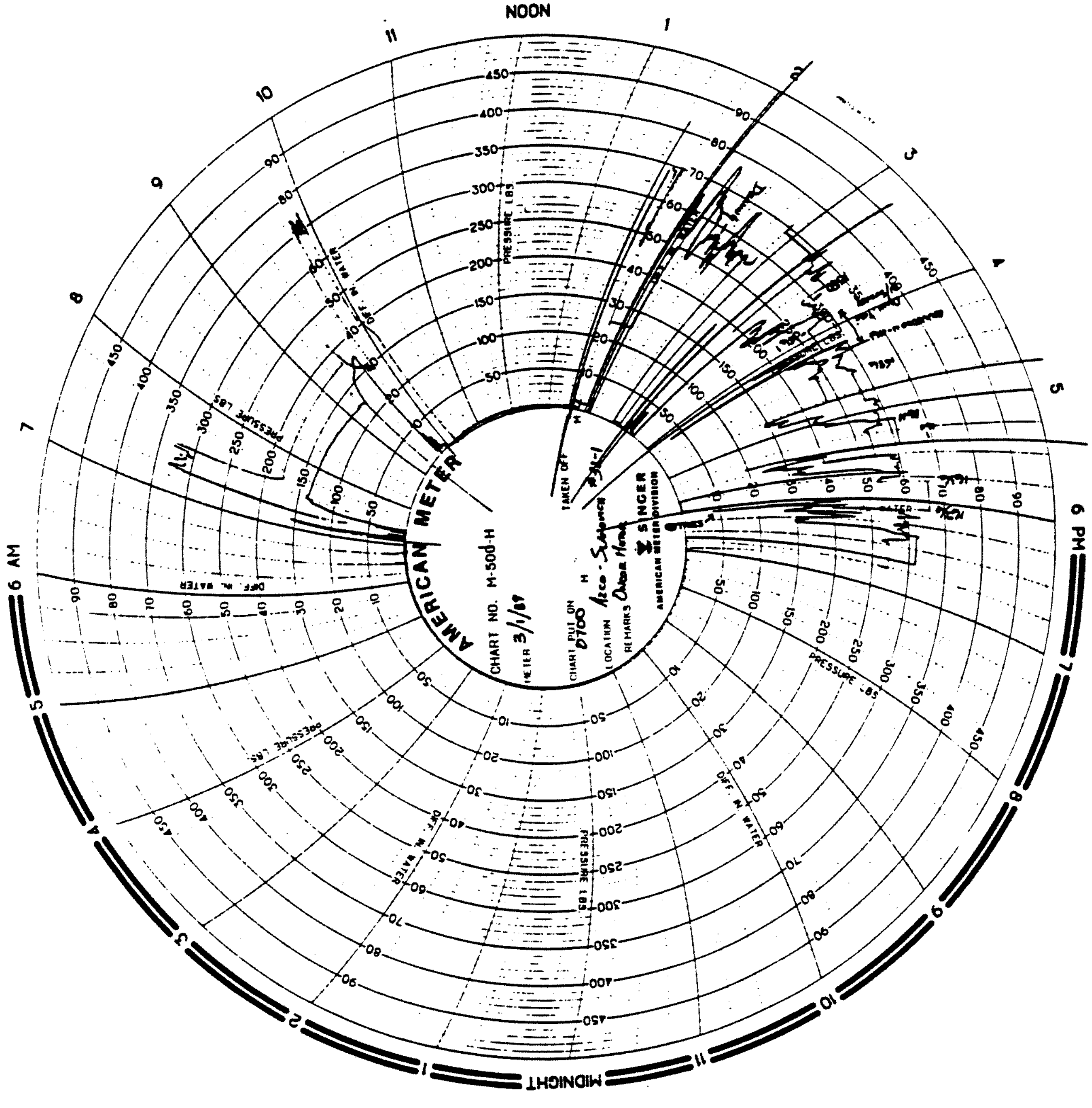
METER 8/24/89

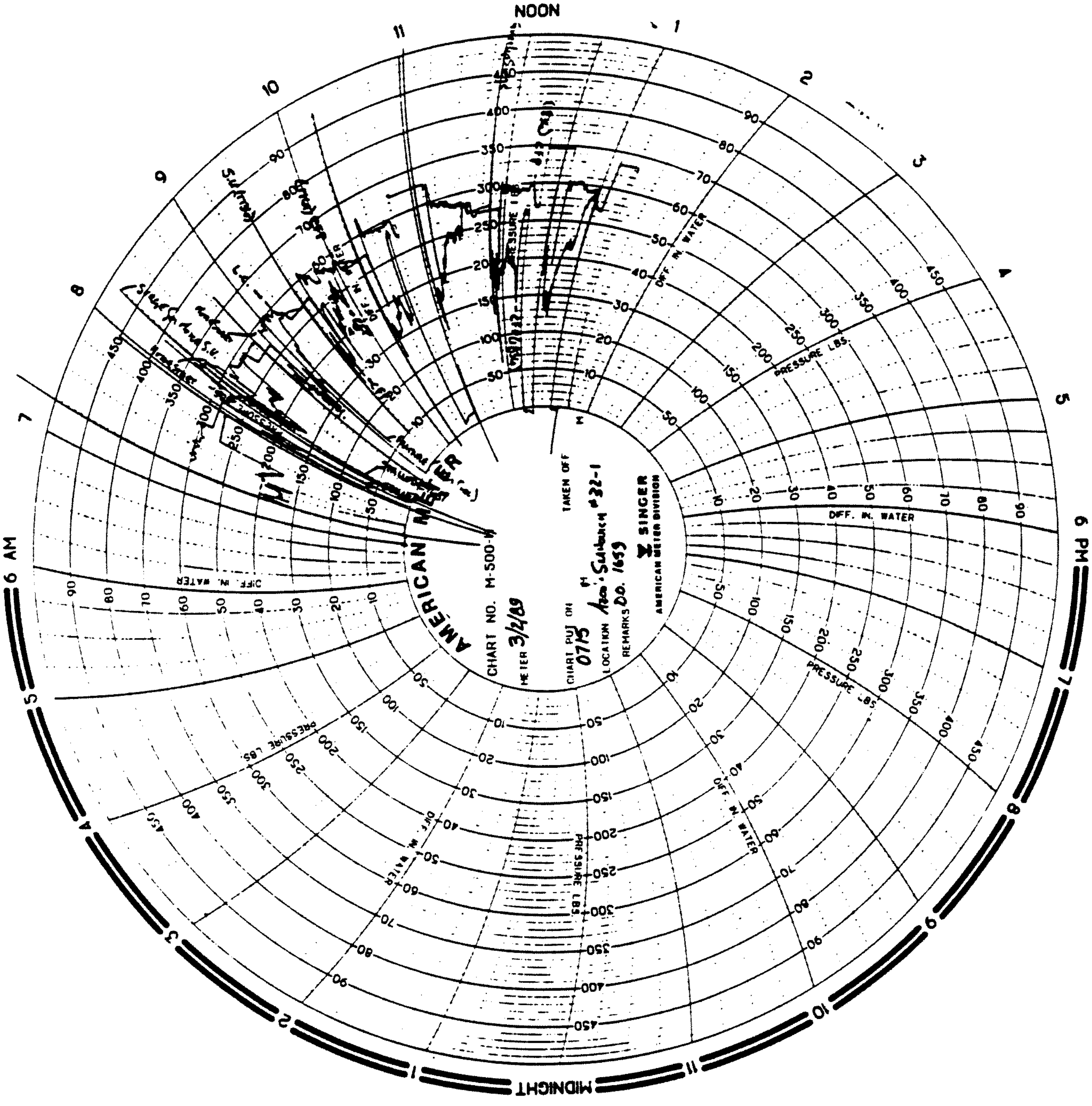
CHART PUT ON 0700 M

TAKEN OFF 1635 M

LOCATION Azco - Simmons #38-1

REMARKS DD-701


NOON
1
2
3
4
5
6 PM
7
8
9
10
11
MIDNIGHT
1
2
3
4
5
6 AM
7
8
9
10
11
PRESSURE LBS.
DIFF. IN. WATER
AMERICAN METER
CHART NO. M-500-H
METER 3/1/89
CHART PUT ON 0700
TAKEN OFF
#32-1
LOCATION Arco - Schlumberger
REMARKS Outdoor Home
SINGER
AMERICAN METER DIVISION


NOON
MIDNIGHT
6 AM
6 PM
1
2
3
4
5
7
8
9
10
11
DIFF. IN. WATER
PRESSURE LBS.
AMERICAN METER
CHART NO. M-500-H
METER 3/2/89
CHART PUT ON 0715
TAKEN OFF
LOCATION Amoco Slaughter #32-1
REMARKS D.O. 1659
SINGER
AMERICAN METER DIVISION

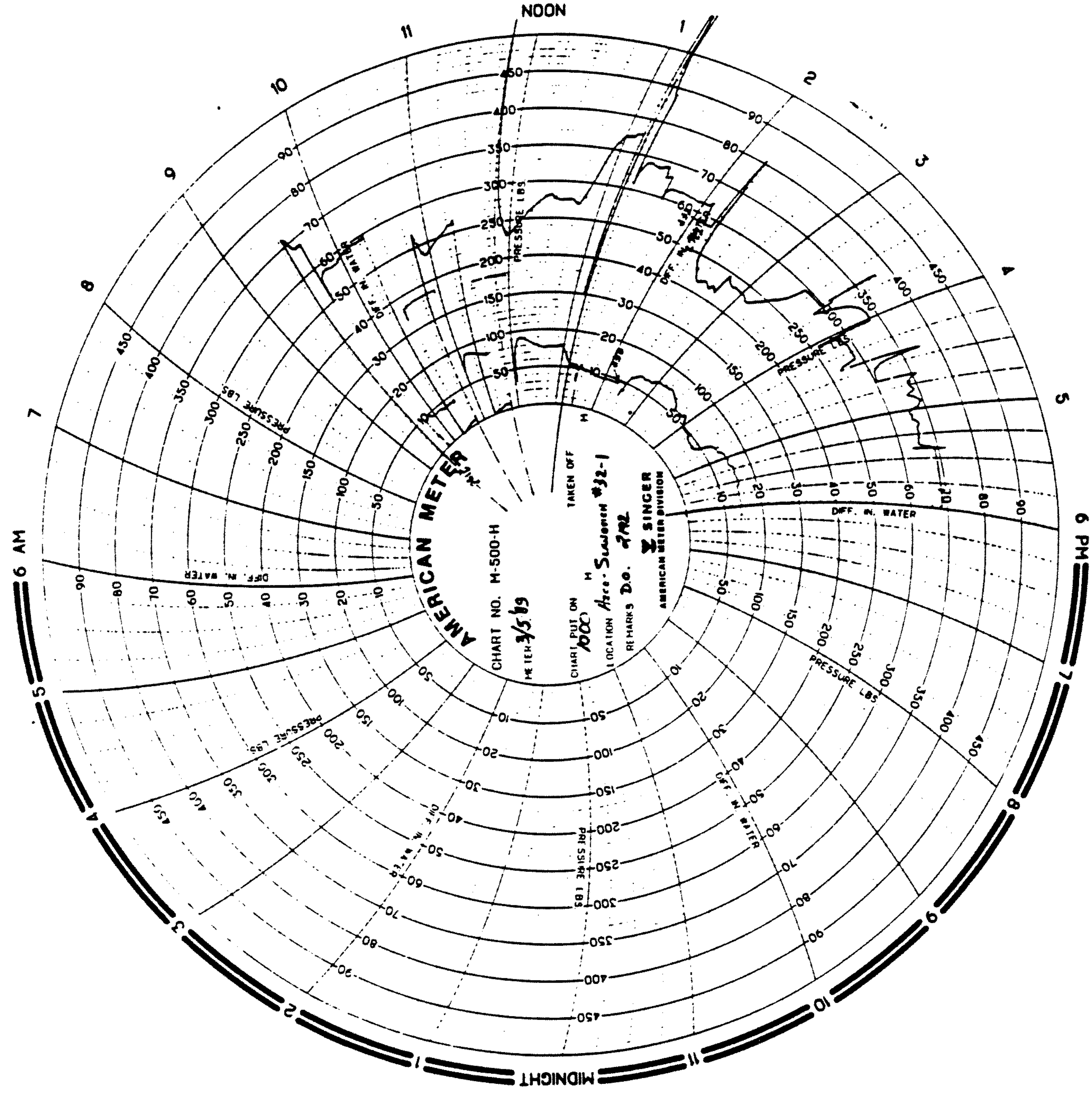


CHART NO. M-500-H

METER 3/5/69

CHART PUT ON 1000 M

TAKEN OFF M

LOCATION Azco-Swanson #32-1

REMARKS D.O. 2PM

Appendix B

PDM Specifications

PDM SPECIFICATIONS COMPARISON

DRILEX **D475 *versus* OTHER PDM's**

	DRILEX	BAKER/HUGHES		EASTMAN-CHRISTENSEN NAVI-DRILL			SMITH INTERNATIONAL DYNA-DRILL			TELECO MAGNA-DRILL		MAXI-TORQUE	
	D475	BAKER	ONCOR	Mach 1	Mach 2	Mach 3	D500	D1000	Slospeed	2 Series	3 Series	Direct Drive	Speed Reducer
SIZE O.D. (INCHES)	4-3/4	5	4-3/4	4-3/4	4-3/4	4-3/4	5	6	--	4-3/4	5-1/2	4-3/4	4-3/4
LENGTH (FEET)	21.0	17.2	21.0	17.4	20.	17.4	19.8	21.6	--	20.0	20.0	21.0	23.0
WEIGHT (POUNDS)	770	740	1100	710	840	680	911	1099	--	850	1000	N/A	N/A
CONNECTIONS TOP (API REG) BOTTOM (API REG)	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 -- --	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2	 3-1/2 3-1/2
ROTOR/STATOR PROFILE	5/6	3/4	1/2	5/6	1/2	1/2	1/2	1/2	--	1/2	1/2	1/2	1/2
MAXIMUM BIT PRESSURE (PSI)	1500	1000	1000	N/A	N/A	N/A	500	1000	--	N/A	N/A	500	800
FLOW RATE RANGE (GPM)	100-250	150-275	120-270	80-185	100-240	80-185	180-250	180-250	--	125-225	150-300	180-250	180-250
SPEED RANGE (RPM)	140-350	120-220	250-549	90-215	245-600	270-680	350-482	369-512	--	315-580	245-500	350-482	118-180
MAXIMUM MOTOR PRESSURE DIFFERENTIAL (PSI)	800-1000	400	375	580	580	580	360	375	--	500	375	825	825
MAXIMUM TORQUE (FT-LBS)	1500-1800	700	566	1040	585	415	480	850	--	600	690	550	1650
POWER OUTPUT at MAXIMUM SPEED and TORQUE (HP)	120	29	59	43	67	54	44	64	--	66	66	51	50

Note: "N/A" indicates information not available. "– –" indicates product not available.

Revised 11/87

Appendix C

Source Code

=== main.c ===

```
void main(int argc, char **argv)
{


   if(argc < 4)
   {
     printf("Usage : CAL_DRIL INFILE OUTFILE PROFILENAME\n");
   }

   cal_dril(argv[1],argv[2],argv[3]);

} /* end of main */
```

