COO/4098-1
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FINAL REPORT

FULL-SCALE LABORATORY DRILLING TESTS ON SANDSTONE AND DOLOMITE

By

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August, 1977

Contract No. E(34-1)-0038

Submitted to

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ABSTRACT

Full-scale laboratory drilling experiments were performed under simulated downhole conditions to determine what effect changing various drilling parameters has on penetration rate. The two rock types, typical of deep oil and gas reservoirs, used for the tests were Colton Sandstone and Bonne Terre Dolomite. Drilling was performed with standard 7 7/8 inch rotary insert bits and water base mud. Variations in drilling parameters are as follows:

Weight on Bit	5,000-40,000 pounds
Rotary Speed	40-100 RPM
Mud Flow	80-220 gpm
Mud Pressure	100-5,000 psi
Confining Pressure on Rock	0-9,000 psi

Penetration rates from about three feet per hour to about 90 feet per hour were obtained.

The results showed the penetration rate to be strongly dependent on bit weight, rotary speed and borehole mud pressure. There was only a small dependence on mud flow rate. The drilling rate decreased rapidly with increasing borehole mud pressure for borehole pressures up to about 2,000 psi. Above this pressure, the borehole pressure and rotary speeds had a smaller effect on penetration rate. The penetration rate was then dependent mostly on the bit weight. Penetration rate per horsepower input was also shown to decrease at higher mud pressures and bit weights.

The ratio of horizontal confining stress to axial overburden stress was maintained at 0.7 for simulated overburden stresses between 0 and 12,800 psi. For this simulated downhole stress state, the undrilled rock sample was within the elastic response range and the confining pressures were found to have only a small or negligible effect on the penetration rate. Visual examination of the bottomhole pattern of the rocks after simulated downhole drilling, however, revealed ductile chipping of the Sandstone, but more brittle behavior in the Dolomite.

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INTRODUCTION

This report summarizes the results of full-scale laboratory drilling of rock types typically found in deep oil and gas reservoirs in the United States. The need for full-scale drilling, as opposed to small scale tests, is generally recognized because of the complex phenomena involved when bits cut into rock. At deep hole drilling conditions where rock plasticity and hydraulic hold-down of cuttings impede chip removal, the need for full-scale drilling is even more apparent. In a study by J.B. Cheatham (Appendix A), it is pointed out that actual drilling rates fall below theoretically achievable rates and that a study of the kinematics of drilling is needed to utilize the fundamental knowledge to achieve faster drilling.

The object of the work reported here was to determine the effects of changing various drilling parameters on the drilling rate while drilling at simulated depths. To accomplish this objective, a study was first performed to identify rock types typical of deep oil and gas reservoirs in the United States. This study, given in Appendix B, identified four rock types typical of deep oil and gas reservoirs. These were sandstone, shale, dolomite and limestone. Samples of Colton Sandstone, Mancos Shale and Bonne Terre Dolomite were selected as representative of the rock types encountered in oil and gas reservoirs and then obtained from surface outcrops. The shale samples proved to be unusable, so the study was conducted with drilling data obtained only from the Colton Sandstone and Bonne Terre Dolomite.

The drilling tests were performed at the Drilling Research Laboratory in Salt Lake City, Utah. The large drill rig and wellbore simulator were used so that full-scale simulation of bit size and downhole pressure could be achieved. A description of the facility is given in Appendix C. The rock samples drilled under pressure were 13.5 inches in diameter and approximately three feet long. This sample size allowed drilling with a standard 7 7/8 inch insert roller bit without the sample failing under the applied pressure.

This work, done under contract to ERDA, required effort to get the equipment operational in order to obtain the specified test conditions, as well as acquiring the test data. Although the data obtained forms an important base of information, it is also recognized that continuation of this type of work is needed to obtain a more complete body of data.

ROCK SELECTION

From the rock selection study (Appendix B), it was decided that the rock types representing a large percentage of the drilling found in the deep reservoirs consisted of shales, sandstones, limestones and dolomites. Based on the physical and mechanical properties typical to these rock types, a list of candidate rocks was compiled (Table VII in Appendix B). For the full-scale drilling tests there was an additional constraint that the rock samples be obtained in large sizes and from quarries or other locations free from surface weathering. From the candidate list the Colton Sandstone, Bonne Terre Dolomite and Mancos Shale satisfied both the requirements to be representative of the deep oil and gas wells and samples were available in large sizes.

The Colton Sandstone was selected from the stock of building stone at Hansen Stone Quarries, Sandy, Utah. Blocks approximately three feet by three feet by five feet were selected by visual inspection to be as homogeneous as possible. The Bonne Terre Dolomite was obtained from Valley Mineral Products Company, Bonne Terre, Missouri, and was also received in building stone blocks approximately three feet by three feet by five feet by visual inspection to be as uniform as possible. The Mancos Shale was obtained from a home construction site near Price, Utah, where an excavation was being made in the shale. At this excavation site, sample points were identified where large irregular samples were broken loose specifically for this study.

ROCK PROPERTIES

The mechanical and physical properties of the blocks of rock received for the drilling tests were determined on small (3/4 inch diameter by 2 inch long) samples cut from the blocks. These small samples were tested in the Rock Mechanics Laboratory at Terra Tek. Table 1 summarizes the test results. Note that the properties measured by Terra Tek are reasonably close to the typical values, where properties are are available, used for the rock selection (Table VII in Appendix B).

Triaxial compression tests at three different confining pressures were also done at Terra Tek to define the volume strain relationships and the failure points. In these tests the samples were gaged so the axial and radial strains in the sample could be measured as the pressures were applied. The axial pressure and confining pressure were independently controlled so the desired stress difference between the two pressures could be obtained. To perform the triaxial test the sample is first loaded along the hydrostatic path (where the axial and confining pressure are equal) until the specified confining pressure is reached. From this point, the confining pressure is held constant and the axial pressure is increased until the sample fails. This test determines the compressibility of the rock and manner of failure (failure envelope) resulting from large differential stresses.

The data obtained from the triaxial compression of the sandstone and dolomite are shown in Figures 1 through 5. The axial and transverse strains in these figures are used to obtain the volume change curves

TABLE 1

MECHANICAL AND PHYSICAL PROPERTIES OF TEST ROCK

	COLTON SANDSTONE	BONNE TERRE DOLOMITE	MANCOS SHALE
TOTAL POROSITY (% of Total Volume)	10.9%	8.4%	7.9%
AIR VOIDS (% of Total Volume)	8.4%	8.1%	4.7%
INITIAL SATURATION (% of Pore Volume)	18.4%	4.8%	41%
DENSITY (As Received)	2.38 gm/cm^3	2.66 gm/cm^3	
DRY DENSITY (Sample Dried 24 hrs @ 105°C)	2.35 gm/cm^3	2.656 gm/cm^3	2.52 gm/cm^3
GRAIN DENSITY	2.65 gm/cm^3	2.90 gm/cm^3	2.70 gm/cm^3
PERMEABILITY (With P_{conf} @ 5,000 psi)	40 x 10^{-6} darcies	47 x 10^{-9} darcies	
UNCONFINED COMPRESSIVE STRENGTH	7,600 psi	25,500 psi	
COMPRESSIONAL WAVE VELOCITY	2880 M/Sec	6510 M/Sec	
SHEAR WAVE VELOCITY	1960 M/Sec	3590 M/Sec	
APPARENT YOUNG'S MODULI	2.8 x 10^6 psi	12.7 x 10^6 psi	