=== cal_dril.c ===

```
#define DEBUG 1


#include <dir.h>
#include <dos.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>


#define PI        4.0 * atan(1.0)
#define sqr(x)    (x * x)
#define EVER      ;;


struct{
        char CURRENT_TD[8];
        char Q_SURFACE[8];
        char Q_PRESS[8];
        char Q_TEMP[8];
        char INJ_RATE[8];
        char BARO_PRESS[8];
        char DP_ID[8];
        char DP_OD[8];
        char DC_ID[8];
        char DC_OD[8];
        char DC_LENGTH[8];
        char BIT_SIZE[8];
        char ROP[8];
        char AVE_CUT_DIA[8];
        char INCREMENT[8];
        char P_DROP_SURF[8];
        char MOTOR_LENGTH[5];
      }well;


char infile[33],
     outfile[33];


void cal_dril(char *infilename, char *outfilename, char *profilename)
{

  FILE *in,
     *out,
     *profile,
     *print;

  struct ffblk ffblk;

  int et,
      i,
      num,
      c,
      erflag;
```

```
int HALL=1;

int startdrive,
    result,
    EXIST;


static double current_depth,
              q_scfs,
              q_press_surf,
              temp_line,
              temp_surf,
              p_drop_surf,
              inj_rate,
              baro_press,
              dp_id,
              dp_od,
              dc_id,
              dc_od,
              dc_length,
              bit_size,
              rop,
              motor_length,
              current_td,
              temp_prev,
              press_prev,
              x_sect_area,
              diameter,
              zfact,
              u_g,
              rho_g,
              v_g,
              press_drop,
              q_g,
              w_g,
              w_s,
              w_fluid,
              rho_s,
              f_s,
              f_m,
              dL,
              temp_grad,
              f_fluid,
              spgr_inj,
              u_w,
              salinity,
              q_solid,
              v_fluid,
              visc_fluid,
              rho_fluid,
              rho_mix,
              solid_size,
              spgr,
              co2,
              xn2,
              h2s,
              pcr,
              tcr,
              dzdp,
              gascmp,
```

```
                 bhp_id,
                 bhp_od,
                 Re_fluid,
                 rho_liquid,
                 liquid_holdup,
                 foam_quality,
                 p_drop_head,
                 p_drop_fric;

   char string[82];



   /* Open input and output streams */

   if( (in = fopen(infilename,"r")) == NULL)
   {
      printf("ERROR OPENING %s\n",*infilename);
      exit(-1);
   }

   if( (out = fopen(outfilename,"w")) == NULL)
   {
      printf("ERROR OPENING %s\n",*outfilename);
      exit(-1);
   }

   if( (profile = fopen(profilename,"w")) == NULL)
   {
      printf("ERROR OPENING %s\n",*profilename);
      exit(-1);
   }

   if( (print = fopen("print.prn","a")) == NULL)
   {
      printf("ERROR OPENING print.prn\n");
      exit(-1);
   }


   /* Read in values to be processed */

   fscanf(in,"%s",well.CURRENT_TD);
   fscanf(in,"%s",well.Q_SURFACE);
   fscanf(in,"%s",well.Q_PRESS);
   fscanf(in,"%s",well.Q_TEMP);
   fscanf(in,"%s",well.INJ_RATE);
   fscanf(in,"%s",well.BARO_PRESS);
   fscanf(in,"%s",well.DP_ID);
   fscanf(in,"%s",well.DP_OD);
   fscanf(in,"%s",well.DC_ID);
   fscanf(in,"%s",well.DC_OD);
   fscanf(in,"%s",well.DC_LENGTH);
   fscanf(in,"%s",well.BIT_SIZE);
   fscanf(in,"%s",well.ROP);
   fscanf(in,"%s",well.AVE_CUT_DIA);
   fscanf(in,"%s",well.INCREMENT);
```

```
fscanf(in,"%s",well.P_DROP_SURF);
fscanf(in,"%s",well.MOTOR_LENGTH);

fclose(in);

/* end of data entry */


/* convert string arrays to doubles */

q_scfs        = (atof(well.Q_SURFACE))/60.0;
q_press_surf = atof(well.Q_PRESS);
temp_line     = atof(well.Q_TEMP);
inj_rate      = (atof(well.INJ_RATE))/60.0;
baro_press    = atof(well.BARO_PRESS);

dp_id = atof(well.DP_ID);
dp_od = atoi(well.DP_OD);

dc_id = atoi(well.DC_ID);
dc_od = atof(well.DC_OD);

dc_length = atof(well.DC_LENGTH);

bit_size = atof(well.BIT_SIZE);

rop = atof(well.ROP);

current_td = atof(well.CURRENT_TD);

dL = atof(well.INCREMENT);

p_drop_surf = atof(well.P_DROP_SURF);

solid_size = atof(well.AVE_CUT_DIA);

motor_length = atof(well.MOTOR_LENGTH);


/* theses are setup as constants for all calculations */

temp_surf     = 60.0;
spgr_inj      = 1.12;
temp_grad     = 0.01;
salinity      = 2.5;
rho_s         = (2.71 * 62.37);



/* setup critcal PVT values for air */

spgr = 1.0;
co2  = 0.0;
xn2  = 79.0;
h2s  = 0.0;

critical(spgr,co2,xn2,h2s,&pcr,&tcr);
```

```
  /* setup up values for finite difference */


  /* set press_prev to standpipe pressure (psia) */
  press_prev = q_press_surf + baro_press - p_drop_surf;
  temp_prev  = temp_line;


  strcpy(outfile,outfilename);


  /* print out input information */

  fprintf(out,"Depth          = %f Feet    \n",current_td);
  fprintf(out,"Air Flow Rate  = %f S.C.F.M.\n",q_scfs*60);
  fprintf(out,"Line Press.    = %f psia    \n",q_press_surf);
  fprintf(out,"Line Temp.     = %f °F      \n",temp_line);
  fprintf(out,"Surf. Temp     = %f °F      \n",temp_surf);
  fprintf(out,"Water Inj Rate = %f C.F.M.  \n",inj_rate*60);
  fprintf(out,"Sp.Gr Inj.Fluid= %f gm/cc   \n",spgr_inj);
  fprintf(out,"Barometric Pres= %f psia    \n",baro_press);
  fprintf(out,"Drill Pipe (ID)= %f in      \n",dp_id);
  fprintf(out,"Drill Pipe (OD)= %f in      \n",dp_od);
  fprintf(out,"Drill Coll.(ID)= %f in      \n",dc_id);
  fprintf(out,"Drill Coll.(OD)= %f in      \n",dc_od);
  fprintf(out,"BHA Length     = %f feet    \n",dc_length);
  fprintf(out,"Bit Size       = %f in      \n",bit_size);
  fprintf(out,"Rate of Pene.  = %f ft/hr   \n",rop);

  fprintf(out,"Incr. Length   = %f ft      \n",dL);
  fprintf(out,"Temp. Gradient = %f °/ft    \n",temp_grad);
  fprintf(out,"Pres.Drop(Surf)= %f psia    \n",p_drop_surf);
  fprintf(out,"Salinity       = %f % by wt \n",salinity);
  fprintf(out,"Ave. Cutting Sz= %f in      \n",solid_size);
  fprintf(out,"Dens. of Solids= %f #/ft^3  \n",rho_s);


/*****************************************/
/* start calculations down drill pipe id */
/*****************************************/

  clrscr();


for(current_depth=0;current_depth<current_td-motor_length;current_depth+
=dL)
  {

    if(current_depth>(current_td - dc_length))
    {
      x_sect_area = PI/4.0 * sqr(dc_id) / 144.0;
      diameter = dc_id/12.0;
    }
    else
    {
      x_sect_area = PI/4.0 * sqr(dp_id) / 144.0;
```

```
    diameter = dp_id/12.0;
  }


   /**************************/
   /* gas phase calculation */
   /**************************/
   z_factor(HALL,press_prev,temp_prev,pcr,tcr,
                      &zfact,&dzdp,&gascmp,&erflag);

   q_g =  (zfact * baro_press * q_scfs * (temp_prev + 460.0) /
                                        (520.0 * press_prev));

   rho_g = ( 2.7 * press_prev * spgr) /
                                 ( (temp_prev + 460.0) * zfact);

   visc_gas(&u_g,press_prev,zfact,(temp_prev + 460.0),spgr);

   v_g   = q_g / x_sect_area;


   /*****************************/
   /* liquid phase calculation */
   /*****************************/
   visc_wat(&u_w,press_prev,(temp_prev + 460.0),salinity);

   liquid_holdup = inj_rate / (q_g + inj_rate);

   foam_quality = q_g / ( q_g + inj_rate );

   rho_liquid = spgr_inj * 62.37;


   /****************************************/
   /* "fluid" (gas + liquid) calculations */
   /****************************************/


   visc_fluid = (u_g * q_g + u_w * inj_rate) / (q_g + inj_rate);

   rho_fluid = foam_quality * rho_g + (1- foam_quality) * rho_liquid;

   v_fluid = (q_g + inj_rate) / x_sect_area;

   Re_fluid  = 1488. * (rho_fluid * v_fluid * diameter) / visc_fluid;


   /* FRICTION BASED ON IKOKU */

   if(Re_fluid < 100000.0) f_fluid = 0.0701 / pow(Re_fluid,0.25);
   else      f_fluid = 0.0008 + (0.0552 / (pow(Re_fluid,0.237)));

   p_drop_head = rho_fluid * dL / 144.0;
   p_drop_fric = (2 * f_fluid * rho_fluid * sqr(v_fluid) * dL) /
                       (144.0 * 32.174 * diameter);

   press_drop  = p_drop_head - p_drop_fric;
```

```
    fprintf(profile,"%g , %g , %g , %g , %g , %g , %g , %g , %g , %g\n"
             ,current_depth
             ,press_prev
             ,press_drop
             ,p_drop_head
             ,p_drop_fric
             ,rho_fluid
             ,v_fluid
             ,Re_fluid
             ,f_fluid
             ,foam_quality);


    cprintf("%6.2f\r",current_depth);


    if(current_depth == 0)
         fprintf(out,"Surface Injection Rate = %f C.F.M.\n",q_g*60);



    press_prev += press_drop;
    temp_prev += (temp_grad * dL);



    /* if pressure ever drops to atmospheric.... stop     */
    if( press_prev < baro_press ) exit(1);  /* for safety */


  } /* end of calculation down drill string [i.e. for(increment)]*/



  bhp_id = press_prev;


  printf("\nPressure at Top of Motor  (ID)      = %f psia\n",bhp_id);
  printf("\nFlow Rate at Top of Motor (ID)      = %f cfm
\n",q_g*60.+inj_rate*60.);

  fprintf(out,"\nPressure at Top of Motor  (ID) = %f psia\n",bhp_id);
  fprintf(out,"\nFlow Rate at Top of Motor (ID) = %f cfm
\n",q_g*60.+inj_rate*60.);


  fprintf(print,"%f,%f,%f,%f,%f,",
      current_td,q_press_surf,bhp_id,q_g*60.+inj_rate*60.,foam_quality);


  /******************************************************/
  /* Now start from surface and work down annulus using */
  /*     q_scfs, baro_pres, and 60F as a starting point */
  /******************************************************/

  press_prev = baro_press;
  temp_prev  = 60.0;
```

```
for(current_depth=0;current_depth<current_td;current_depth+=dL)
{
  if(current_depth>(current_td - dc_length))
  {
    x_sect_area = PI/4.0 * (sqr(bit_size) - sqr(dc_od)) / 144.0;
    diameter = (bit_size - dc_od)/12.0;
  }
  else
  {
    x_sect_area = PI/4.0 * (sqr(bit_size) - sqr(dp_od)) / 144.0;
    diameter = (bit_size - dp_od)/12.0;
  }

  /***************************/
  /* gas phase calculations */
  /***************************/


  z_factor(HALL,press_prev,temp_prev,pcr,tcr,
                       &zfact,&dzdp,&gascmp,&erflag);

  q_g = zfact * (baro_press * q_scfs * (temp_prev + 460.0)) /
                                         (520.0 * press_prev);

  visc_gas(&u_g,press_prev,zfact,(temp_prev + 460.0),spgr);


  rho_g = (2.7 * press_prev * spgr) / ( (temp_prev + 460.0) * zfact);

  w_g = q_g * rho_g;

  v_g   = q_g / x_sect_area ;


  /******************************/
  /* liquid phase calculations */
  /******************************/

  visc_wat(&u_w,press_prev,(temp_prev + 460.0),salinity);

  liquid_holdup = inj_rate / (q_g + inj_rate);

  foam_quality = q_g / ( q_g + inj_rate );

  rho_liquid = spgr_inj * 62.37;


  /****************************************/
  /* "fluid" (gas + liquid) calculations */
  /****************************************/

  visc_fluid = (u_g * q_g + u_w * inj_rate) / (q_g + inj_rate);

  rho_fluid = foam_quality * rho_g + (1- foam_quality) * rho_liquid;

  v_fluid = (q_g + inj_rate) / x_sect_area;

  Re_fluid  = 1488. * (rho_fluid * v_fluid * diameter) / visc_fluid;
```

```
    w_fluid   = w_g + (inj_rate * spgr *62.37);


    /* FRICTION BASED ON IKOKU */

    if(Re_fluid < 100000.0) f_fluid = 0.0701 / pow(Re_fluid,0.25);
    else      f_fluid = 0.0008 + (0.0552 / (pow(Re_fluid,0.237)));


    /******************************/
    /* solid phase calculations */
    /******************************/

    q_solid = rop * (PI/4.0 * sqr(bit_size)/144.0) / 3600.0;

    w_s   =  q_solid * rho_s;

    f_s  = 110.0 * pow((32.174 * solid_size/12.0 )/sqr(v_fluid),0.985) *

pow((w_s/w_fluid),1.088);

    /*********************************************/
    /* mixture (gas+liquid+solid) calculations */
    /*********************************************/

    f_m = f_s + f_fluid;


    rho_mix = ((rho_g * q_g) + (spgr_inj * 62.37 * inj_rate) + w_s)
                                              / ( q_g + inj_rate +
q_solid);


    p_drop_head = rho_fluid * dL / 144.0;
    p_drop_fric = (2 * f_m * rho_fluid * sqr(v_fluid) * dL) /
                                         (144.0 * 32.174 * diameter);

    press_drop  = p_drop_head + p_drop_fric;


    fprintf(profile,"%g , %g , %g , %g , %g , %g , %g , %g , %g , %g\n"
              ,current_depth
              ,press_prev
              ,press_drop
              ,p_drop_head
              ,p_drop_fric
              ,rho_fluid
              ,v_fluid
              ,Re_fluid
              ,f_fluid
              ,foam_quality);


    cprintf("%6.2f\r",current_depth);

    press_prev += press_drop;
    temp_prev += (temp_grad * dL);
```

```
  } /* end of annular calculations */


  bhp_od = press_prev;


  printf("\nPressure at Bottom of Hole  (OD)      = %f psia\n",bhp_od);
  printf("\nFlow Rate at Bottom of Hole (OD)      = %f cfm
\n",q_g*60.+inj_rate*60.);

  printf("\nBottom Hole Pressure differential     = %f
psia",(bhp_id-bhp_od));
  printf("\nPercent Difference in BHP's(wrt/BHPID)= %f\%   ",

(fabs(bhp_od-bhp_id)/bhp_id*100));

  printf("\nFoam Quality @ bottom of hole         = %f     ",
                                                  (q_g/(q_g + inj_rate
+ q_solid)));

  fprintf(out,"\nPressure at Bottom of Hole  (OD)      = %f
psia\n",bhp_od);
  fprintf(out,"\nFlow Rate at Bottom of Hole (OD)      = %f cfm \n",

q_g*60.+inj_rate*60.);

  fprintf(out,"\nBottom Hole Pressure differential     = %f
psia",(bhp_id-bhp_od));
  fprintf(out,"\nPercent Difference in BHP's(wrt/BHPID)= %f\%   ",

(fabs(bhp_od-bhp_id)/bhp_id*100));

  fprintf(out,"\nFoam Quality @ bottom of hole         = %f     ",
                                                  (q_g/(q_g + inj_rate
+ q_solid)));


  fprintf(print,"%f,%f,%f\n",bhp_od,q_g*60.+inj_rate*60.,foam_quality);

  fclose(print);
  fclose(out);
  fclose(profile);

} /* end of main */
```

=== z_factor.c ===

```
/*
                ***** z_factor.c *****

  original fortran code by Louise Zimmerman, CSM, Sept 1986
  conversion to C       by Wade A. Bard    , CSM, May  1990

  zfactr: routine to calculate the z factor of a non-ideal gas
    using either 1) hall and yarborough or 2) dranchuck.

  usage:  zfactr (choice,pres,tempf,pcr,tcrr,zfact,dzdp,gascmp,erflag);

  where:  choice;(integer);the number of the z-factor correlation.
      1 - hall and yarborough
      2 - dranchuk, purvis and robinson
      pres  ;(real)   ;the pressure of the gas      (psi).
      tempf ;(real)   ;the temperature of the gas (deg f).
      pcr   ;(real)   ;the critical pressure        (psi).
      tcrr  ;(real)   ;the critical temperature   (deg r).
      zfact ;(real)   ;(returned) the value of z-factor.

      dzdp  ;(real)   ;(returned) the value of dz/dp  (choice=2)
      gascmp;(real)   ;(returned) gas compressibility (choice=2)
      erflag;(integer);(returned/passed) error flag

  (passed) erflag <  0  will suppress error printing
  (passed) erflag >= 0  prints error messages to (*)
       (returned) erflag =  0  no error
  (returned) erflag >= 0  an error occured in this
                          subroutine.
  (returned) erflag >= 100 *** fatal     error
  (returned) erflag <  100 *** non fatal error

*/

#include <math.h>

#define sqr(x)  x * x

z_factor(choice,pres,tempf,pcr,tcrr,zfact,dzdp,gascmp,erflag)

double pres,tempf,pcr,tcrr,*zfact,*dzdp,*gascmp;
int choice,*erflag;
{

    double t,ffact,rho,tcrf,tempr,pr,tr;
    double fprime,rhonew,consta;
    double a,b,c,d,e,f,g;
    int rtnflg;

/*     evaluate the input data for range of validity. */

    rtnflg = 0;
    tcrf = tcrr - 460.0;

/*     check for a valid choice for the correlation. */

    if((choice != 1)&&(choice != 2))
```

```
    {
     rtnflg = 100;
     if (erflag >= 0)
     {
      printf("ERROR");
      /*write(*,100)*/
      /*write (*,500) choice, pres, tempf, pcr, tcrr, erflag*/

     }

     *erflag = rtnflg;

     return;

    }

    if (pres <= 0.0)
    {
     rtnflg = 200;
     if (erflag >= 0)
     {
/*      write (*,200)*/
/*      write (*,500) choice, pres, tempf, pcr, tcrr, erflag*/
     }

     *erflag = rtnflg;
     return;
    }

    if (tempf <= -460.0)
    {
     rtnflg = 300;
     if (erflag >= 0)
     {
/*      write (*,300)*/
/*      write (*,500) choice, pres, tempf, pcr, tcrr, erflag*/
     }

     *erflag = rtnflg;
     return;
    }

    if (pcr <= 0.0)
    {
     rtnflg = 400;
     if (erflag >= 0)
     {
/*      write (*,400)*/
/*      write (*,500) choice, pres, tempf, pcr, tcrr, erflag*/
     }

     *erflag = rtnflg;
     return;
    }

    if (tcrf <= -460.0)
    {
     rtnflg = 500;
     if (erflag >= 0)
     {
```

```
/*      write (*,450)*/
/*      write (*,500) choice, pres, tempf, pcr, tcrr, erflag*/
     }

     *erflag = rtnflg;
     return;
    }

/*     convert temperature from fahrenheit to rankine. */

    tempr = tempf + 460.;

/*     calculate the reduced temperature and pressure. */

    pr = pres  / pcr;
    tr = tempr / tcrr;

/*     hall and yarborough z-factor correlation. */

    if (choice == 1)
    {

/*     make initial guess for reduced density (rho). */

    rho = .001;

    t   = 1.0 / tr;

125:
    ffact = - 0.06125 * pr * t * exp(-1.2 * sqr(1.0 - t))
        + (rho + sqr(rho) + pow(rho,3.0) - pow(rho,4.0)) /(pow((1.-
rho),3.0))
        - ((14.76 * t - 9.76 * sqr(t) + 4.58 * pow(t,3.0)) * sqr(rho))
        + (90.7 * t - 242.2 * sqr(t) + 42.4 * pow(t,3.0))
        * pow(rho,(2.18 + 2.82 * t));

    fprime = (1.0 + 4.0*rho + 4.0*sqr(rho) - 4.0*pow(rho,3.0)
         + pow(rho,4.0)) / (pow((1.0 - rho),4.0))
         - (29.52 * t - 19.52 * sqr(t) + 9.16 * pow(t,3.0)) * rho
         + (2.18 * 2.82 * t) * (90.7 * t - 242.2 * sqr(t)
         + 42.4 * pow(t,3.0)) * pow(rho,(1.18 + 2.82 * t));

    rhonew = rho - (ffact / fprime);

    if (fabs(ffact / fprime) <= .0000001)
    {
      consta = 0.06125 * pr * t * exp(-1.2 * sqr(1.0 - t));
      *zfact   = consta / rhonew;
      *dzdp    = 0.0;
      *gascmp = 0.0;
    }
    else
    {
      rho = rhonew;
      goto 125;
    }

    }

/*     dranchuk, purvis and robinson  z-factor */
```

```
    if (choice == 2)
    {

    rho = .27 * pr / tr;
    g   = .27 * pr;
    f   = .6845;
    e   = .6816 / sqr(tr);
    d   = tr;
    c   = .3151 * tr - 1.0467 - (.5783 / sqr(tr));
    b   = .5353 * tr - .6123;
    a   = .06423;

150:
    fprime = (6. * a * pow(rho,5.)) + (3. * b * sqr(rho)) + (2. * c *
rho)
          + (d) + e * sqr(rho) * (3. + f * sqr(rho) * (3. - 2. * f
          * sqr(rho))) * exp( -f * sqr(rho));

    ffact  = (a * pow(rho,6.)) + (b * pow(rho,3.)) + (c * sqr(rho)) +
          (d * rho) + (e * pow(rho,3.)) * (1. + f * sqr(rho)) *
          exp(-f * sqr(rho)) - g;

    rhonew = rho - (ffact / fprime);

    if (fabs(ffact / fprime) <= .0000001)
    {
      *zfact = 0.27 * pr / rhonew / tr;
      *dzdp  = 1.0 / (rhonew * tr) * ((5.0 * a * pow(rhonew,5.0)) +
          (2. * b * sqr(rhonew)) + (c * rhonew) +
          (2. * e * sqr(rhonew)) * (1. + f * sqr(rhonew) - sqr(f) *
          pow(rhonew,4.)) * exp(-f * sqr(rhonew)));

      *gascmp =  1.0 / pr / pcr * (1.0 / (1.0 + rhonew / *zfact *
(*dzdp)));
    }
    else
    {
      rho = rhonew;
      goto 150;
    }
    }

/*     define required format statements for this subroutine */

/*100   format (/,1x,'? Fatal  - 100 - choice out of range',/
     &          1x,'                 choice = 1 or 2    ',/
     &          1x,'                 1 = h&y, 2 = dp&r  ',/)

200   format (/,1x,'? Fatal  - 200 - pressure out of range',/
     &          1x,'                 0.0 < Pres           ',/
     &          1x,'                 pressure is (psia)   ',/)

300   format (/,1x,'? Fatal  - 300 - temperature out of range',/
     &          1x,'                 -460.0 < Tempf          ',/
     &          1x,'                 temperature is (deg f)  ',/)

400   format (/,1x,'? Fatal  - 400 - critical pressure out of range',/
     &          1x,'                 0.0 <  Pcr                     ',/
     &          1x,'                 critical presure is (psia)     ',/)
```

```
450   format (/,1x,'? Fatal  - 500 - critical temp   out of range   ',/
     &          1x,'                 -460.0 <  Tcrf                 ',/
     &          1x,'                 critical temperature is (deg f)',/)

500   format (1x,'input parameters for (zfactr)',/
     &         1x,'   choice         = ',i15,' n/a',/
     &         1x,'   pressure       = ',e15.8,' Psia',/
     &         1x,'   temperature    = ',e15.8,' Deg f',/
     &         1x,'   critic. Press. = ',E15.8,' Psia',/
     &         1x,'   critic. Temp.  = ',E15.8,' Deg f',/
   &         1x,'   erflag         = ',i15,/)
*/

/*     reset erflag to 0 and return to the main program */

    *erflag = 0;

    return;

} /* end of z_factor.c */
```

=== visc_wat.c ===

```
#include <math.h>


visc_wat(vis,p,t,sal)
double *vis,p,t,sal;
{

      double aa,tk,tc,tf,tx,ab,ps,pb,salp;
      int i;

/*       water viscosity including salinity correction  (salinity as %
nacl) */


      double data[9] ={-7.419242,   -.29721,  -.1155286, -.008685635,
                         .001094098, .00439993, .002520658,
.0005218684};



/*       Determine saturation pressure for water */


        aa  = 0.;
        tk  = .55555555 * t;
        tc  = tk - 273.15;
        tf  = t - 459.67;
        tx  = .65 - .01 * tc;




    for(i=1;i<9;i++) aa = aa + data[i] * pow(tx,(i - 1));

    ab  = (374.136 - tc) * aa / tk;
    ps  = 3203.594 * exp(ab);


/*       calculate uncorrected water viscosity */


    pb  = .068947573 * (p - ps);
    aa  = 1. + 1.0467e-06 * pb * (tk - 305.);
    ab  = 247.8 / (tk - 140.);
    *vis= .02414 * aa * pow(10.,ab);


/*       salinity correction */


    if(sal == 0.) return;
    salp= .0001 * sal;
    aa  = (.00276 - .000344 * sqrt(salp)) * salp;
    ab  = (sqrt(tf) - .0135 * tf) * aa;
    *vis*= (1. - .00187 * sqrt(salp) + .000218 * pow(salp,2.5) + ab);
```

```
    return;

} /* end of visc_water.c */
```

=== visc_gas.c ===

```
#include <math.h>


visc_gas(vis,p,z,t,spgr)

   double  *vis,p,z,t,spgr;

{

/*

       subroutine visg (vis,p,z,t,spgr)
c
c      lee*s correlation for non-ideal gas viscosity
c


*/

      double am,den,ak,x,y,tst;


       am = 28.85 * spgr;
       den = .00150274 * p*am / (t*z);
       ak = (9.4+ .02*am) * pow(t,1.5) / (209. + 19.*am + t);
       x = 3.5 + (986./t) + .01*am;
       y = 2.4 - .2*x;
       tst = x * pow(den,y);
       if(tst<1.E-06) tst = 1.E-06;
       if(tst>20.) tst = 20.;
     *vis = 1.E-04 * ak * exp(tst);
     return;


} /* end of visc_gas.c */
```

=== critical.c ===

```
critical(spgr,co2,xn2,h2s,crit_p,crit_t)

       double  spgr,co2,xn2,h2s,*crit_p,*crit_t;

{


/*     subroutine critp (spgr,co2,xn2,h2s,pcr,tcr)
c
c     determine critical pressure and temperature without
c     impurities corrections
c
c     values determined from curve fits of the *iocc* tables
c
*/


     double sg,pccor,tccor,pncor,tncor,pscor,tscor;

       double pcr,tcr;


         sg = 100. * spgr;
         if (sg<96.67) pcr = 689. - .3 * sg;
         if (sg>=96.67) pcr = 718. - .6 * sg;
         if (sg<59.67) tcr = 88.9 + 4.5 * sg;
         if (sg>=59.67) tcr = 160.5 + 3.3 * sg;
/*
c
c     correct for carbon dioxide
c
*/
       pccor = 0.;
         tccor = 0.;
         if (co2<=0.) goto 15;
         if (co2>=1.) goto 11;
         pccor = 3.47 * co2;
         tccor = -1. * co2;
       goto 15;
11:   if (co2<16.18) goto 12;
         pccor = 1.4413 + 4.291 * co2;
       goto 13;
12:    pccor = -.97 + 4.44 * co2;
13:    if (co2<5) goto 14;
         tccor = -(2. + 5.*co2) /3.;
       goto 15;
14:    tccor = 1. - 2. * co2;
/*
c
c      correct for nitrogen
c
*/
15:    pncor = 0.;
         tncor = 0.;
```

```
          if (xn2<=0.) goto 110;
          if (xn2>=1.) goto 16;
          pncor = -1. * xn2;
          tncor = -3. * xn2;
        goto 110;
16:     if (xn2<5.) goto 17;
          pncor = -(2. + 5. * xn2) / 3.;
        goto 18;
17:     pncor = 1. - 2. * xn2;
18:     if (xn2<13.8) goto 19;
          tncor = -.94 - 2.7 * xn2;
        goto 110;
19:     tncor = -.25 - 2.75 * xn2;
/*
c
c       correct for hydrogen sulfide
c
*/
110:    pscor = 6. * h2s;
          tscor = 1.4 * h2s;
/*
c
c       sum corrections for corrected critical pressure and temperature
c
*/
          *crit_p = pcr + pccor + pncor + pscor;
          *crit_t = tcr + tccor + tncor + tscor;


        return;


} /* end of critical.c */
```

Appendix D

Data Tables

WELL: AZCO - SLANOVICH #32-1
OPERATOR: AZCO PETROLEUM CO.
CONTRACTOR: FUTURE DRILLING CO.