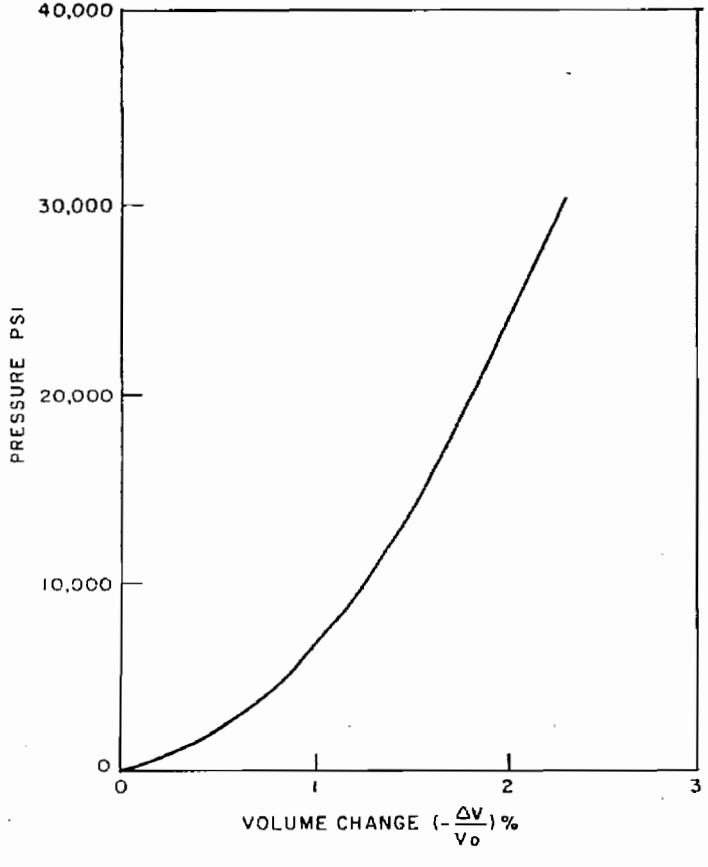

FIGURE 1

Hydrostatic Compression of
Dry Colton Sandstone

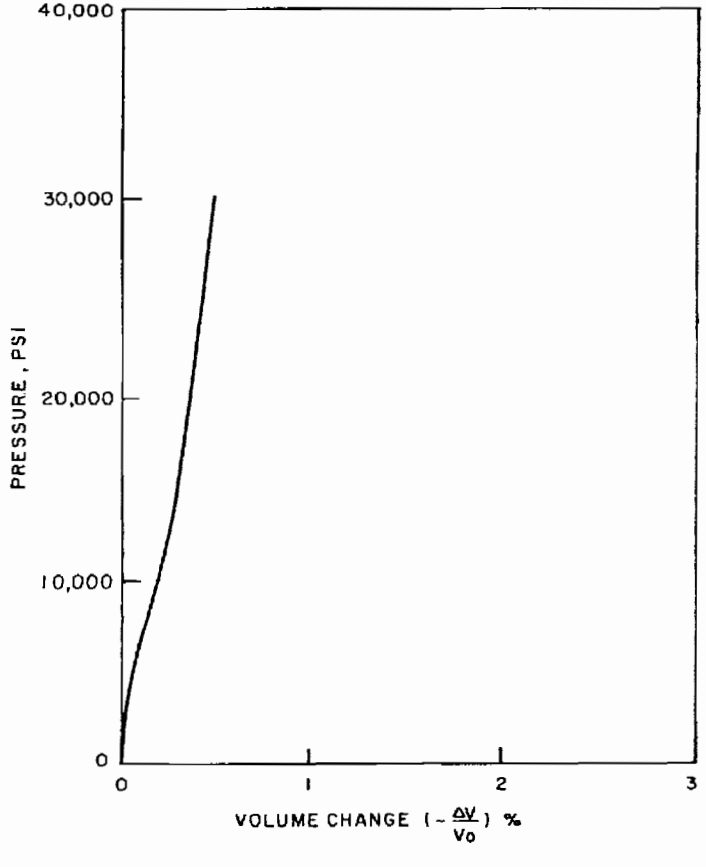

FIGURE 2

Hydrostatic Compression of
Dry Bonne Terre Dolomite

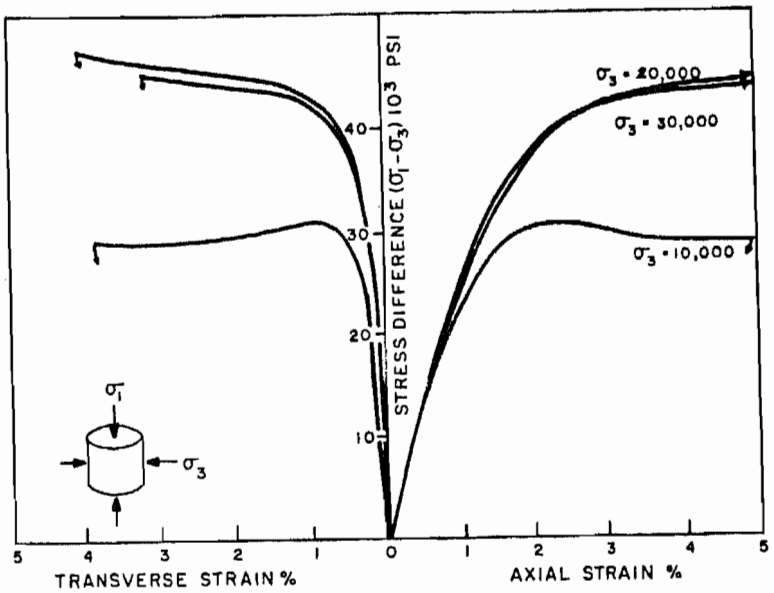

FIGURE 3

Shortening Strain Under Confining Pressure for Colton Sandstone without Pore Pressure