(1) DEPTH [feet]	(2) CIRCULATION METHOD	(3) DATE	(4) BAROMETRIC PRESSURE [psia]	(5) BAROMETRIC PRESSURE [in. HG]	(6) AMBIENT TEMPERATURE [C]
785	CONVENTIONAL	02/26/89	12.04	24.50	10.0
810	CONVENTIONAL	02/26/89	12.04	24.50	10.0
860	CONVENTIONAL	02/26/89	12.04	24.50	10.5
900	CONVENTIONAL	02/26/89	12.04	24.50	12.5
930	CONVENTIONAL	02/26/89	12.04	24.50	14.7
950	CONVENTIONAL	02/26/89	12.04	24.50	13.2
975	CONVENTIONAL	02/26/89	12.04	24.50	14.0
1000	CONVENTIONAL	02/26/89	12.04	24.50	13.5
1026	CONVENTIONAL	02/26/89	12.04	24.50	15.0
1050	CONVENTIONAL	02/26/89	12.04	24.50	13.7
1075	CONVENTIONAL	02/26/89	12.04	24.50	13.5
1100	CONVENTIONAL	02/26/89	12.04	24.50	12.5
1500	DIRECTIONAL	02/26/89	12.04	24.50	1.8
1511	DIRECTIONAL	03/01/89	12.04	24.50	0.0
1536	DIRECTIONAL	03/01/89	12.04	24.50	7.7
1550	DIRECTIONAL	03/01/89	12.04	24.50	6.2
1575	DIRECTIONAL	03/01/89	12.04	24.50	5.5
1601	DIRECTIONAL	03/01/89	12.04	24.50	4.2
1611	DIRECTIONAL	03/01/89	12.04	24.50	4.1
1625	DIRECTIONAL	03/01/89	12.04	24.50	3.4
1636	DIRECTIONAL	03/01/89	12.04	24.50	2.8
1661	DIRECTIONAL	03/01/89	12.04	24.50	0.3
1702	DIRECTIONAL	03/02/89	12.01	24.44	4.2
1730	DIRECTIONAL	03/02/89	12.01	24.44	3.0
1750	DIRECTIONAL	03/02/89	12.01	24.44	5.6
1786	DIRECTIONAL	03/02/89	12.01	24.44	8.7
1811	DIRECTIONAL	03/02/89	12.01	24.44	11.1
1827	DIRECTIONAL	03/02/89	12.01	24.44	14.0
1836	DIRECTIONAL	03/02/89	12.01	24.44	14.0

Orifice Meter-Run Factors

Basic Orifice: 542.26

"b" : 0.0772552

Specific Gravity: 1

Beta Constant: 0.725689

(7) PRESSURE DOWNSTREAM FLANGE TAP [psig]	(8) DIFFERENTIAL PRESSURE METER-RUN [in H2O]	(9) TEMPERATURE METER-RUN [lF]	(10) ORIFICE PLATE DIAMETER [in]	(11) FLOWING TEMPERATURE FACTOR	(12) REYNOLDS NUMBER FACTOR	(13) hw/pf	(14) EXPANSION FACTOR	(15) Z FACTOR	(16) SUPER COMPRESSIBILITY FACTOR
45.0	68.0	88.0	1.5	0.9741	1.0012	1.1922	1.0049	0.9977	1.0011
45.0	67.0	91.0	1.5	0.9715	1.0012	1.1747	1.0048	0.9978	1.0011
45.0	66.5	92.0	1.5	0.9706	1.0013	1.1659	1.0048	0.9978	1.0011
46.0	67.0	96.0	1.5	0.9671	1.0012	1.1544	1.0047	0.9978	1.0011
47.0	67.0	98.0	1.5	0.9653	1.0012	1.1349	1.0046	0.9978	1.0011
48.0	66.0	97.0	1.5	0.9662	1.0012	1.0993	1.0045	0.9978	1.0011
48.0	66.5	97.0	1.5	0.9662	1.0012	1.1076	1.0045	0.9978	1.0011
48.0	66.0	98.0	1.5	0.9653	1.0012	1.0993	1.0045	0.9978	1.0011
48.0	66.0	99.0	1.5	0.9645	1.0012	1.0993	1.0045	0.9978	1.0011
48.0	65.0	98.0	1.5	0.9653	1.0012	1.0827	1.0044	0.9978	1.0011
48.0	65.0	94.0	1.5	0.9688	1.0012	1.0827	1.0044	0.9977	1.0011
45.0	62.5	94.0	1.5	0.9688	1.0013	1.0958	1.0045	0.9978	1.0011
205.0	24.0	93.0	1.5	0.9697	1.0011	0.1106	1.0004	0.9922	1.0039
150.0	34.0	95.0	1.5	0.9680	1.0010	0.2098	1.0008	0.9941	1.0029
280.0	57.0	120.5	1.5	0.9465	1.0006	0.1952	1.0008	0.9919	1.0041
290.0	47.0	116.0	1.5	0.9501	1.0006	0.1556	1.0006	0.9914	1.0044
275.0	50.0	110.0	1.5	0.9551	1.0006	0.1742	1.0007	0.9913	1.0044
290.0	41.0	106.0	1.5	0.9585	1.0007	0.1357	1.0005	0.9906	1.0047
285.0	44.0	109.0	1.5	0.9560	1.0007	0.1481	1.0006	0.9909	1.0046
295.0	34.0	102.0	1.5	0.9619	1.0008	0.1107	1.0004	0.9901	1.0050
295.0	33.0	100.0	1.5	0.9636	1.0008	0.1075	1.0004	0.9899	1.0051
283.0	48.0	110.0	1.5	0.9551	1.0006	0.1627	1.0007	0.9911	1.0045
290.0	45.0	111.0	1.5	0.9543	1.0007	0.1490	1.0006	0.9910	1.0045
295.0	37.0	108.0	1.5	0.9568	1.0007	0.1205	1.0005	0.9906	1.0047
285.0	50.0	114.0	1.5	0.9518	1.0006	0.1683	1.0007	0.9913	1.0044
298.0	35.0	128.0	1.5	0.9404	1.0007	0.1129	1.0005	0.9920	1.0040
285.0	50.0	121.0	1.5	0.9460	1.0006	0.1683	1.0007	0.9918	1.0041
290.0	39.0	121.0	1.5	0.9460	1.0007	0.1291	1.0005	0.9917	1.0042
305.0	28.0	126.0	1.5	0.9420	1.0008	0.0883	1.0004	0.9917	1.0042

HOLE DATA BIT SIZE: 6.25 IN CUT. SIZE 0.00521 FT
COLLAR OD: 4.75 IN COLLAR ID 2.25 IN
PIPE OD: 3.5 IN PIPE ID 2.75 IN

(17) FLOW RATE S.C.F.M. [14.7 psia / 60 lF]	(18) Density Of Injected Air (#/ft^3)	(19) FLOW RATE (@ Line Cond) [C.F.M.]	(20) MASS FLOW RATE OF AIR LBM/SEC (@ Line Cond)	(21) WATER INJECTION RATE [sec/20stk]	(22) WATER INJECTION RATE [C.F.M.]	(23) MASS FLOW RATE OF WATER LBM/SEC (@ Line Cond)	(24) MINUTES PER 25' JOINT	(25) R.O.P. OF PRIOR JOINT	(26) Ws Mass Rate of Solids
552.2	0.282	122.57	0.58	24.51	0.7986	0.93	26.5	56.6	0.5644
546.6	0.280	122.00	0.57	25.40	0.7706	0.90	20.5	73.2	0.7296
544.1	0.280	121.65	0.57	24.46	0.8003	0.93	22.0	68.2	0.6798
548.9	0.282	121.48	0.57	23.09	0.8477	0.99	21.0	71.4	0.7122
552.5	0.286	120.65	0.58	24.46	0.8003	0.93	22.0	68.2	0.6798
553.4	0.292	118.62	0.58	22.58	0.8669	1.01	23.0	65.2	0.6503
555.5	0.292	119.07	0.58	22.70	0.8623	1.00	25.5	58.8	0.5865
552.9	0.291	118.73	0.58	22.46	0.8715	1.02	22.0	68.2	0.6798
552.4	0.291	118.84	0.58	26.92	0.7271	0.85	23.0	65.2	0.6503
548.7	0.291	117.82	0.57	25.88	0.7563	0.88	21.5	69.8	0.6956
550.7	0.293	117.39	0.57	27.19	0.7199	0.84	23.0	65.2	0.6503
526.4	0.279	118.12	0.55	26.64	0.7348	0.86	22.5	66.7	0.6647
636.0	1.068	37.23	0.66	7.58	2.5824	3.01	25.0	60.0	0.5983
652.5	0.793	51.44	0.68	8.56	2.2867	2.66	25.0	60.0	0.5983
1109.6	1.369	50.66	1.16	8.38	2.3358	2.72	23.0	65.2	0.6503
1028.9	1.428	45.04	1.07	8.65	2.2629	2.64	15.5	96.8	0.9649
1040.1	1.371	47.40	1.08	8.56	2.2867	2.66	15.0	100.0	0.9971
969.8	1.454	41.68	1.01	8.72	2.2448	2.61	16.0	93.8	0.9348
993.5	1.422	43.67	1.03	8.71	2.2473	2.62	16.0	93.8	0.9348
893.7	1.489	37.50	0.93	8.77	2.2320	2.60	12.0	125.0	1.2464
882.1	1.495	36.88	0.92	8.77	2.2320	2.60	12.0	125.0	1.2464
1033.2	1.410	45.81	1.08	8.50	2.3029	2.68	16.5	90.9	0.9064
1011.3	1.441	43.87	1.05	8.69	2.2525	2.62	16.0	93.8	0.9348
927.1	1.473	39.34	0.97	8.71	2.2473	2.62	18.0	83.3	0.8309
1054.2	1.409	46.76	1.10	8.78	2.2294	2.60	22.5	66.7	0.6647
889.9	1.435	38.77	0.93	8.72	2.2448	2.61	18.0	83.3	0.8309
1047.6	1.391	47.06	1.09	8.73	2.2422	2.61	24.5	61.2	0.6105
932.9	1.415	41.21	0.97	8.82	2.2193	2.59	18.0	83.3	0.8309
806.4	1.472	34.23	0.84	8.80	2.2243	2.59	18.0	83.3	0.8309

INJECTION FLUID SpGr: 1.12 gm/cc
Length of B.H.A. : 375 FT

(27) Flow Rate of Solids C.F.M.	(28) Particle Concentration	(29) FOAM QUALITY	(30) MEDIUM VISCOSITY	(31) SURFACE PRESSURE DROP
0.2010	0.0016	0.994	0.01479	1.05
0.2598	0.0021	0.994	0.01453	1.04
0.2421	0.0020	0.993	0.01468	1.04
0.2536	0.0021	0.993	0.01482	1.05
0.2421	0.0020	0.993	0.01452	1.05
0.2316	0.0019	0.993	0.01501	1.06
0.2089	0.0017	0.993	0.01496	1.06
0.2421	0.0020	0.993	0.01499	1.05
0.2316	0.0019	0.994	0.01415	1.04
0.2477	0.0021	0.994	0.01438	1.04
0.2316	0.0020	0.994	0.01430	1.04
0.2367	0.0020	0.994	0.01436	1.00
0.2131	0.0054	0.935	0.05410	1.63
0.2131	0.0040	0.957	0.03892	1.52
0.2316	0.0044	0.956	0.03349	2.23
0.3436	0.0073	0.952	0.03639	2.15
0.3551	0.0071	0.954	0.03690	2.17
0.3329	0.0076	0.949	0.04086	2.11
0.3329	0.0073	0.951	0.03878	2.12
0.4439	0.0112	0.944	0.04510	2.03
0.4439	0.0113	0.943	0.04637	2.03
0.3228	0.0067	0.952	0.03792	2.18
0.3329	0.0072	0.951	0.03824	2.15
0.2959	0.0071	0.946	0.04195	2.06
0.2367	0.0048	0.954	0.03571	2.18
0.2959	0.0072	0.945	0.03697	1.94
0.2174	0.0044	0.955	0.03414	2.15
0.2959	0.0068	0.949	0.03689	2.00
0.2959	0.0081	0.939	0.04031	1.84

DEPTH [feet]	AIR FLOW RATE (@ Line Cond) C.F.M.	INJ FLOW RATE (@ Line Cond C.F.M.	FLUID FLOW RATE (@Line Cond) C.F.M	DENSITY OF 2-PHASE FLUID [#/FT^3]	Fluid Viscosity (cp)
785	122.57	0.80	123.37	0.2816	0.01479
810	122.00	0.77	122.77	0.2800	0.01453
860	121.65	0.80	122.45	0.2795	0.01468
900	121.48	0.85	122.33	0.2824	0.01482
930	120.65	0.80	121.45	0.2862	0.01452
950	118.62	0.87	119.49	0.2916	0.01501
975	119.07	0.86	119.94	0.2916	0.01496
1000	118.73	0.87	119.60	0.2911	0.01499
1026	118.84	0.73	119.56	0.2905	0.01415
1050	117.82	0.76	118.58	0.2911	0.01438
1075	117.39	0.72	118.11	0.2932	0.01430
1100	118.12	0.73	118.86	0.2785	0.01436
1500	37.23	2.58	39.81	1.0678	0.05410
1511	51.44	2.29	53.73	0.7927	0.03892
1536	50.66	2.34	52.99	1.3691	0.03349
1550	45.04	2.26	47.30	1.4278	0.03639
1575	47.40	2.29	49.69	1.3713	0.03690
1601	41.68	2.24	43.93	1.4542	0.04086
1611	43.67	2.25	45.91	1.4220	0.03878
1625	37.50	2.23	39.73	1.4895	0.04510
1636	36.88	2.23	39.11	1.4950	0.04637
1661	45.81	2.30	48.11	1.4098	0.03792
1702	43.87	2.25	46.12	1.4407	0.03824
1730	39.34	2.25	41.59	1.4728	0.04195
1750	46.76	2.23	48.99	1.4089	0.03571
1786	38.77	2.24	41.02	1.4346	0.03697
1811	47.06	2.24	49.30	1.3913	0.03414
1827	41.21	2.22	43.43	1.4149	0.03689
1836	34.23	2.22	36.45	1.4724	0.04031

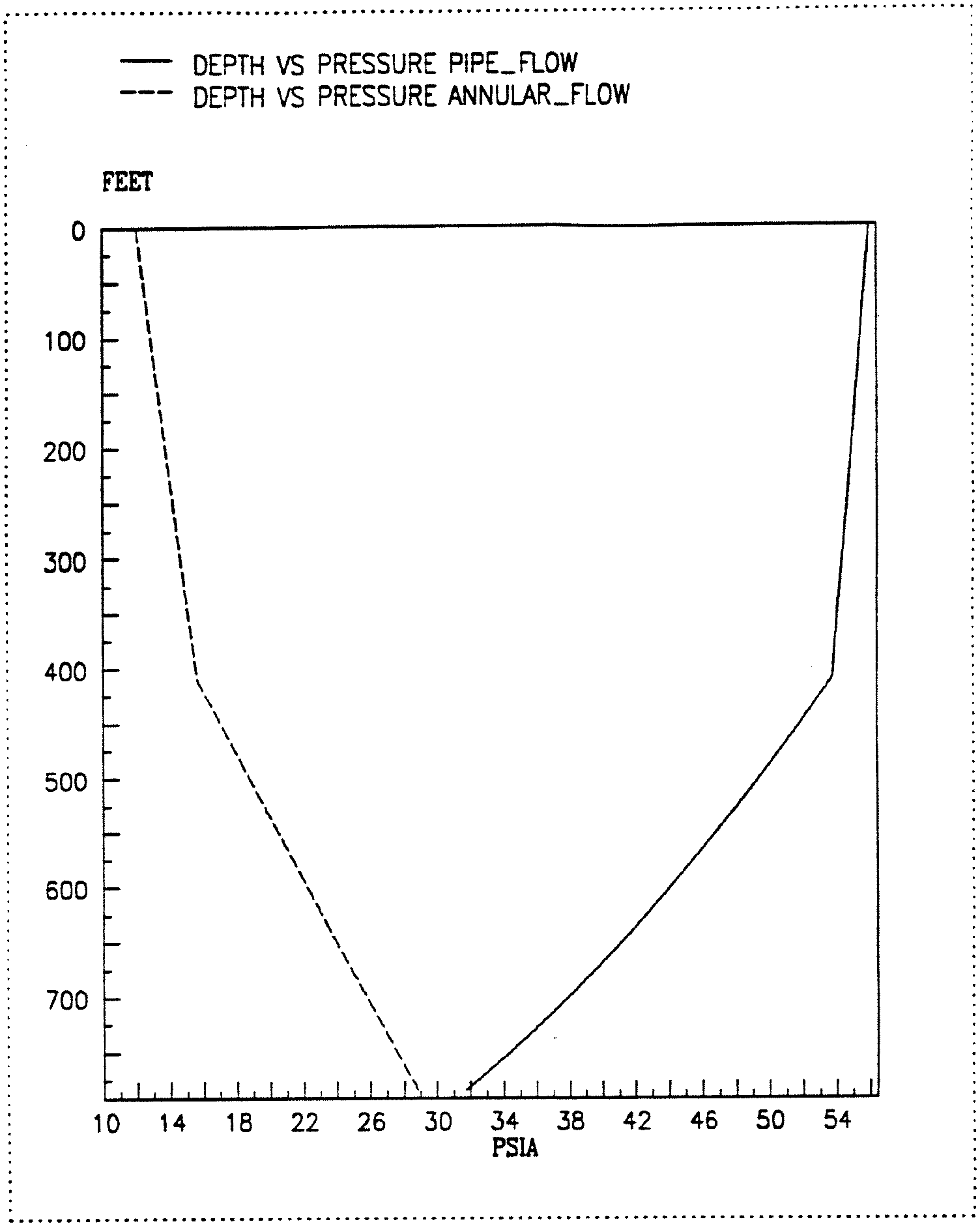
Reynolds Number 2.25	Reynolds Number 2.40625	Reynolds Number 2.75	Reynolds Number 2.764	Reynolds Number 3	Reynolds Number 3.125	Reynolds Number 3.626	Reynolds Number 4
395551	369866	323632	321993	296663	284797	245447	222497
398435	372563	325992	324341	298826	286873	247236	224120
392572	367080	321195	319568	294429	282652	243598	220822
392588	367095	321208	319581	294441	282663	243608	220831
403171	376991	329867	328196	302378	290283	250175	226784
391003	365613	319912	318291	293252	281522	242625	219939
393635	368074	322065	320434	295226	283417	244258	221420
391067	365673	319964	318343	293300	281568	242664	219975
413400	386556	338237	336523	310050	297648	256523	232538
404236	377987	330739	329064	303177	291050	250836	227383
407694	381220	333568	331878	305771	293540	252982	229328
388139	362935	317568	315960	291104	279460	240847	218328
132302	123711	108247	107699	99227	95258	82096	74420
184272	172307	150768	150005	138204	132676	114344	103653
364784	341096	298459	296948	273588	262644	226355	205191
312513	292220	255693	254398	234385	225010	193920	175789
311017	290821	254468	253179	233262	223932	192992	174947
263272	246177	215405	214314	197454	189556	163365	148091
283528	265117	231977	230802	212646	204140	175934	159484
220980	206631	180802	179886	165735	159106	137122	124301
212349	198560	173740	172860	159262	152891	131766	119446
301236	281675	246466	245218	225927	216890	186923	169445
292611	273610	239409	238196	219458	210680	181570	164594
245903	229935	201193	200174	184427	177050	152587	138320
325543	304404	266353	265004	244157	234391	202005	183118
268006	250603	219278	218167	201005	192964	166303	150753
338391	316418	276866	275463	253794	243642	209978	190345
280556	262338	229546	228384	210417	202001	174090	157813
224239	209678	183468	182539	168179	161452	139144	126134

Friction Factor 2.25	Friction Factor 2.40625	Friction Factor 2.75	Friction Factor 2.764	Friction Factor 3	Friction Factor 3.125	Friction Factor 3.626	Friction Factor 4
0.0036	0.0036	0.0037	0.0037	0.0038	0.0038	0.0040	0.0041
0.0036	0.0036	0.0037	0.0037	0.0038	0.0038	0.0040	0.0041
0.0036	0.0036	0.0037	0.0038	0.0038	0.0039	0.0040	0.0041
0.0036	0.0036	0.0037	0.0038	0.0038	0.0039	0.0040	0.0041
0.0036	0.0036	0.0037	0.0037	0.0038	0.0038	0.0040	0.0040
0.0036	0.0036	0.0038	0.0038	0.0038	0.0039	0.0040	0.0041
0.0036	0.0036	0.0037	0.0038	0.0038	0.0039	0.0040	0.0041
0.0036	0.0036	0.0038	0.0038	0.0038	0.0039	0.0040	0.0041
0.0035	0.0036	0.0037	0.0037	0.0038	0.0038	0.0039	0.0040
0.0036	0.0036	0.0037	0.0037	0.0038	0.0038	0.0040	0.0040
0.0036	0.0036	0.0037	0.0037	0.0038	0.0038	0.0040	0.0040
0.0036	0.0036	0.0038	0.0038	0.0038	0.0039	0.0040	0.0041
0.0046	0.0046	0.0048	0.0048	0.0049	0.0049	0.0051	0.0052
0.0042	0.0043	0.0044	0.0044	0.0045	0.0046	0.0047	0.0048
0.0036	0.0037	0.0038	0.0038	0.0039	0.0039	0.0040	0.0041
0.0038	0.0038	0.0039	0.0039	0.0040	0.0041	0.0042	0.0043
0.0038	0.0038	0.0039	0.0039	0.0040	0.0041	0.0042	0.0043
0.0039	0.0040	0.0041	0.0041	0.0042	0.0042	0.0043	0.0044
0.0039	0.0039	0.0040	0.0040	0.0041	0.0041	0.0043	0.0044
0.0041	0.0041	0.0043	0.0043	0.0043	0.0044	0.0045	0.0046
0.0041	0.0042	0.0043	0.0043	0.0044	0.0044	0.0046	0.0047
0.0038	0.0039	0.0040	0.0040	0.0041	0.0041	0.0042	0.0043
0.0038	0.0039	0.0040	0.0040	0.0041	0.0041	0.0042	0.0043
0.0040	0.0040	0.0042	0.0042	0.0042	0.0043	0.0044	0.0045
0.0037	0.0038	0.0039	0.0039	0.0040	0.0040	0.0042	0.0042
0.0039	0.0040	0.0041	0.0041	0.0042	0.0042	0.0043	0.0044
0.0037	0.0038	0.0039	0.0039	0.0039	0.0040	0.0041	0.0042
0.0039	0.0039	0.0040	0.0040	0.0041	0.0042	0.0043	0.0044
0.0041	0.0041	0.0042	0.0042	0.0043	0.0044	0.0045	0.0046