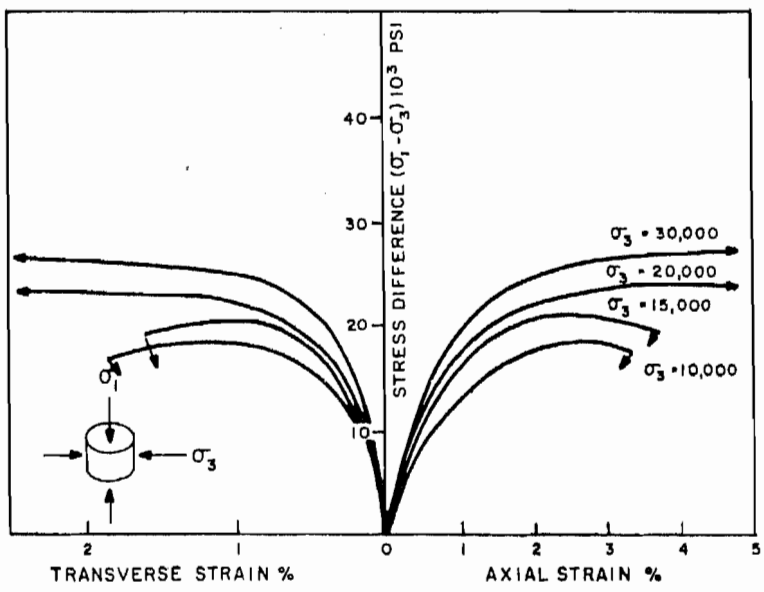

FIGURE 4

Shortening Strain Under Confining Pressure for Colton Sandstone with Pore Pressure ($P_{pore}=\sigma_3/2$)

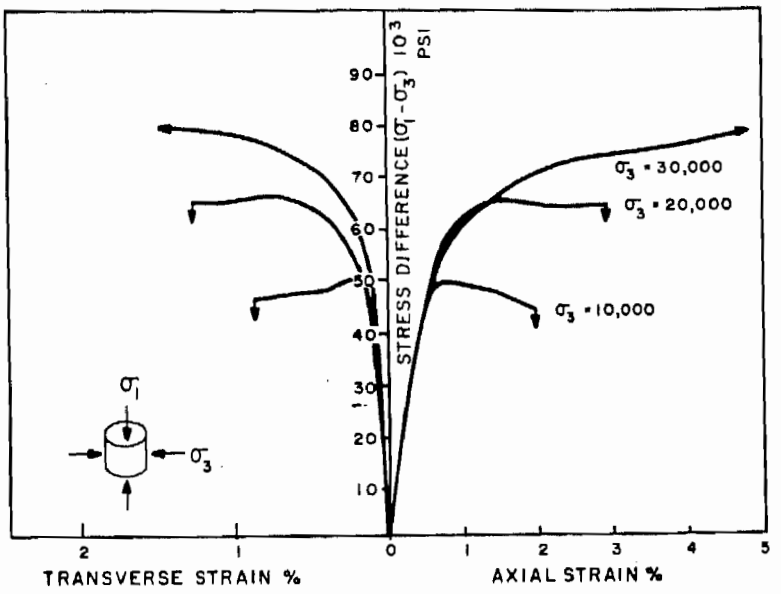

FIGURE 5

Shortening Strain Under Confining Pressure for Bonne Terre Dolomite without Pore Pressure

shown in Figures 6-8 and the Failure Envelope curve in Figure 9.

Also shown on Figures 6-9 are the stress states, or range of stress states, which the samples where placed under in the solid sample ahead of the drill bit. It is thus apparent that the undrilled rock is in its elastic response region. The stress state in the annular rock ring left after the center is drilled out is under a larger stress difference state, but the stress in this region of the sample is only of interest in relation to maintaining sample integrity during the drilling tests.