Pressure Drop	Pressure Drop	Pressure Drop	Pressure Drop	Pressure Drop	Pressure Drop	Pressure Drop	Pressure Drop	Total Pressure Drop
2.25	2.40625	2.75	2.764	3	3.125	3.626	4	
3	30.7	4.63	1.65	80.37	45	0.45	106.1	
3.11E-02	2.60E-01	2.63E-02	9.23E-03	3.52E-01	1.74E-01	1.12E-03	1.96E-01	1.05E+00
3.07E-02	2.57E-01	2.60E-02	9.12E-03	3.47E-01	1.72E-01	1.10E-03	1.94E-01	1.04E+00
3.07E-02	2.57E-01	2.60E-02	9.11E-03	3.47E-01	1.72E-01	1.10E-03	1.93E-01	1.04E+00
3.10E-02	2.59E-01	2.62E-02	9.19E-03	3.50E-01	1.74E-01	1.11E-03	1.95E-01	1.05E+00
3.10E-02	2.59E-01	2.62E-02	9.20E-03	3.50E-01	1.74E-01	1.11E-03	1.95E-01	1.05E+00
3.13E-02	2.62E-01	2.64E-02	9.28E-03	3.54E-01	1.75E-01	1.12E-03	1.97E-01	1.06E+00
3.14E-02	2.62E-01	2.65E-02	9.30E-03	3.54E-01	1.76E-01	1.12E-03	1.97E-01	1.06E+00
3.13E-02	2.62E-01	2.64E-02	9.27E-03	3.53E-01	1.75E-01	1.12E-03	1.97E-01	1.05E+00
3.08E-02	2.58E-01	2.60E-02	9.14E-03	3.48E-01	1.73E-01	1.10E-03	1.94E-01	1.04E+00
3.08E-02	2.57E-01	2.60E-02	9.13E-03	3.48E-01	1.72E-01	1.10E-03	1.94E-01	1.04E+00
3.08E-02	2.58E-01	2.60E-02	9.14E-03	3.48E-01	1.72E-01	1.10E-03	1.94E-01	1.04E+00
2.98E-02	2.49E-01	2.52E-02	8.83E-03	3.36E-01	1.67E-01	1.07E-03	1.87E-01	1.00E+00
4.84E-02	4.05E-01	4.09E-02	1.44E-02	5.47E-01	2.71E-01	1.74E-03	3.05E-01	1.63E+00
4.51E-02	3.78E-01	3.81E-02	1.34E-02	5.10E-01	2.53E-01	1.62E-03	2.84E-01	1.52E+00
6.61E-02	5.53E-01	5.59E-02	1.96E-02	7.48E-01	3.70E-01	2.37E-03	4.16E-01	2.23E+00
6.37E-02	5.33E-01	5.39E-02	1.89E-02	7.20E-01	3.57E-01	2.28E-03	4.01E-01	2.15E+00
6.43E-02	5.38E-01	5.44E-02	1.91E-02	7.27E-01	3.60E-01	2.31E-03	4.05E-01	2.17E+00
6.26E-02	5.23E-01	5.29E-02	1.86E-02	7.07E-01	3.50E-01	2.24E-03	3.94E-01	2.11E+00
6.29E-02	5.26E-01	5.32E-02	1.87E-02	7.11E-01	3.52E-01	2.25E-03	3.96E-01	2.12E+00
6.02E-02	5.04E-01	5.09E-02	1.79E-02	6.81E-01	3.37E-01	2.16E-03	3.79E-01	2.03E+00
6.00E-02	5.02E-01	5.08E-02	1.78E-02	6.79E-01	3.36E-01	2.15E-03	3.78E-01	2.03E+00
6.45E-02	5.40E-01	5.45E-02	1.91E-02	7.29E-01	3.61E-01	2.31E-03	4.06E-01	2.18E+00
6.36E-02	5.32E-01	5.38E-02	1.89E-02	7.19E-01	3.56E-01	2.28E-03	4.00E-01	2.15E+00
6.09E-02	5.10E-01	5.15E-02	1.81E-02	6.88E-01	3.41E-01	2.18E-03	3.83E-01	2.06E+00
6.45E-02	5.40E-01	5.45E-02	1.91E-02	7.29E-01	3.61E-01	2.31E-03	4.06E-01	2.18E+00
5.74E-02	4.80E-01	4.85E-02	1.70E-02	6.49E-01	3.21E-01	2.06E-03	3.61E-01	1.94E+00
6.36E-02	5.32E-01	5.37E-02	1.89E-02	7.19E-01	3.56E-01	2.28E-03	4.00E-01	2.15E+00
5.94E-02	4.97E-01	5.02E-02	1.76E-02	6.71E-01	3.32E-01	2.13E-03	3.74E-01	2.00E+00
5.45E-02	4.56E-01	4.60E-02	1.62E-02	6.16E-01	3.05E-01	1.95E-03	3.43E-01	1.84E+00

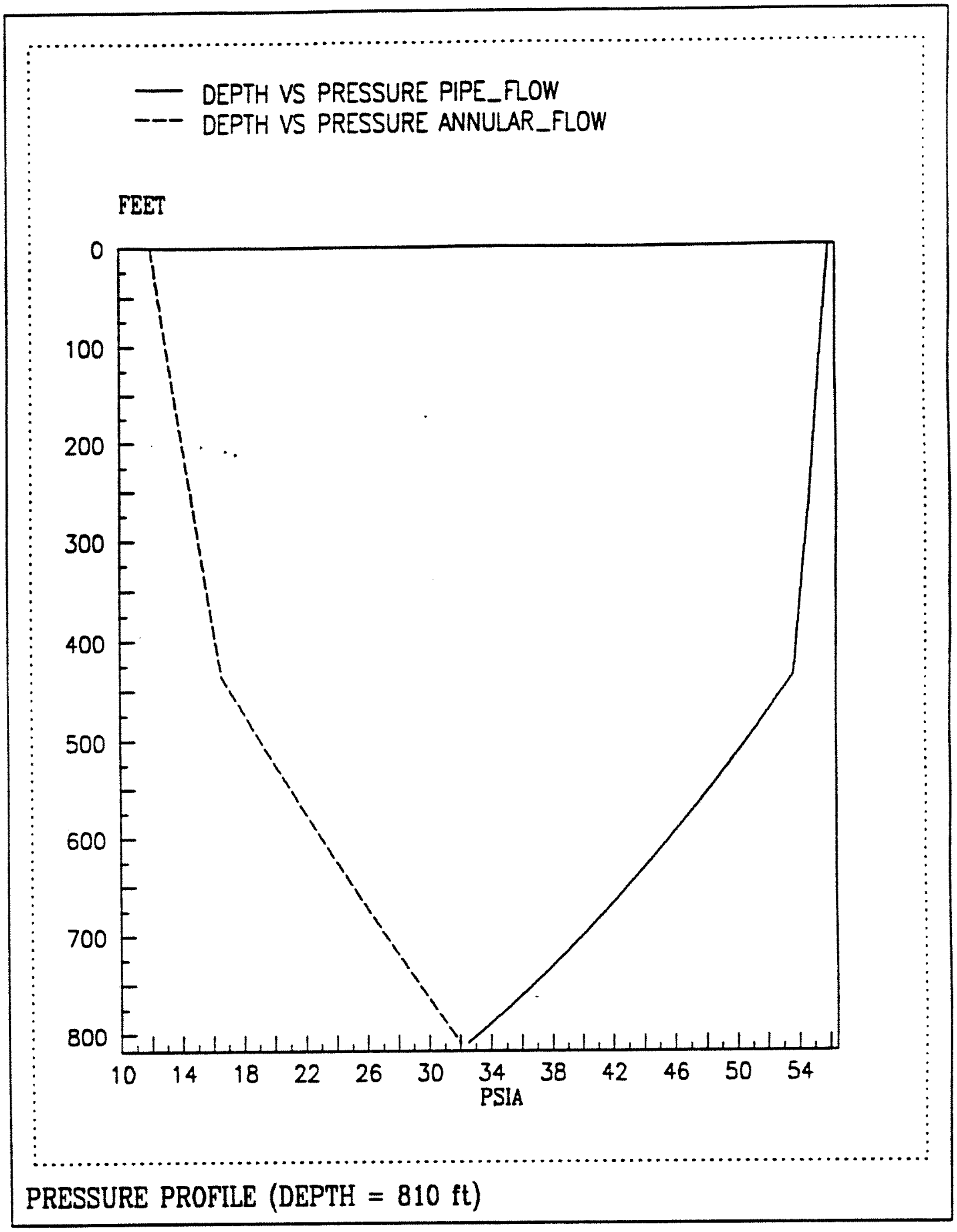
Appendix E

Pressure Profile Graphs

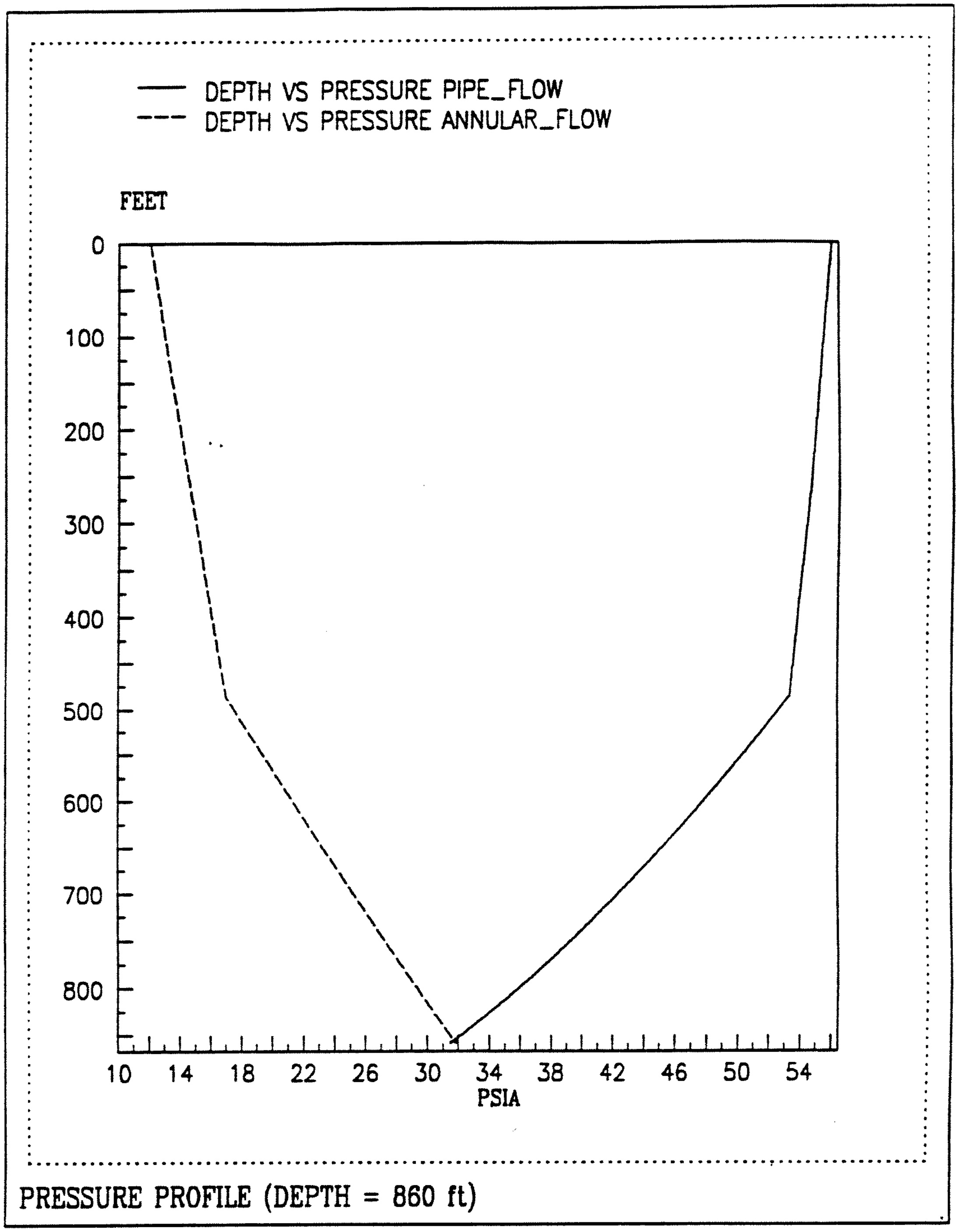


PRESSURE PROFILE (DEPTH = 785 ft)

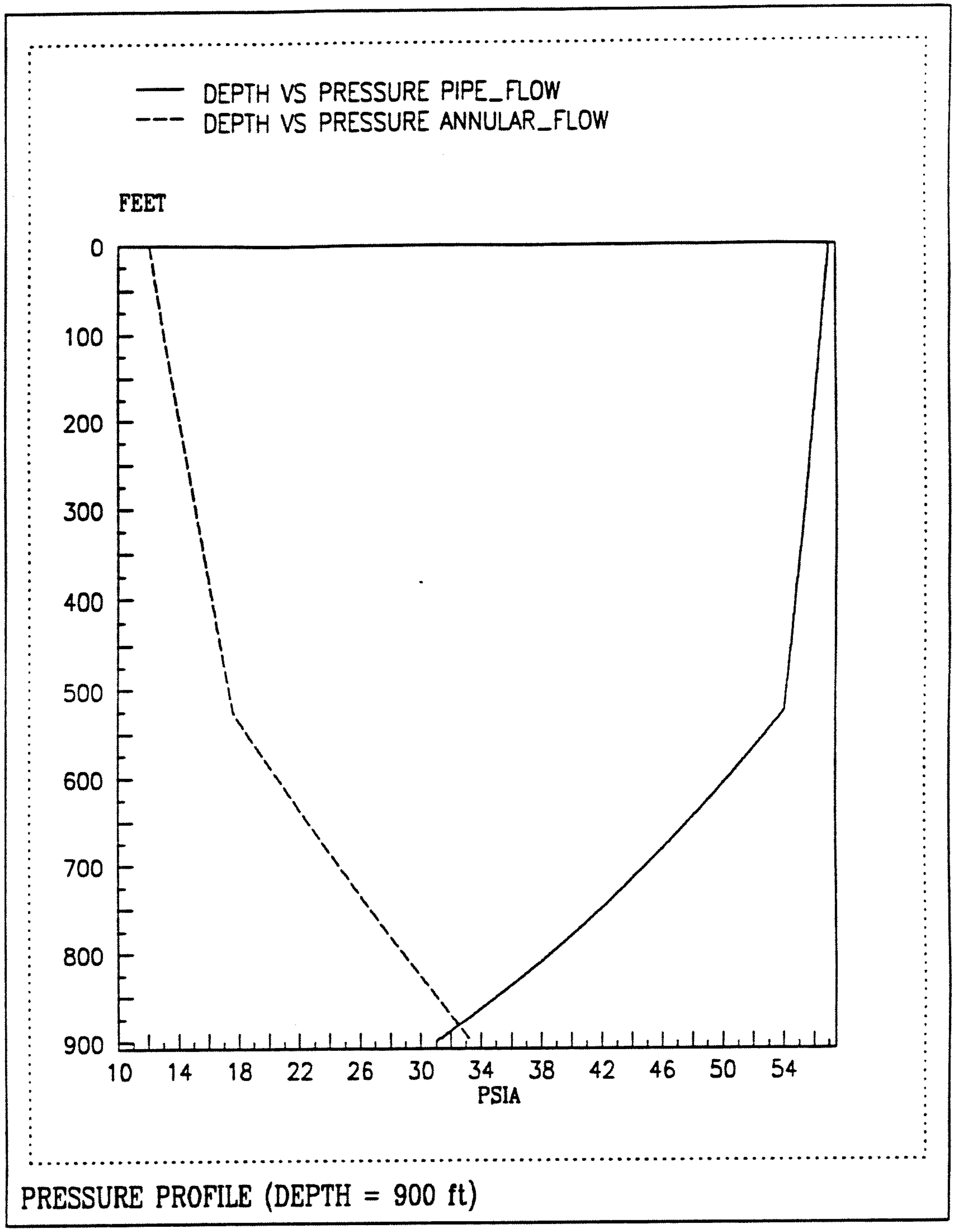
Profile Without PDM in Hole



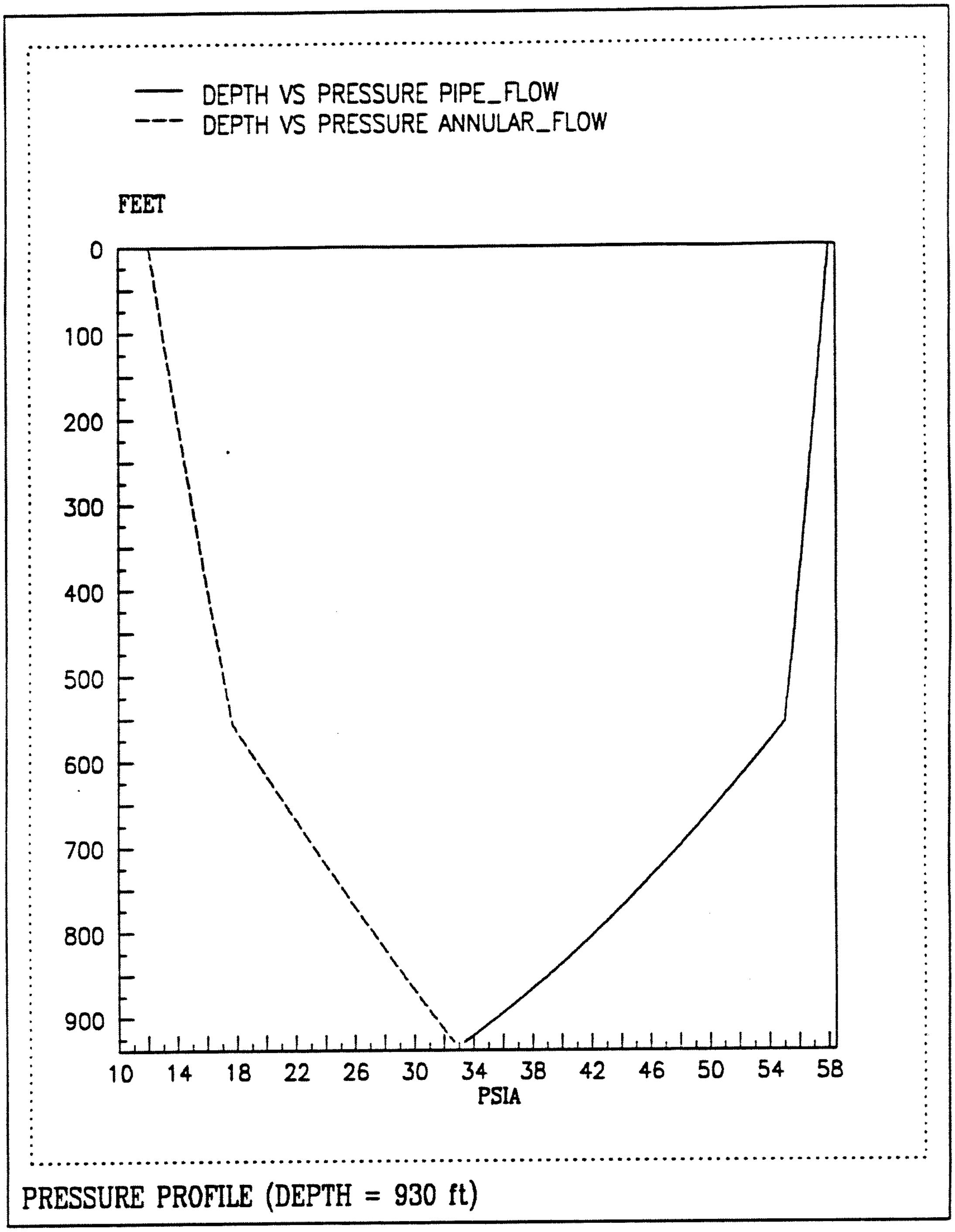
Profile Without PDM in Hole



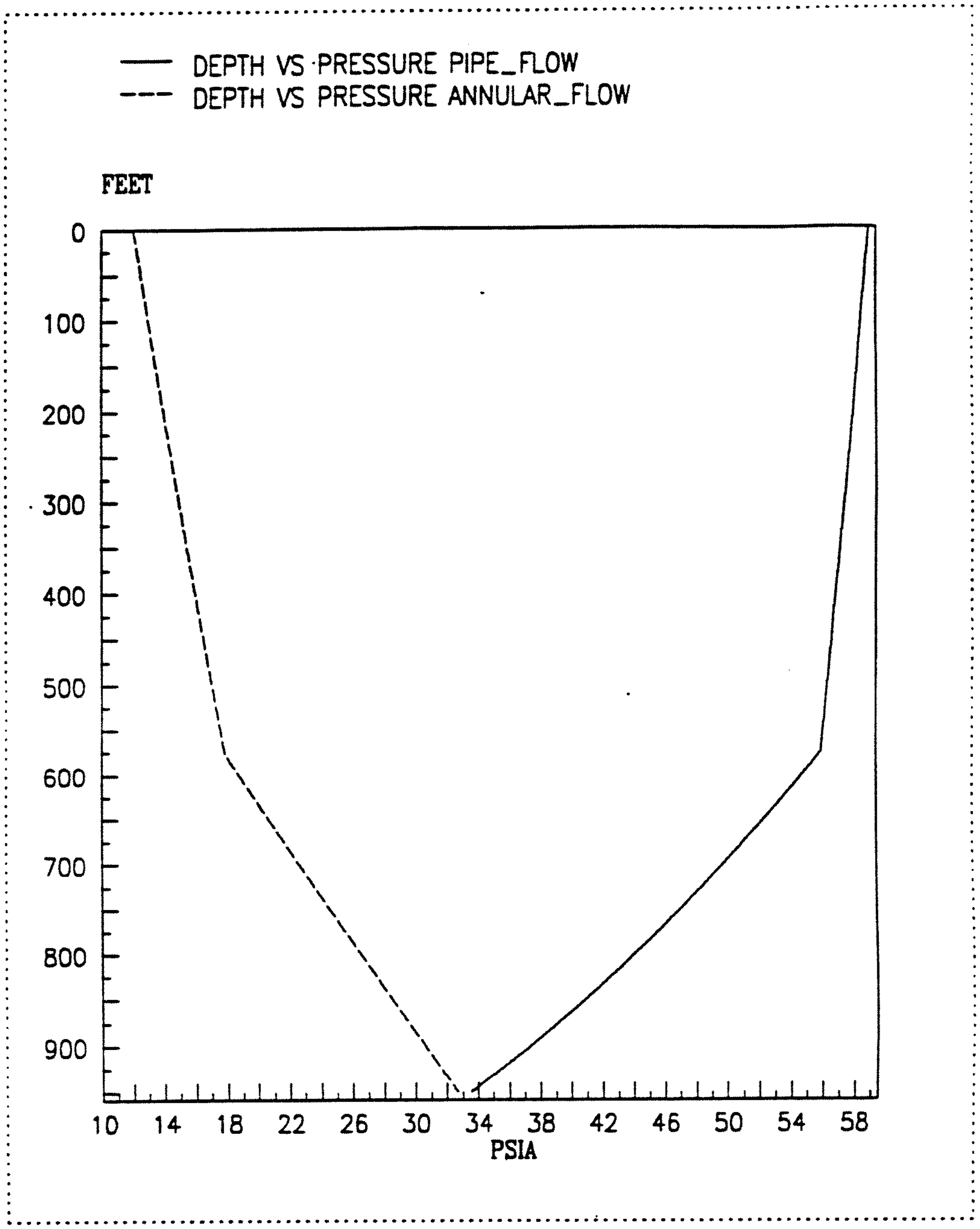
Profile Without PDM in Hole



Profile Without PDM in Hole

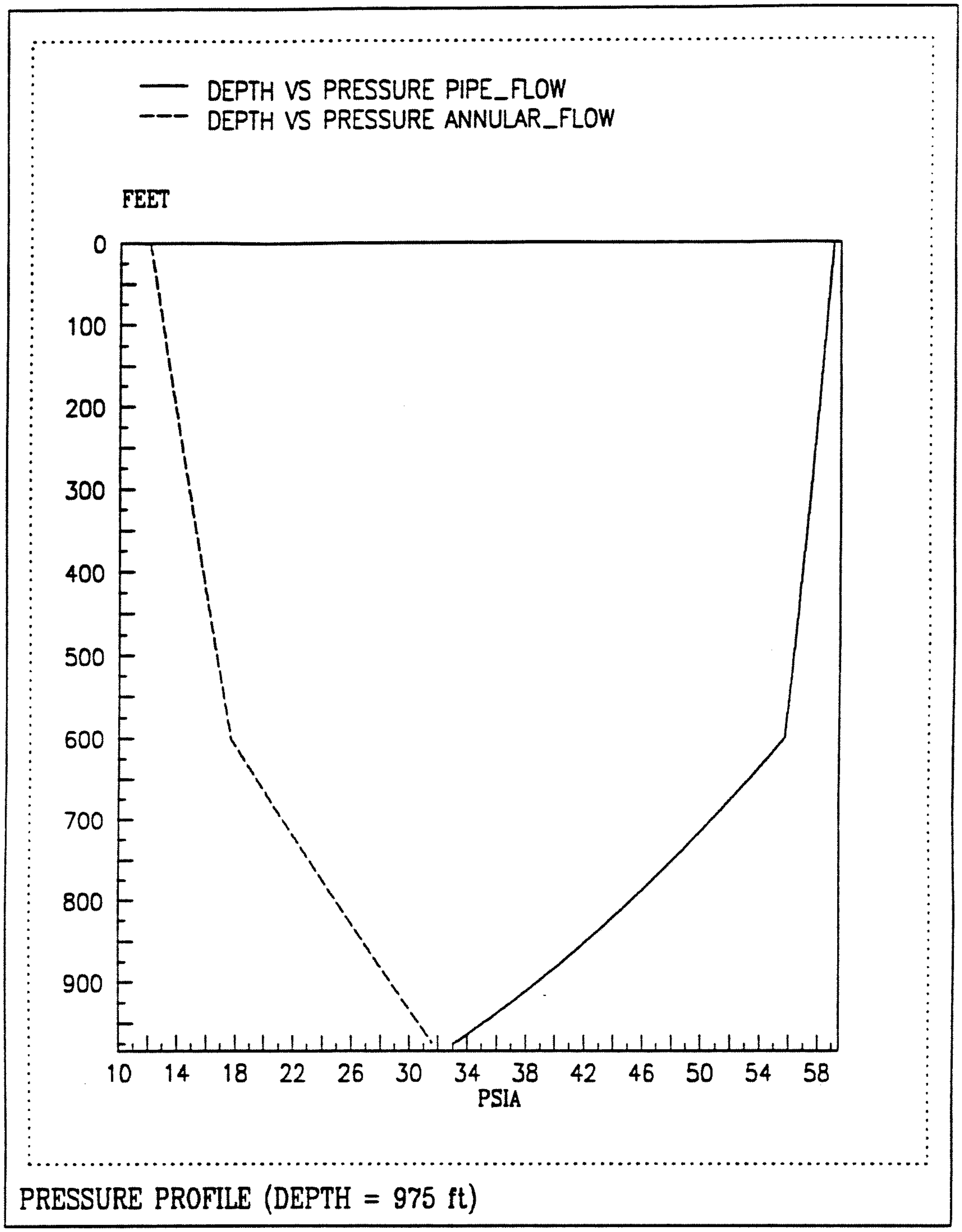


Profile Without PDM in Hole

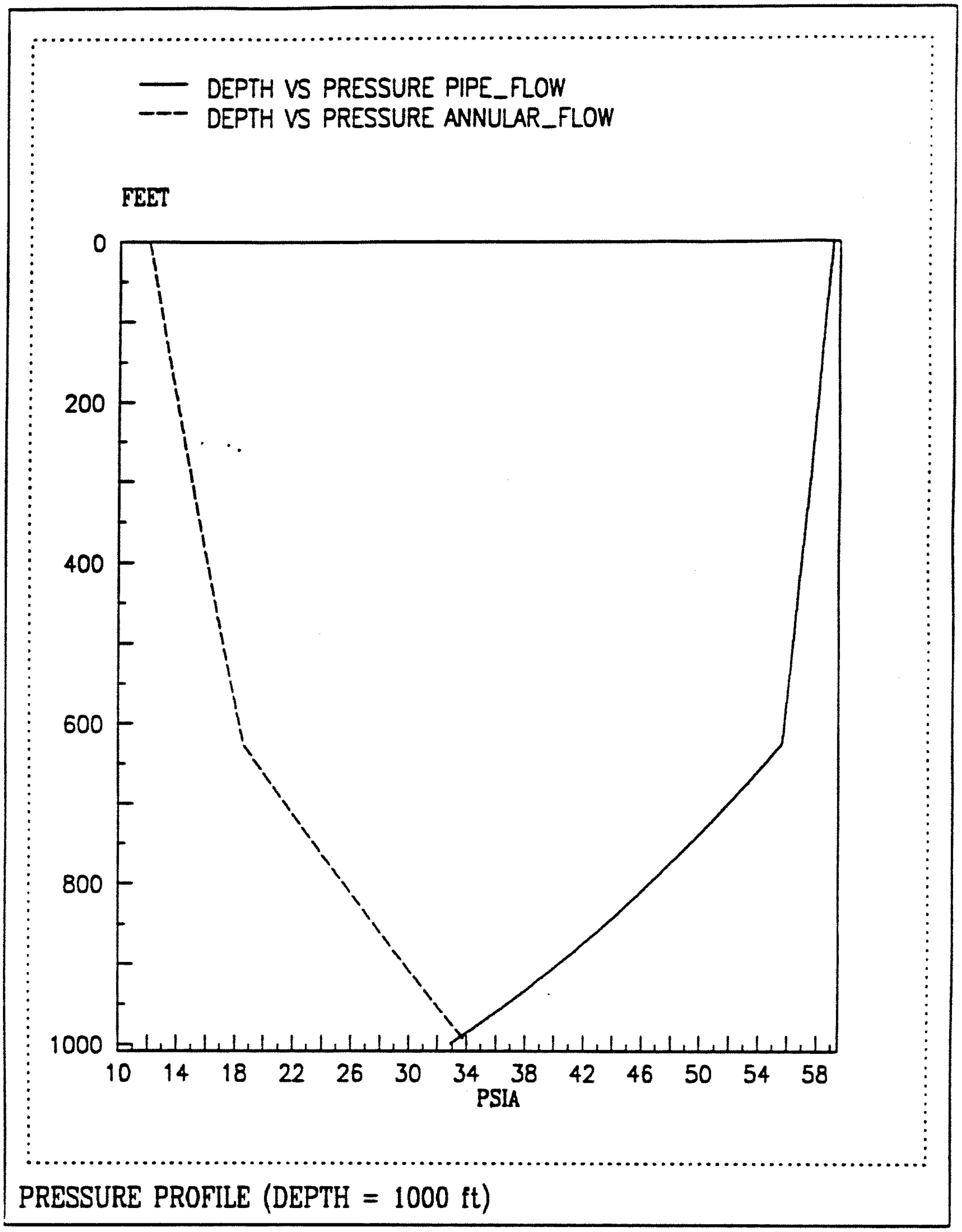


PRESSURE PROFILE (DEPTH = 950 ft)