An attempt was made to saturate the samples with water so that pore pressure could be controlled during the tests, but after soaking the sandstone samples for nearly a month in water, a limiting saturation of only 60% was reached. With this partial saturation, the time required to equalize fluid pore pressure throughout the sample was much too long for pore pressure control during drilling. The long time arises since fluid must flow through the extremely low permeability of the rock matrix to compress the gas trapped in the matrix. After one experimental test where it was verified that pore pressure could not be achieved in reasonable time limits, no further attempt was made to control pore pressures during the drilling tests.

To check the uniformity of the large samples, several holes were drilled through the blocks at constant drilling parameters. Figure 10 shows the penetrated rate as a function of the penetrated depth in the sample for the Shale; Figure 11 shows a similar plot for Sandstone. Because of the highly variable penetration rate in the shale, which reflected the non-

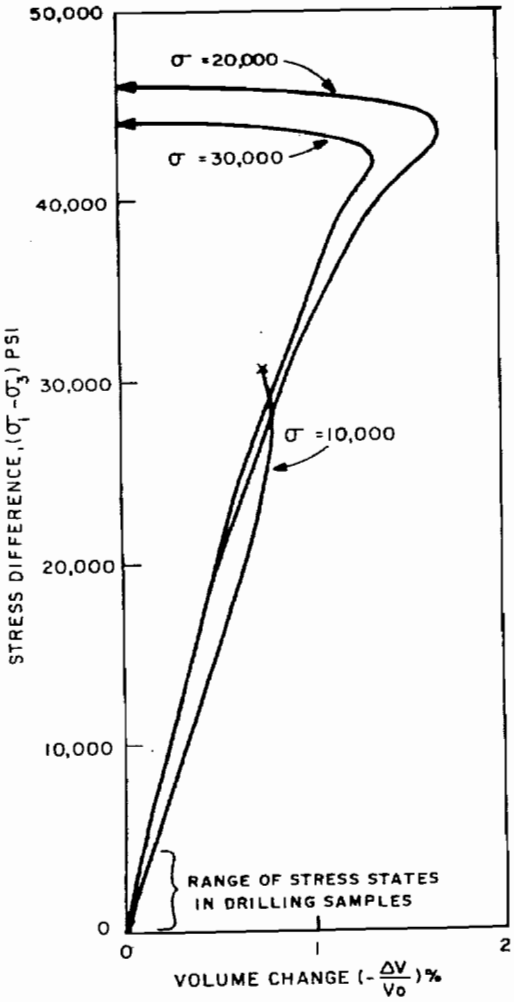

FIGURE 6

Incremental Volume Strain for Triaxial Compression under Confining Pressure for Colton Sandstone without Pore Pressure

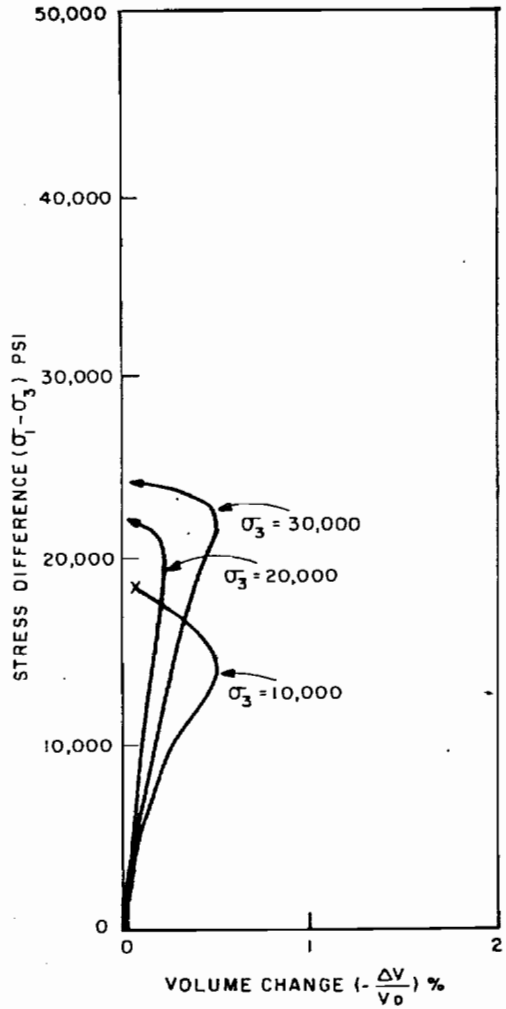

FIGURE 7

Incremental Volume Strain for Triaxial Compression under Confining Pressure for Colton Sandstone with Pore Pressure ($P_{pore}=\sigma_3/2$)