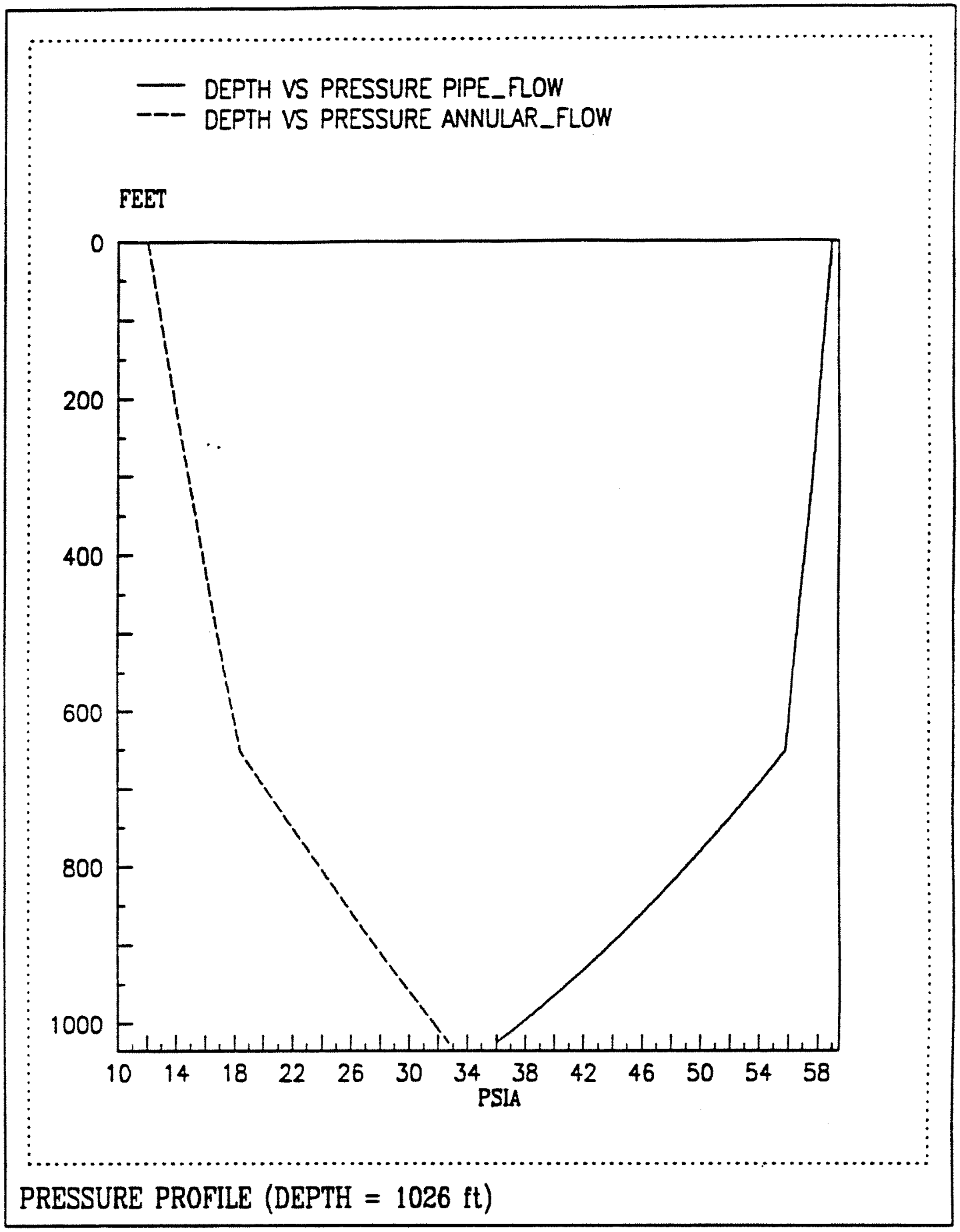
Profile Without PDM in Hole



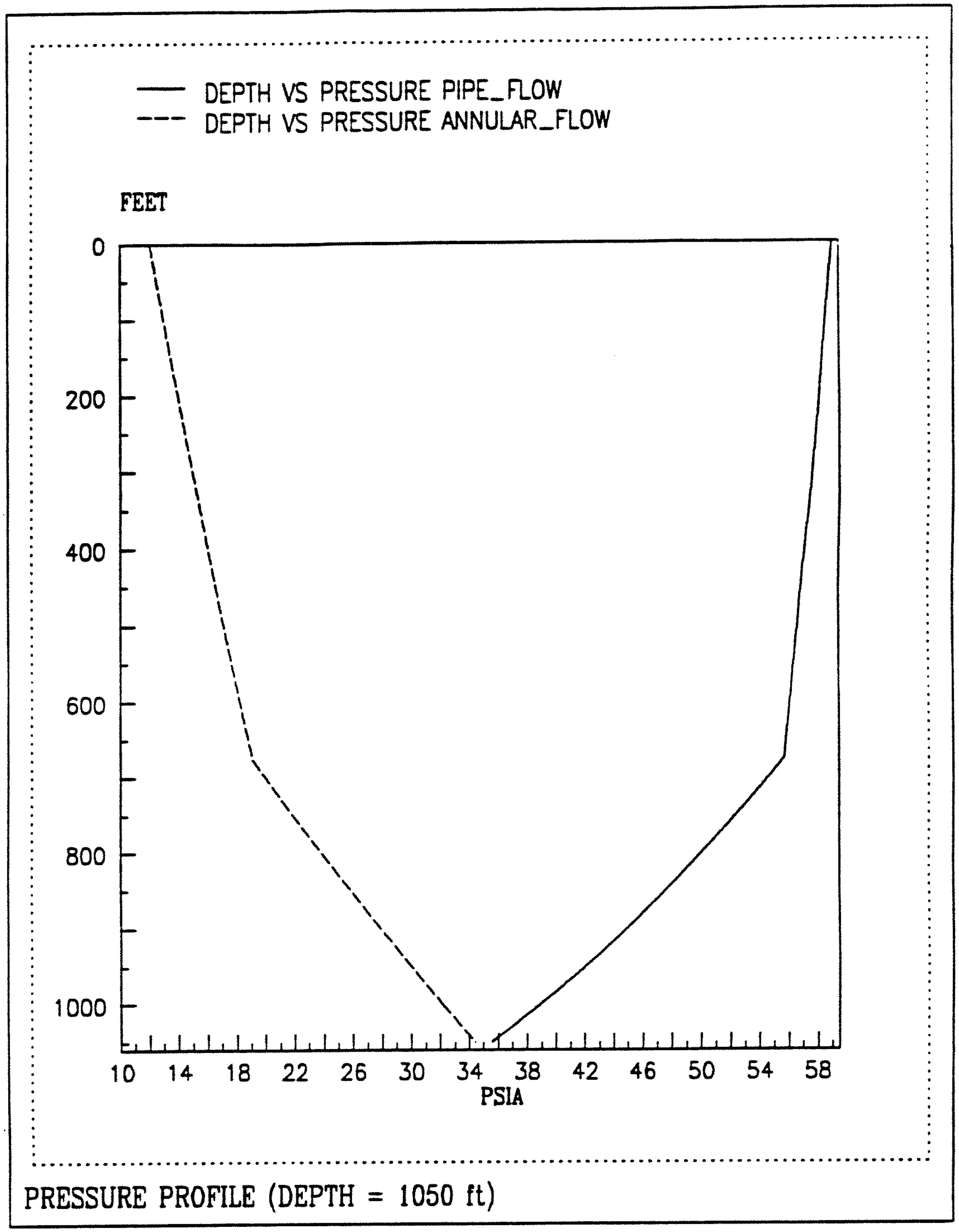
Profile Without PDM in Hole



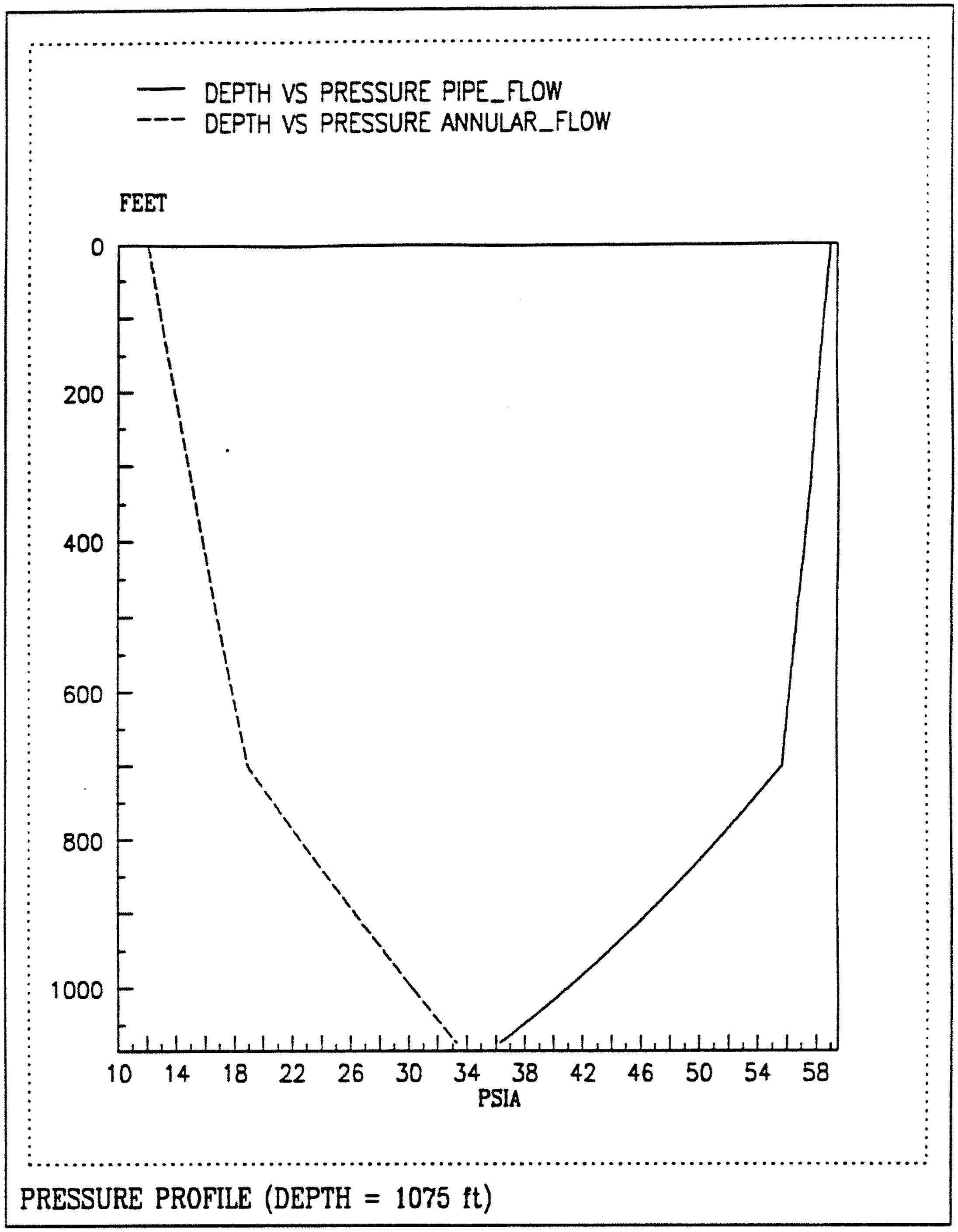
Profile Without PDM in Hole



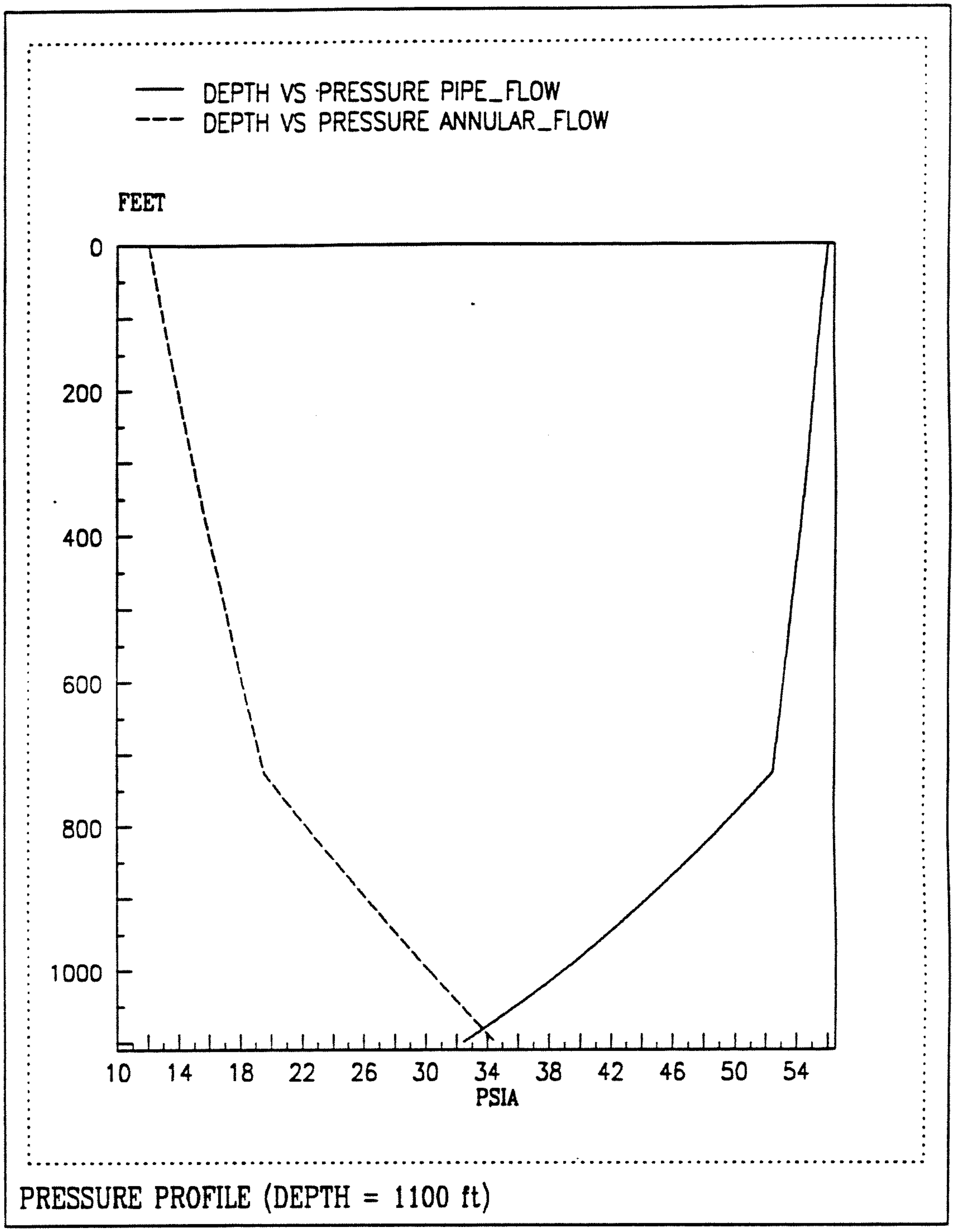
Profile Without PDM in Hole



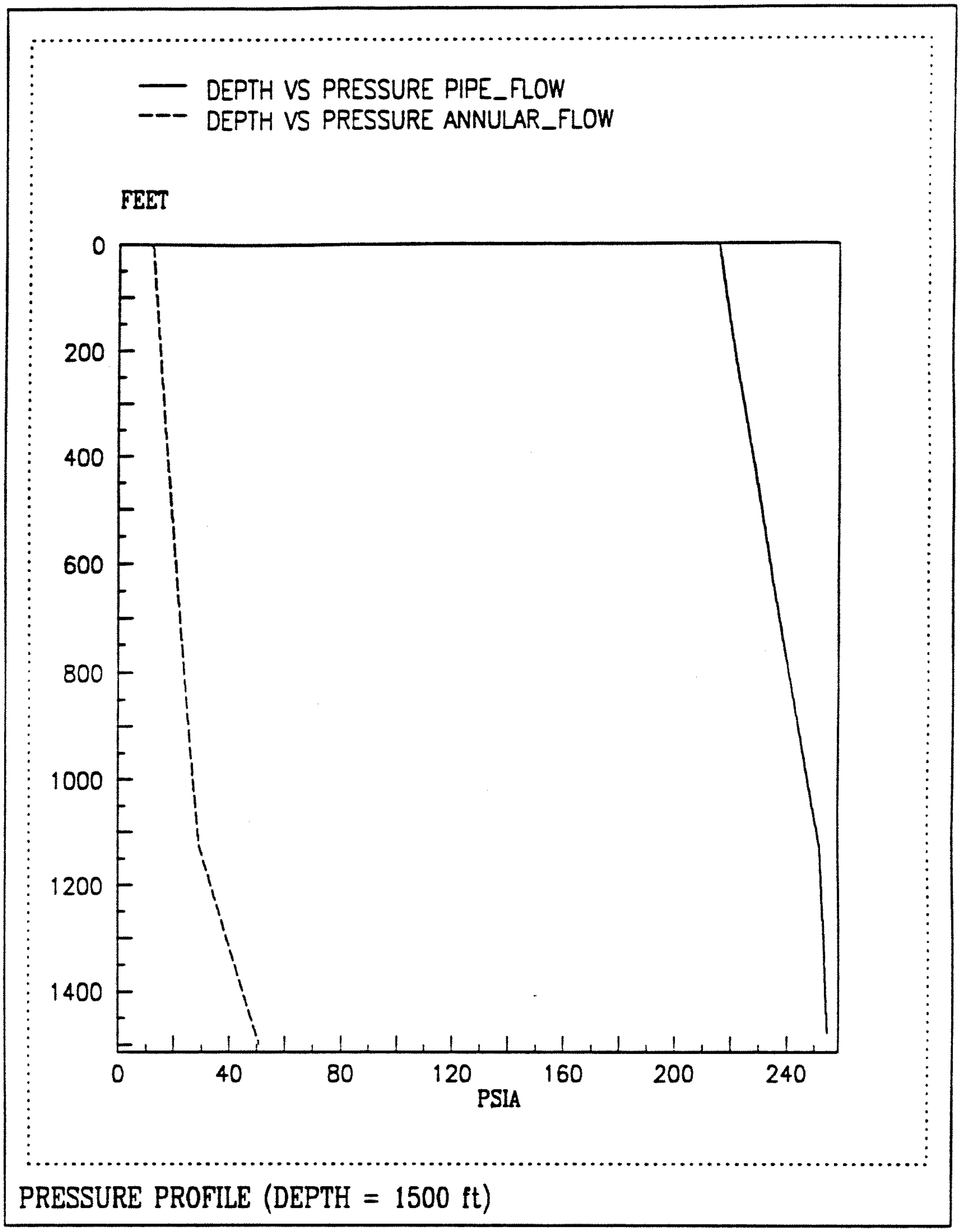
Profile Without PDM in Hole



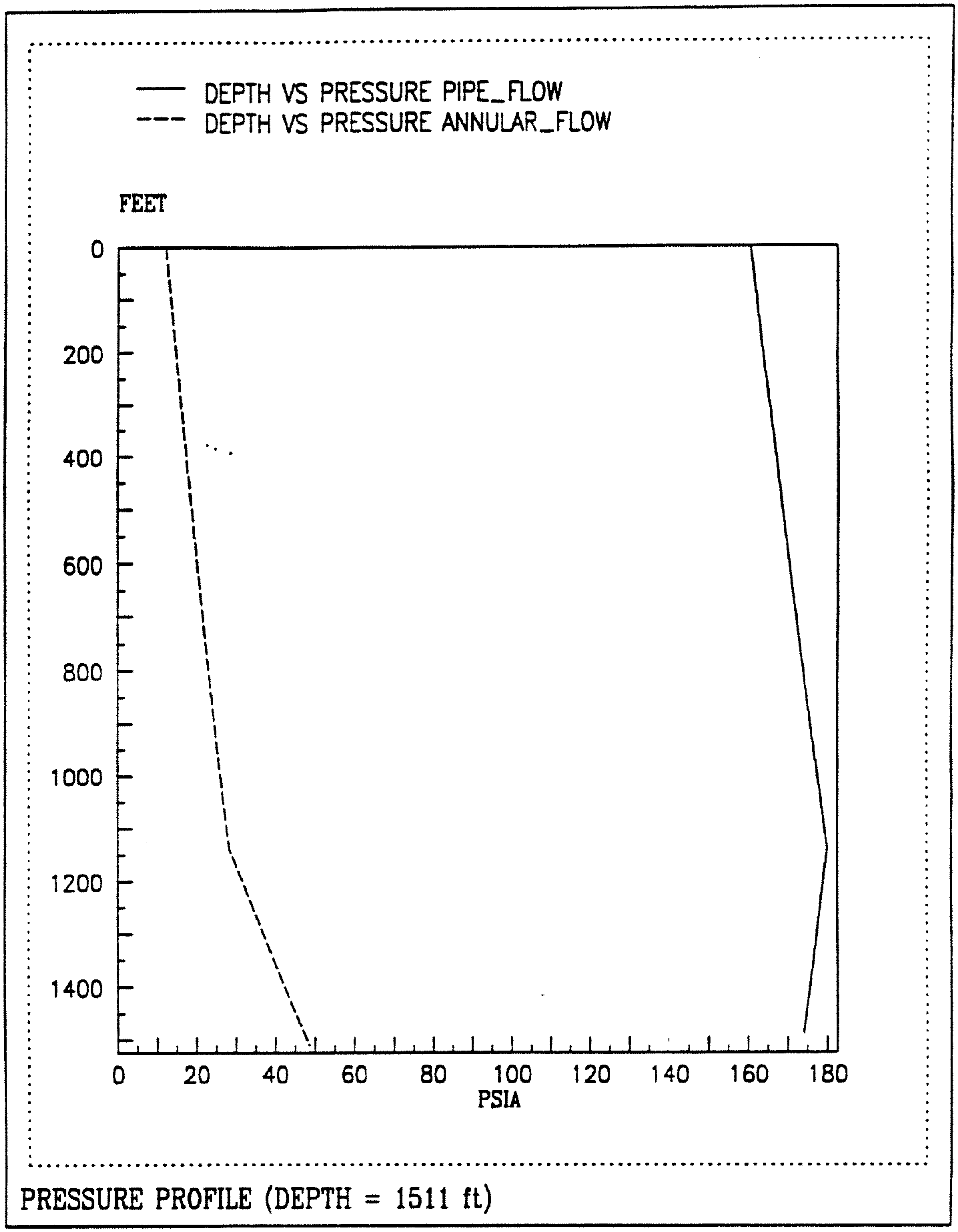
Profile Without PDM in Hole



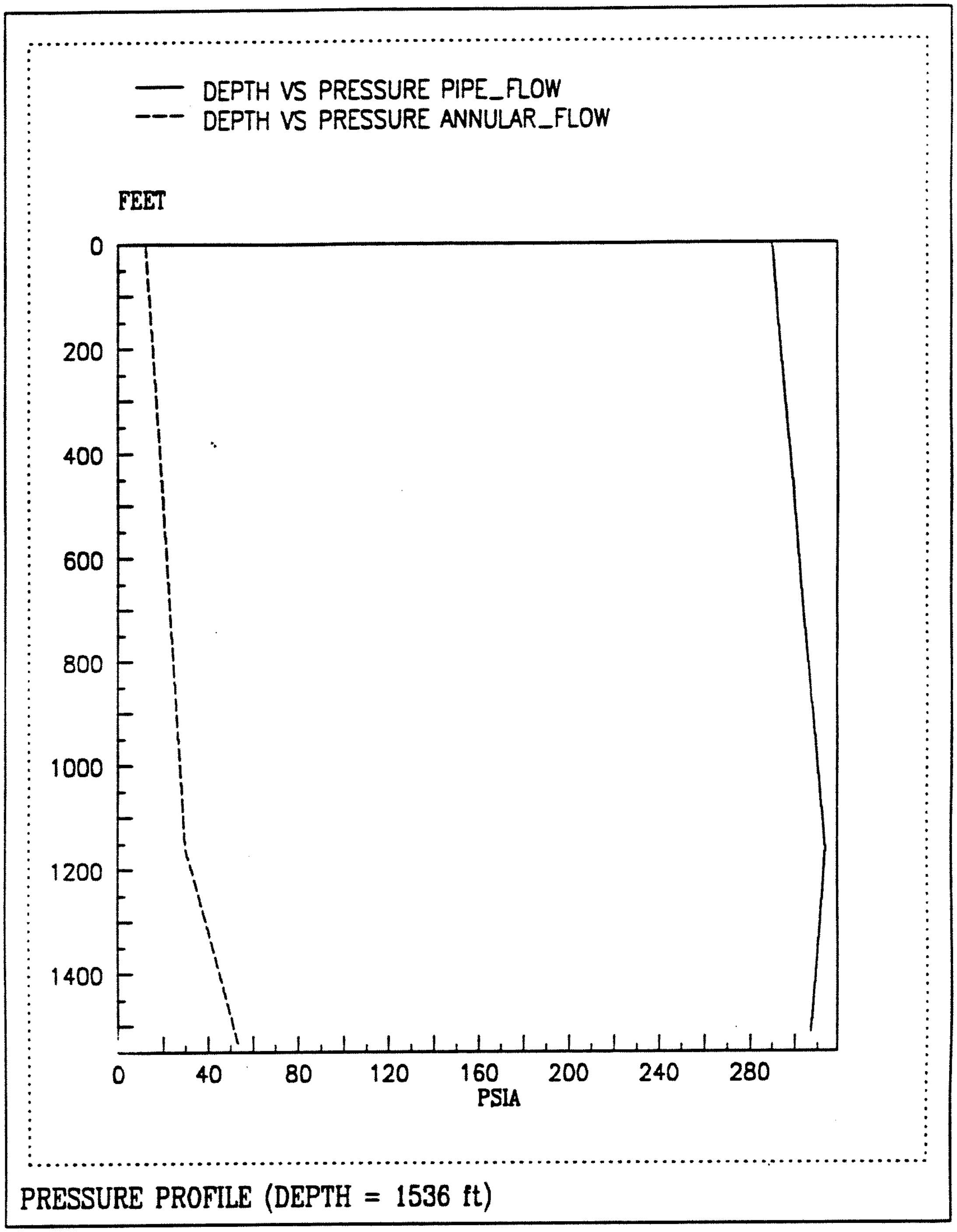
Profile Without PDM in Hole



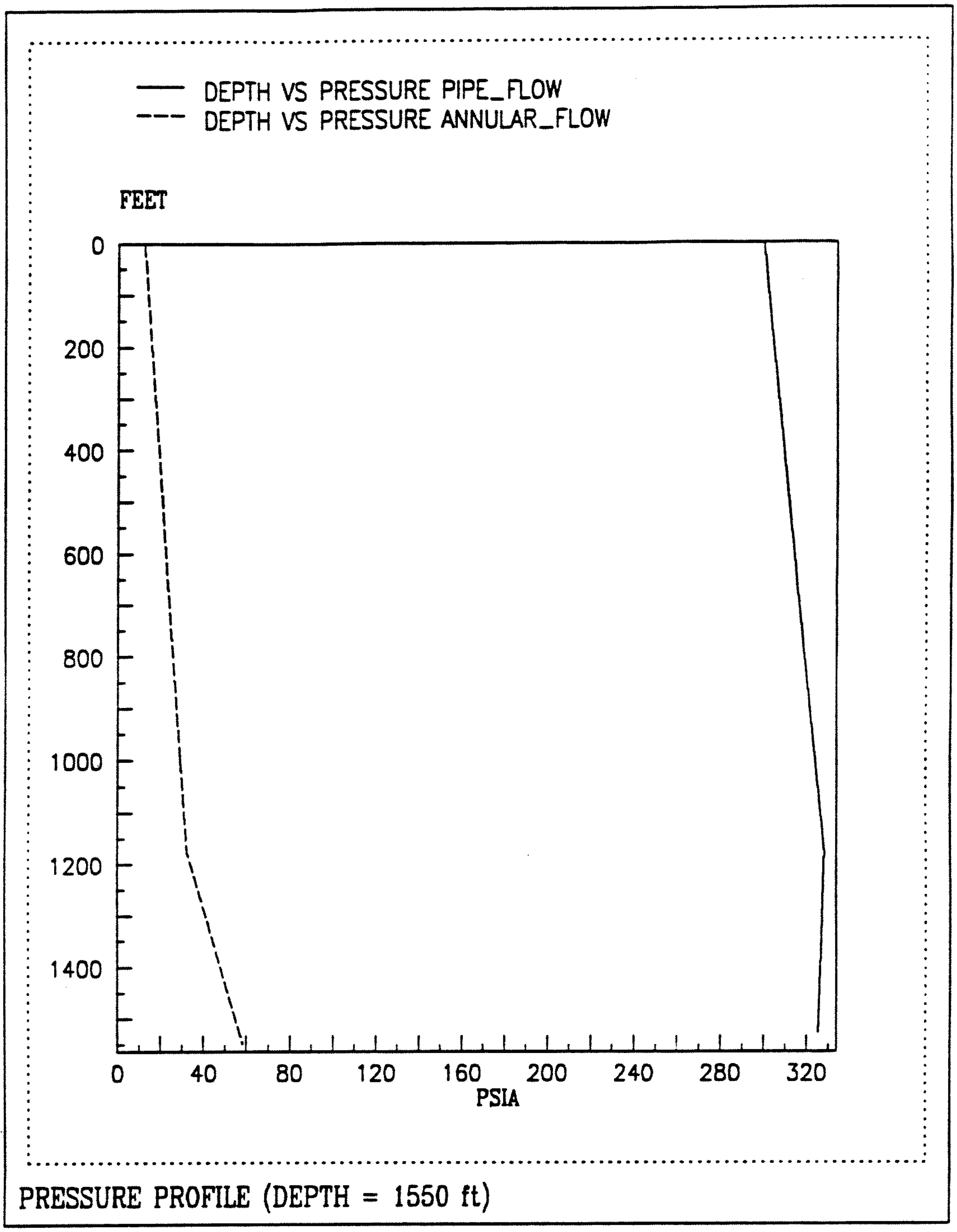
Profile Without PDM in Hole



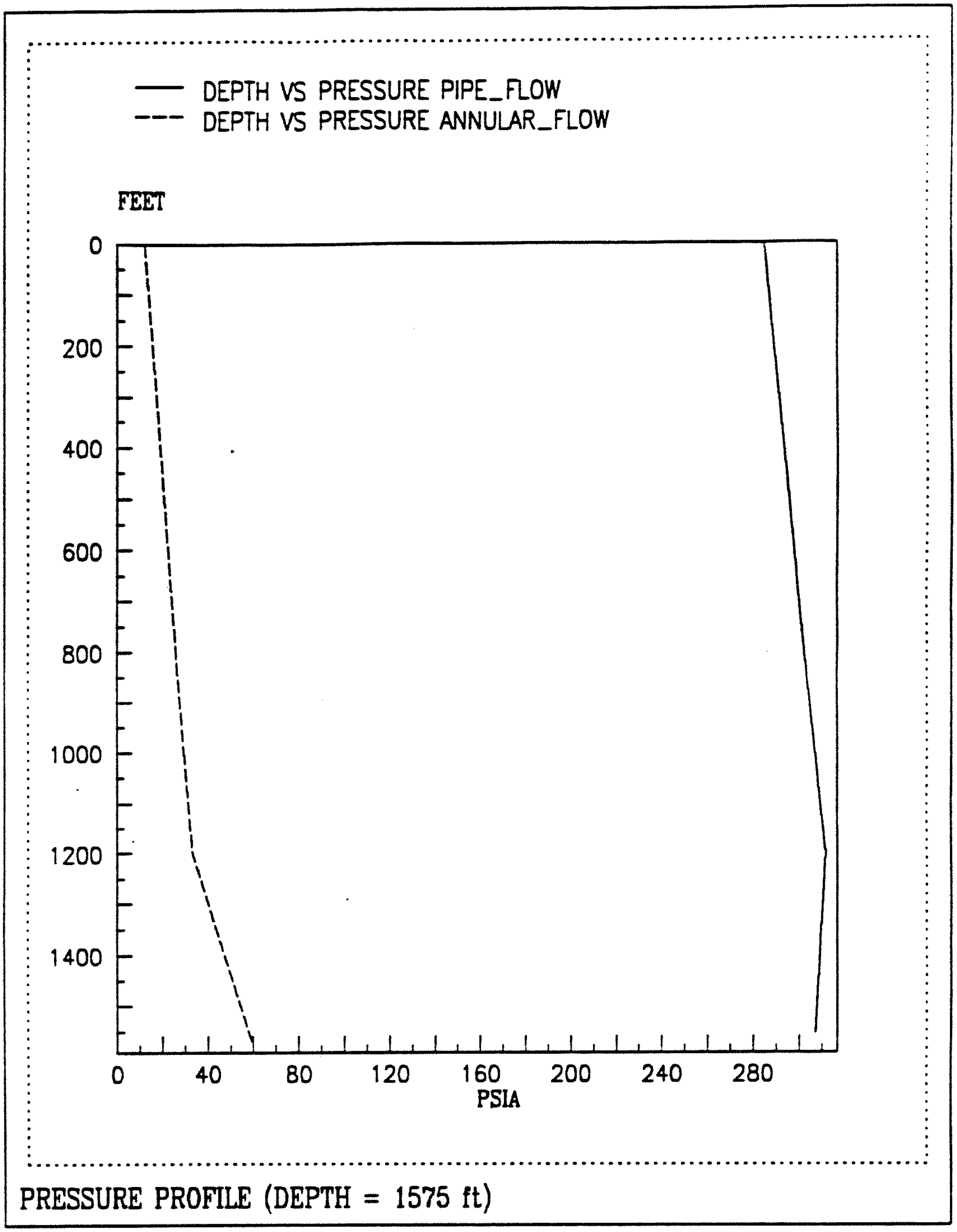
Profile With PDM in Hole



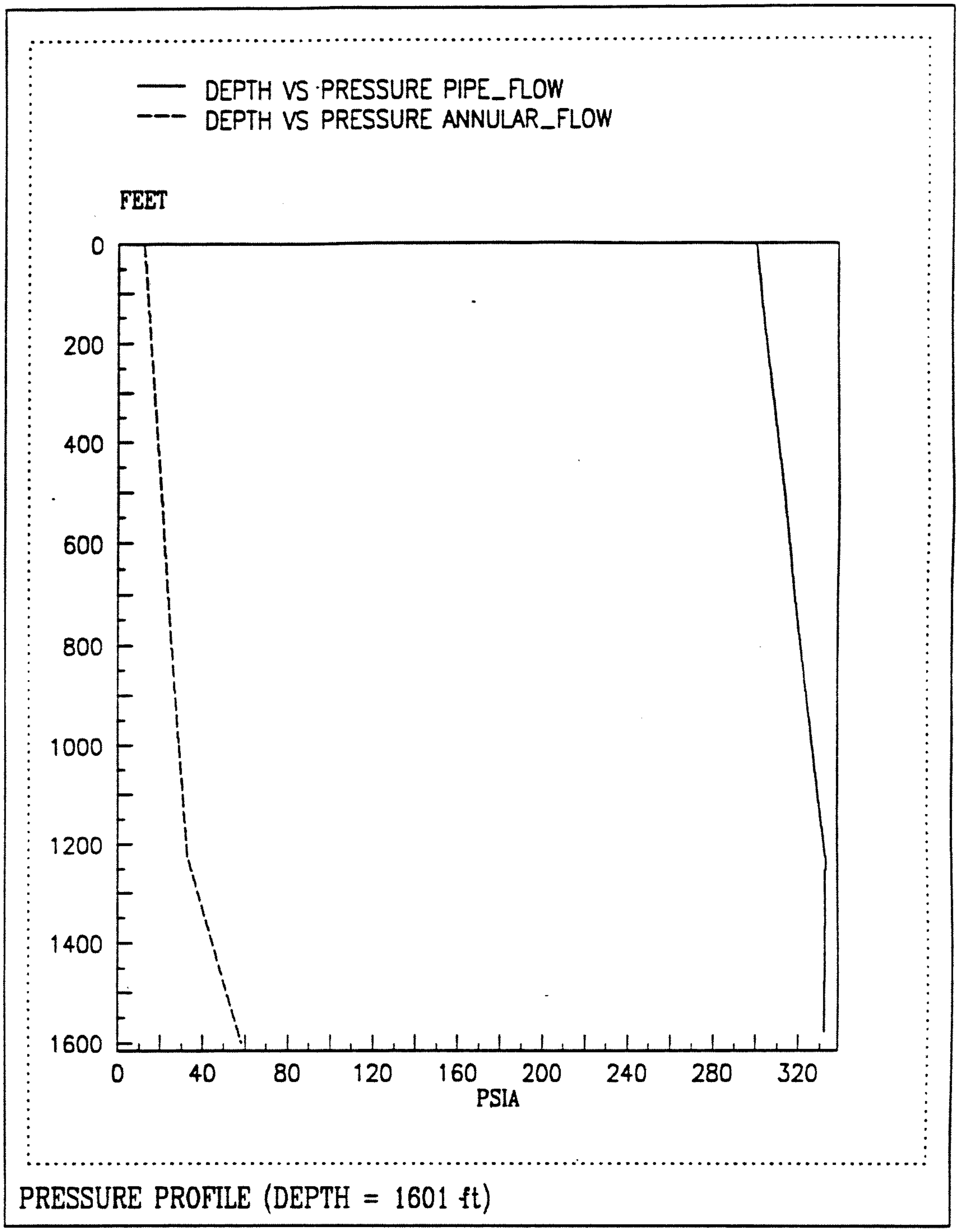
Profile With PDM in Hole



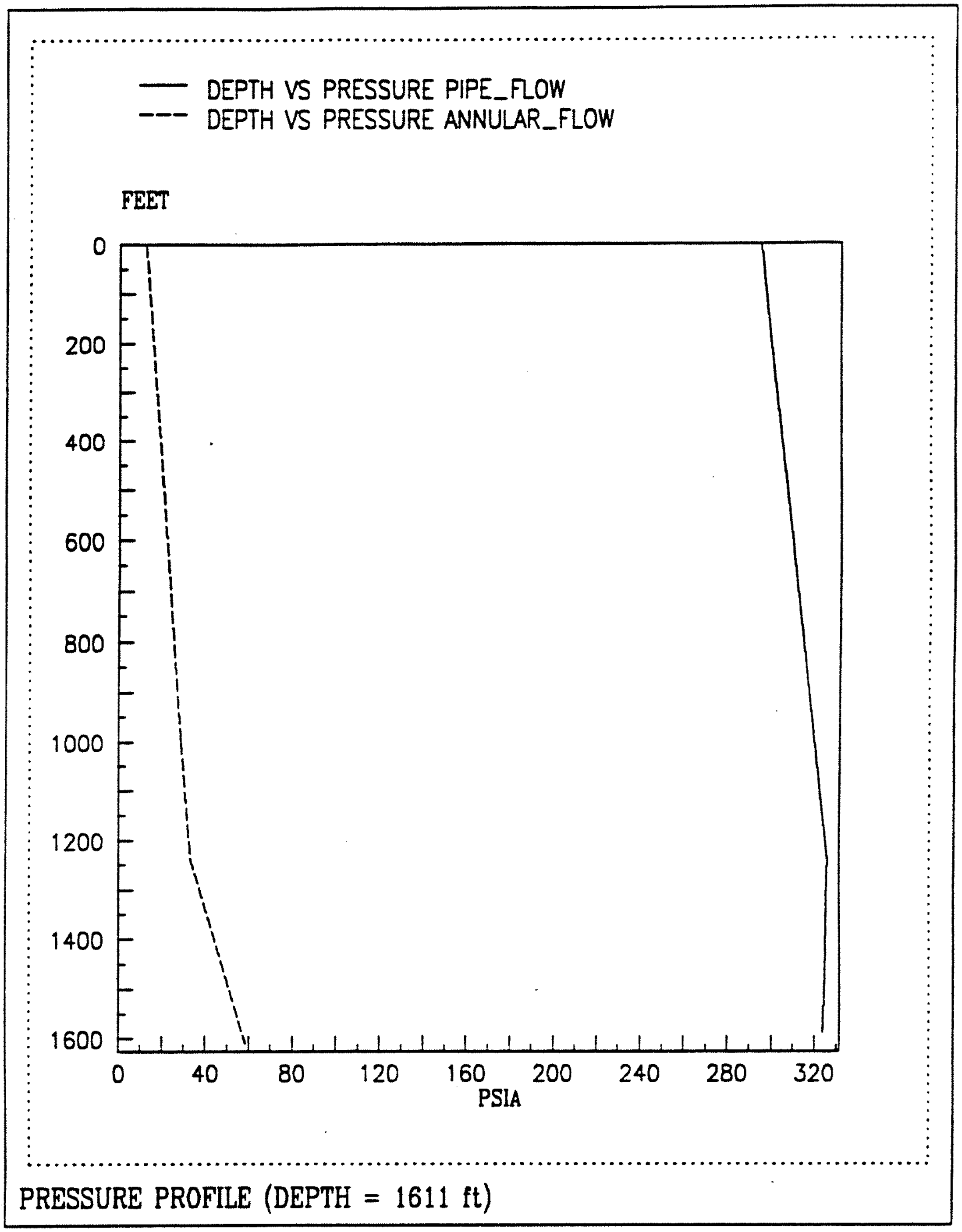
Profile With PDM in Hole



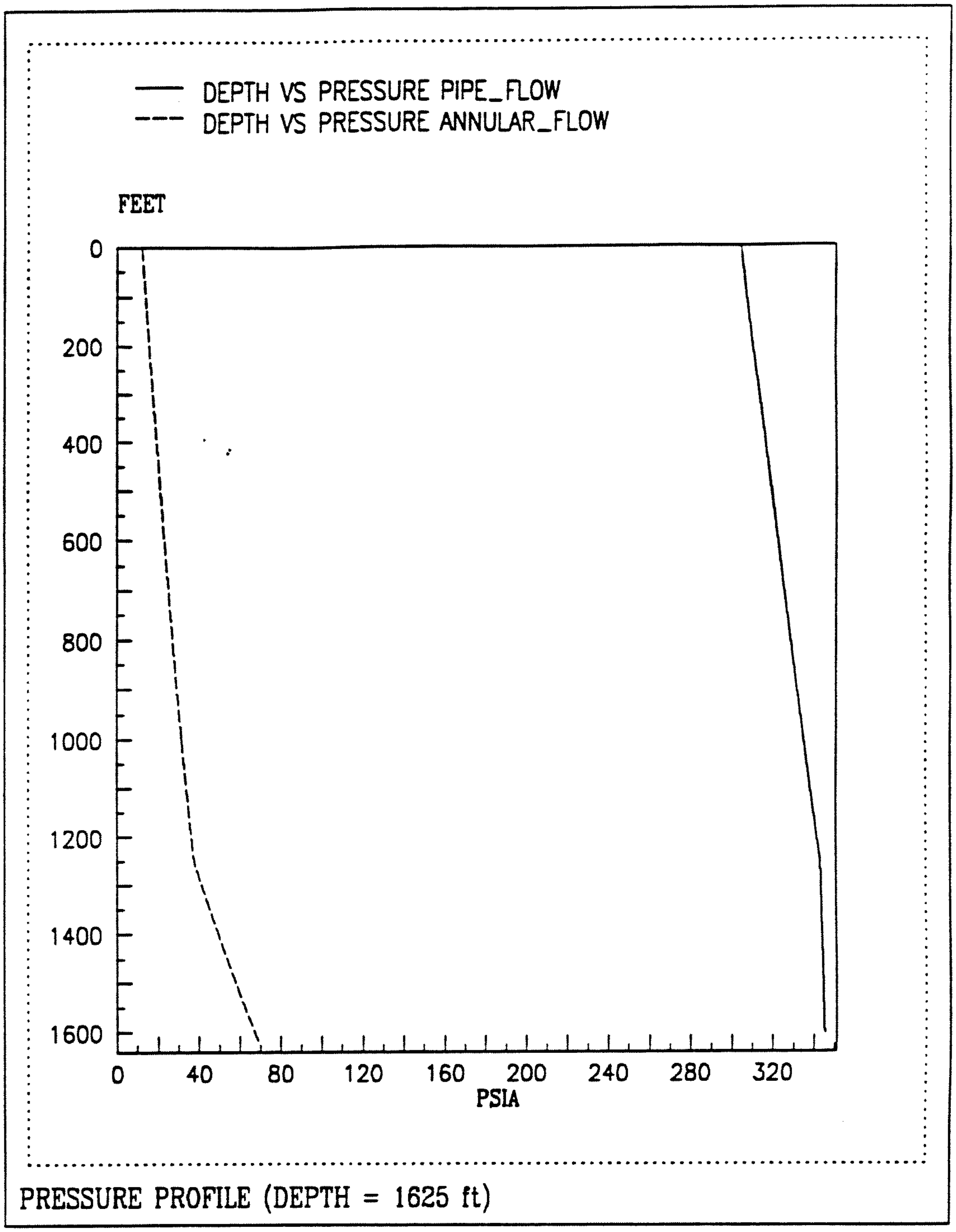
Profile With PDM in Hole



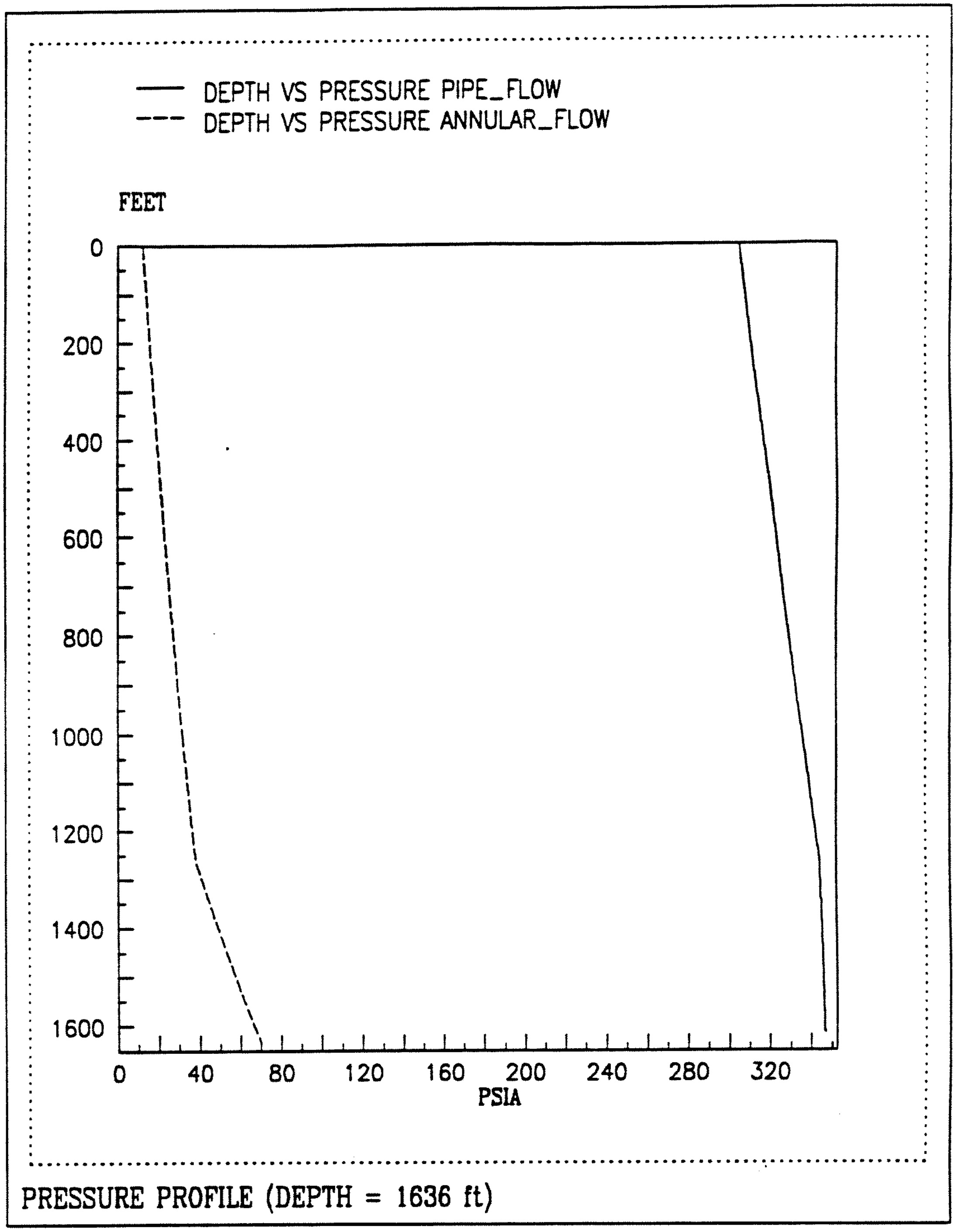
Profile With PDM in Hole



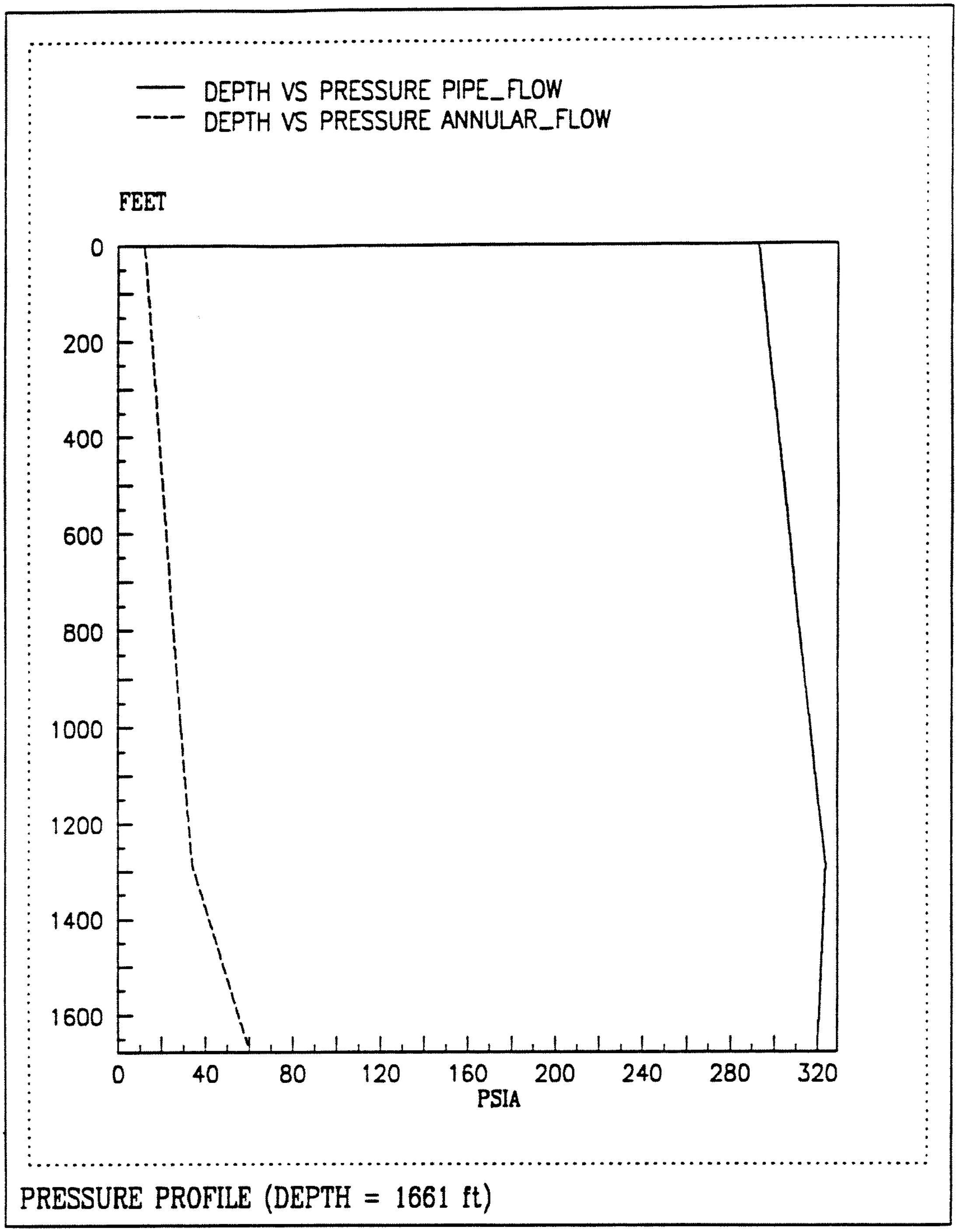
Profile With PDM in Hole



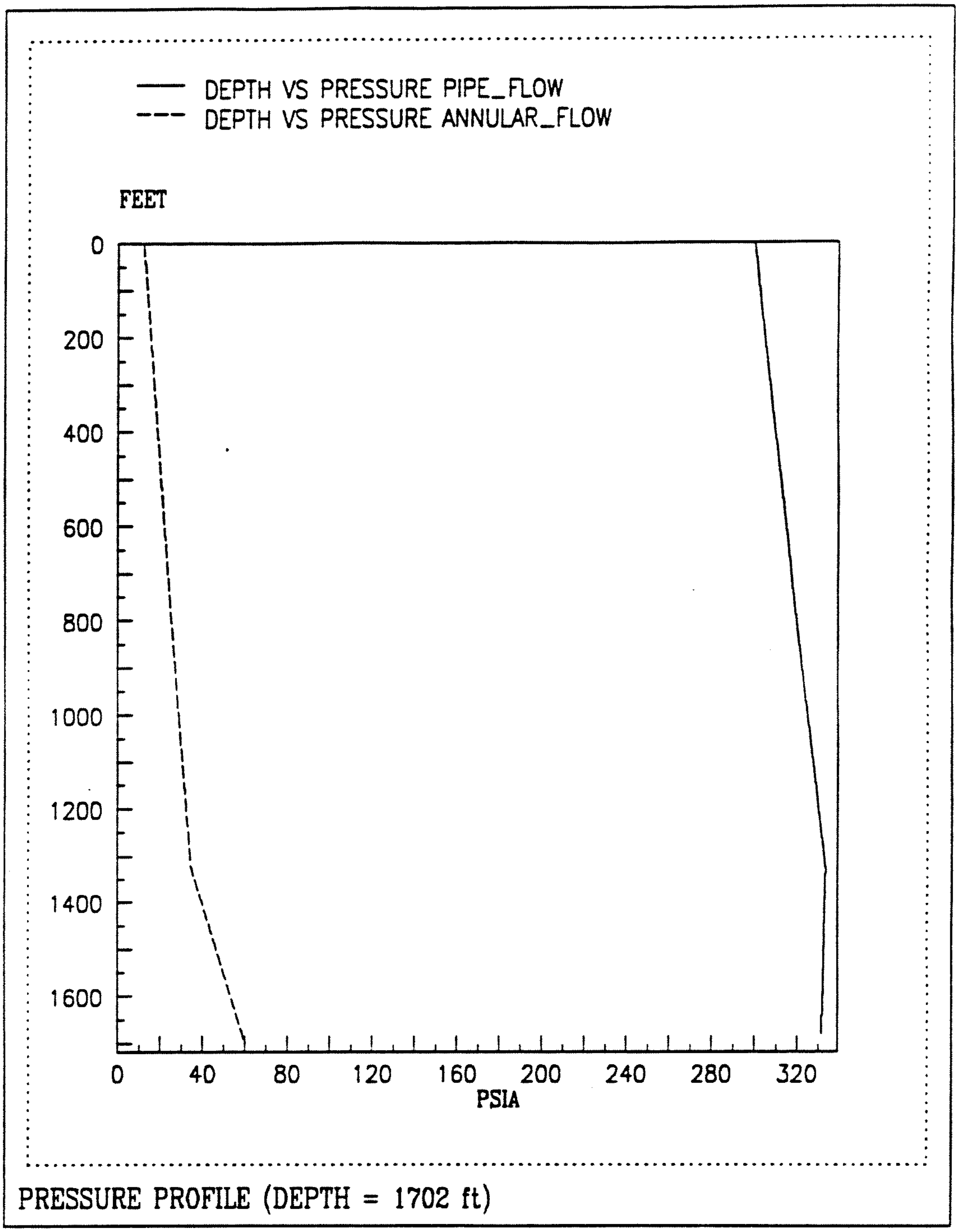
Profile With PDM in Hole



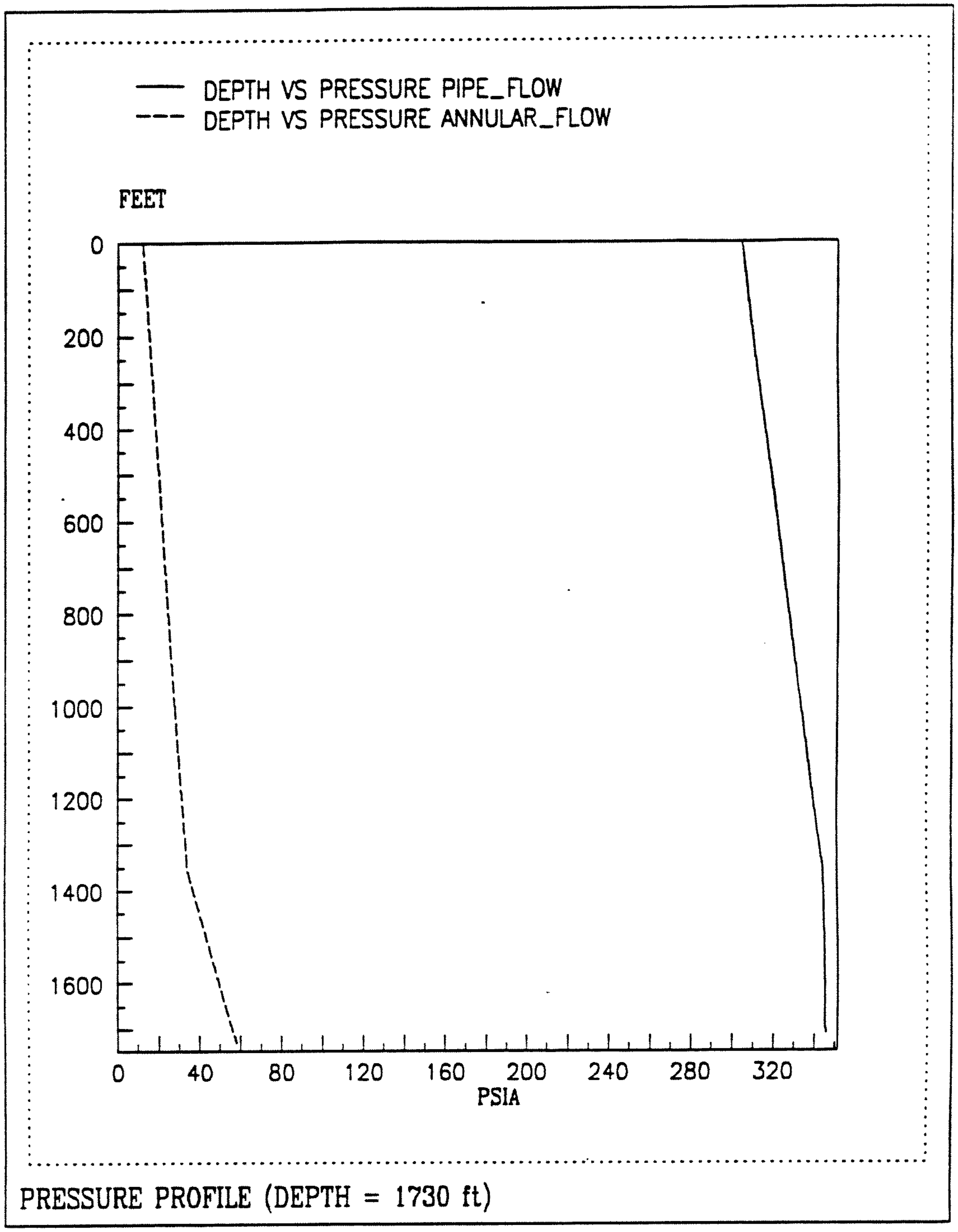
Profile With PDM in Hole



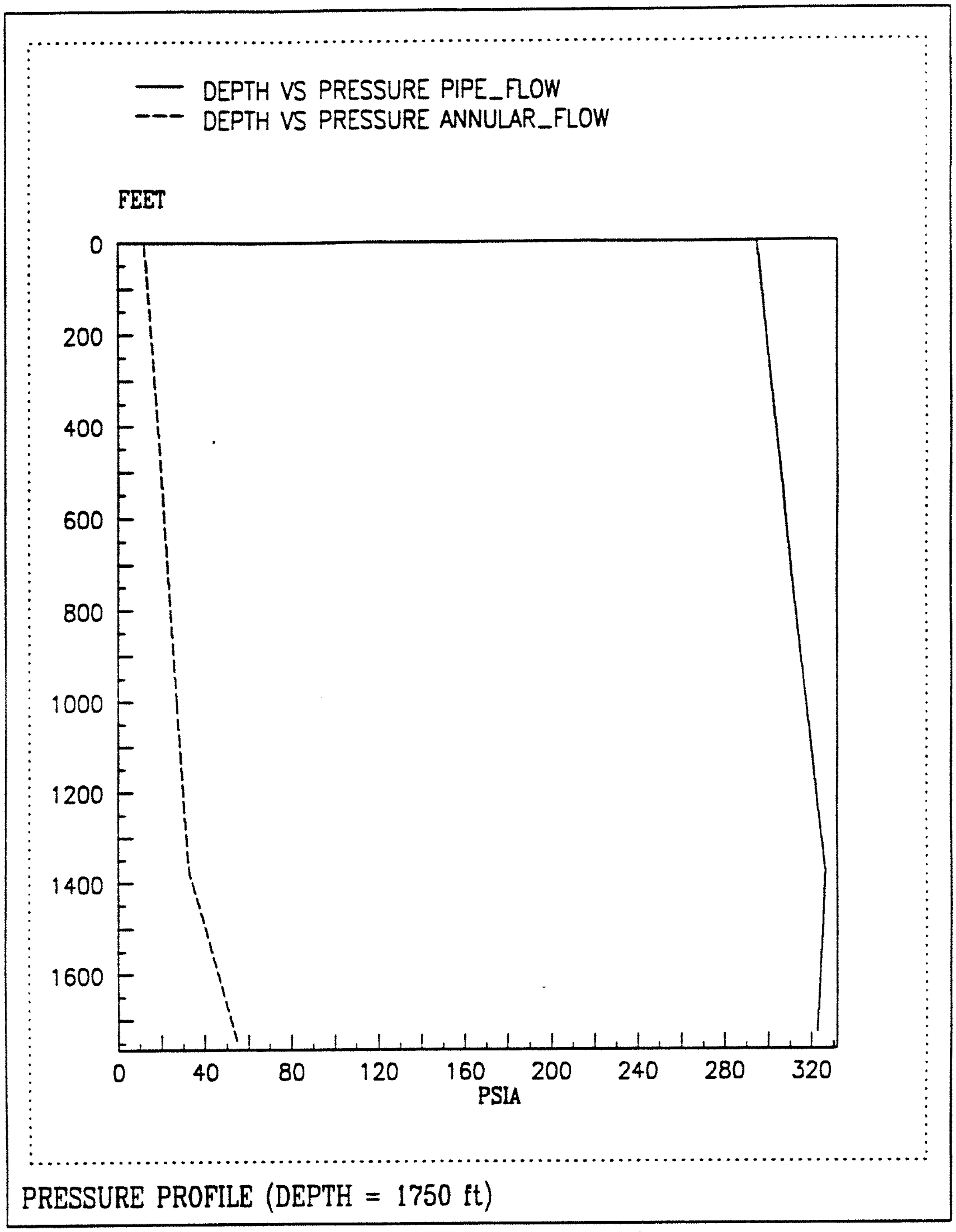
Profile With PDM in Hole



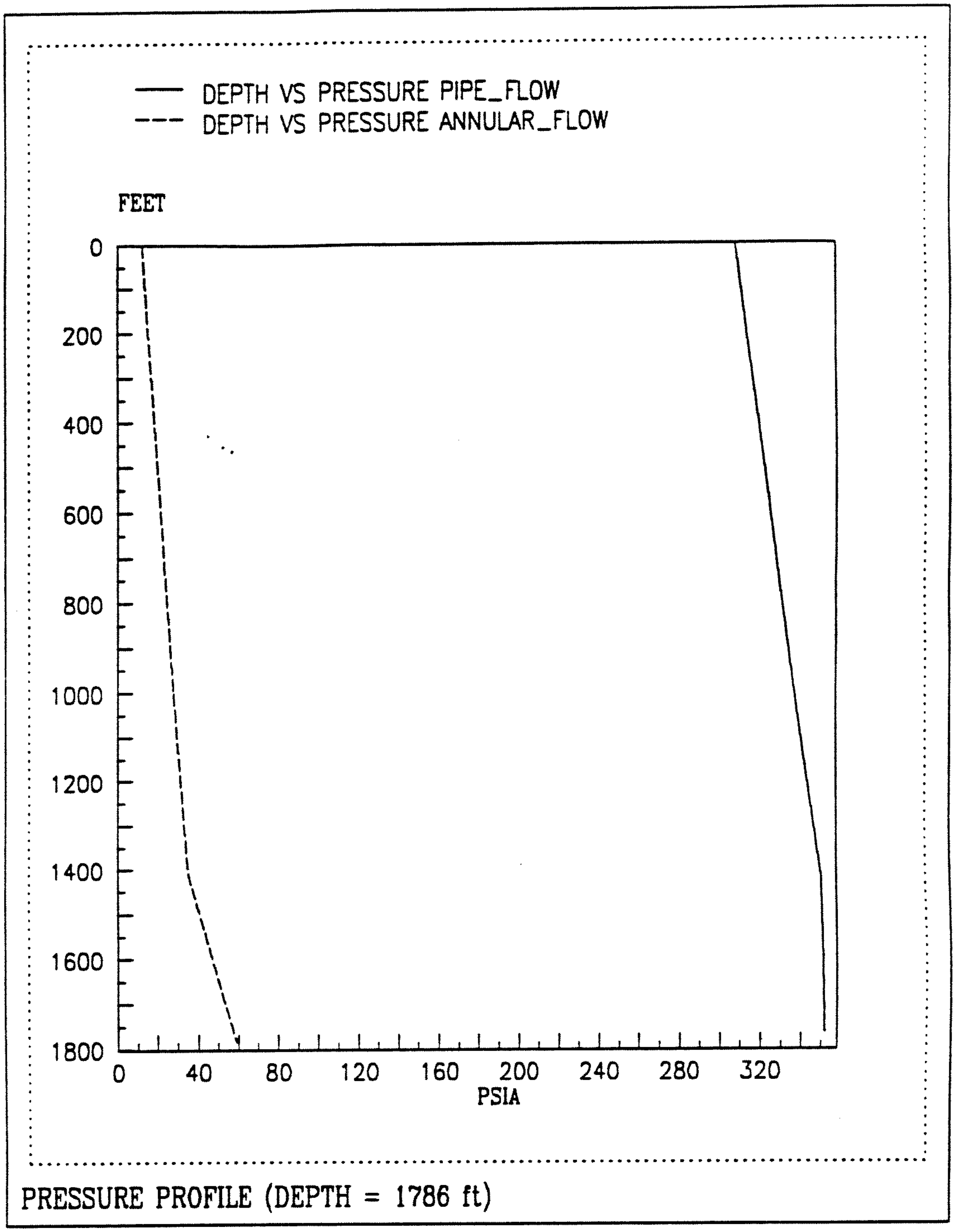
Profile With PDM in Hole



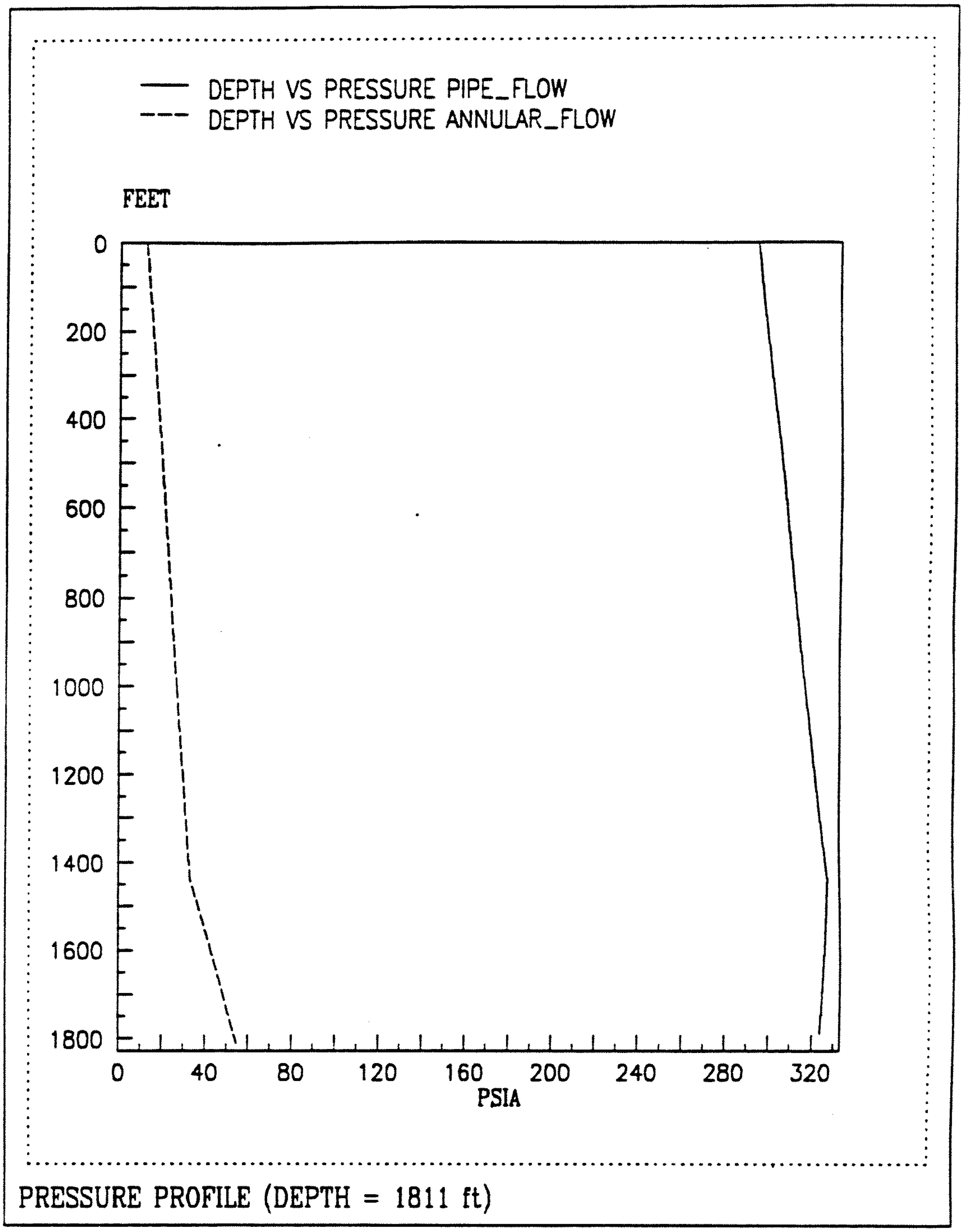
Profile With PDM in Hole



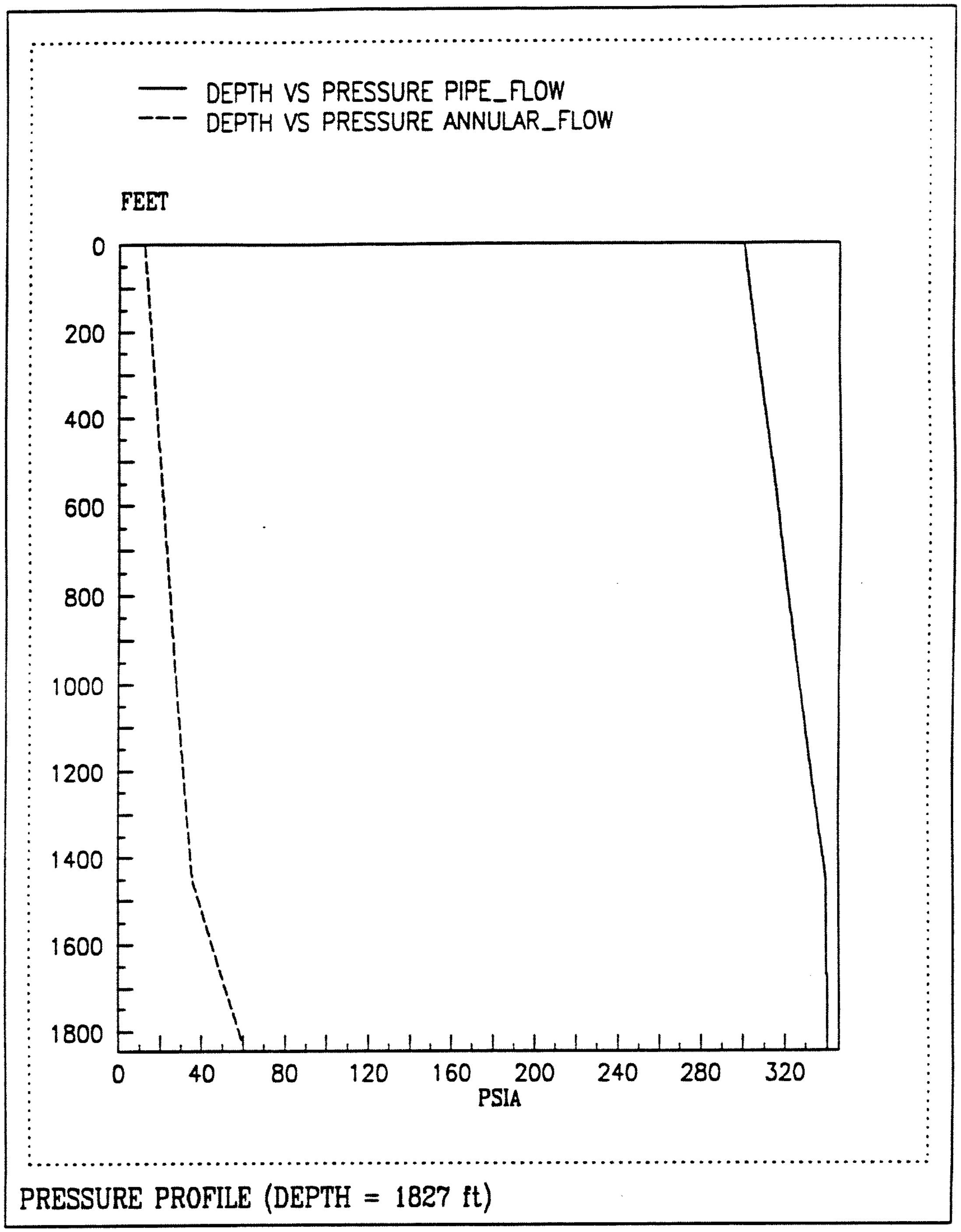
Profile With PDM in Hole



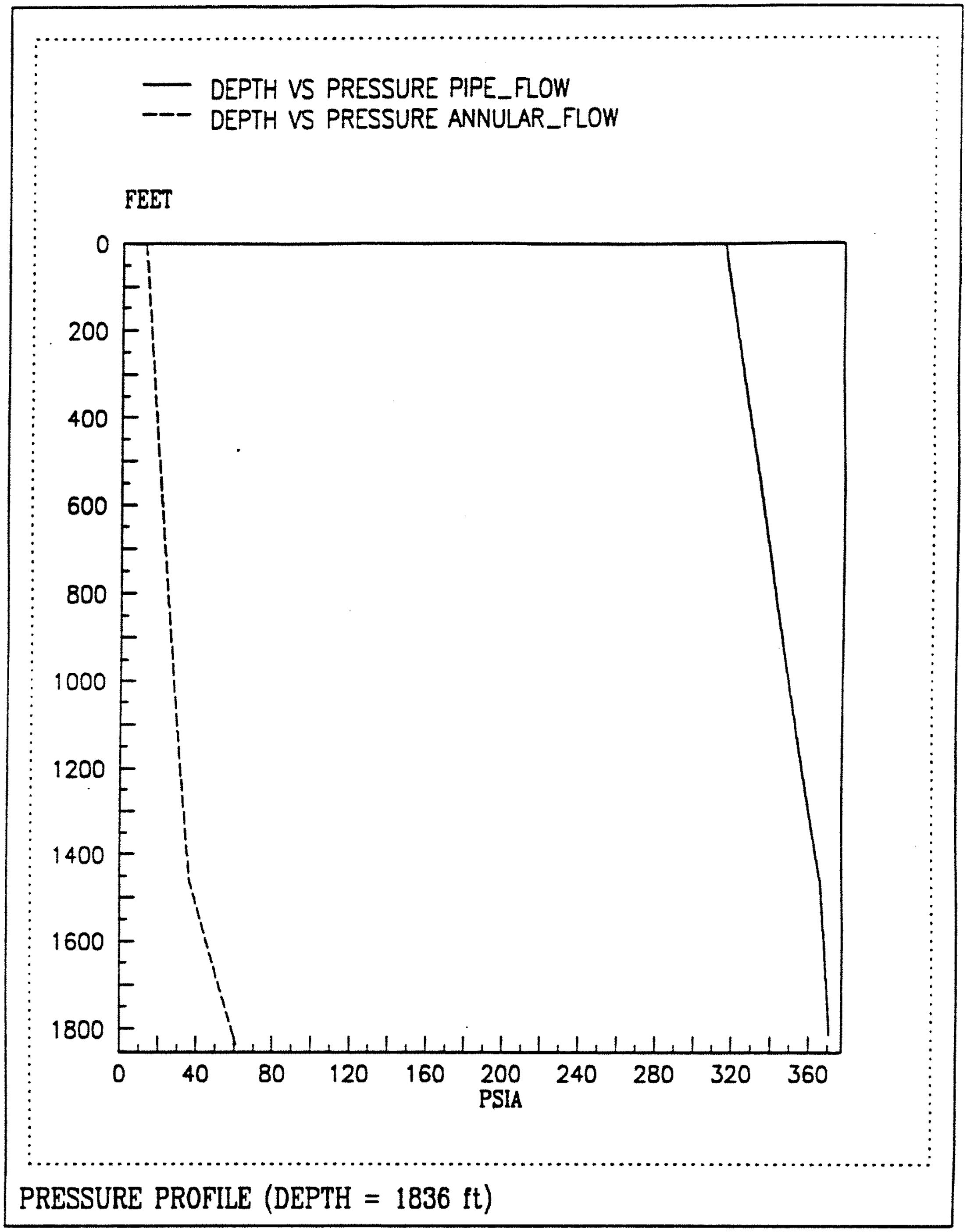
Profile With PDM in Hole



Profile With PDM in Hole



Profile With PDM in Hole



Profile With PDM in Hole