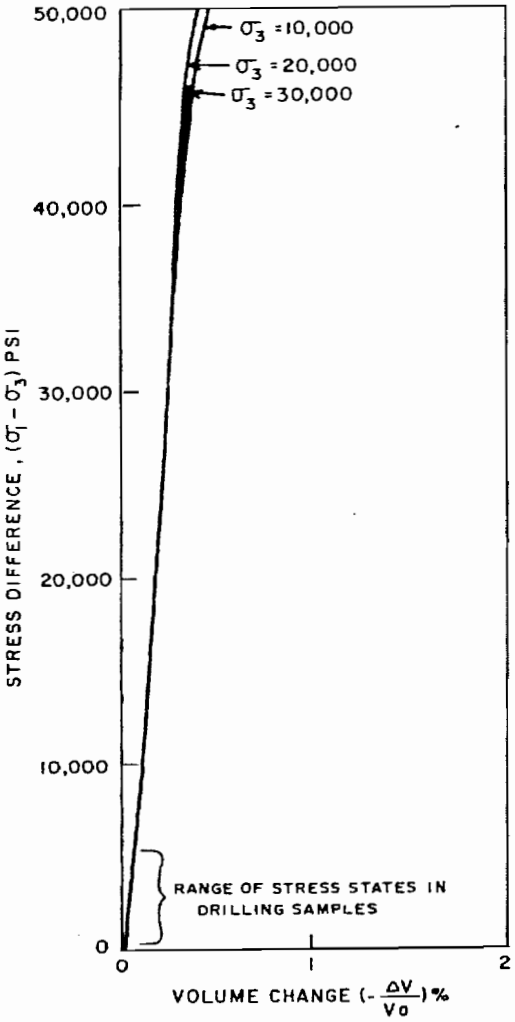

FIGURE 8

Incremental Volume Strain for Triaxial Compression under Confining Pressure for Bonne Terre Dolomite without Pore Pressure

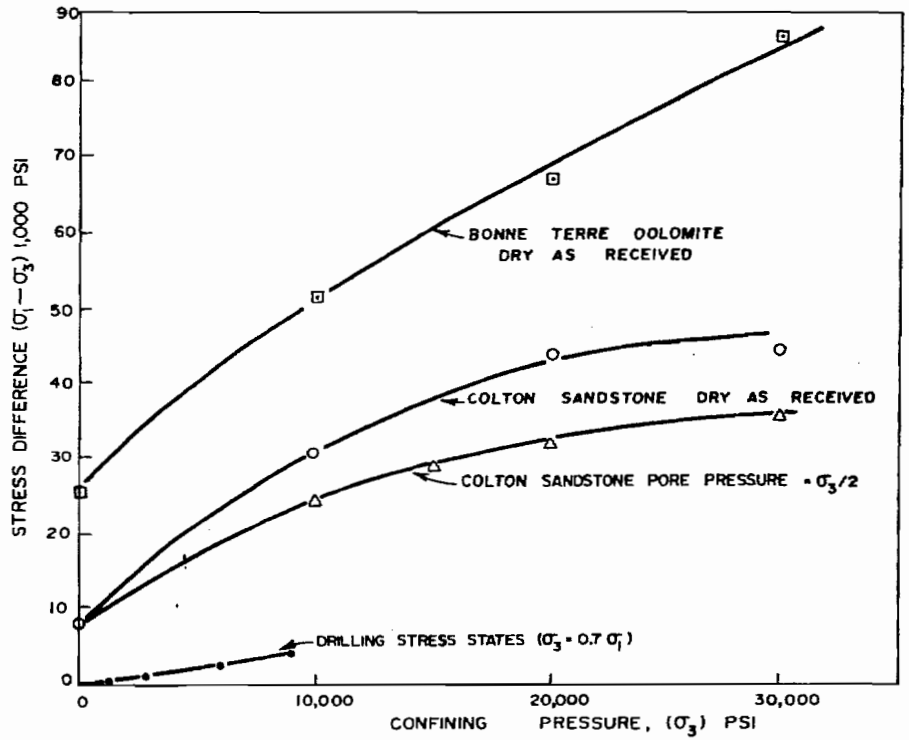

FIGURE 9

Failure Envelopes for Colton Sandstone and Bonne Terre Dolomite

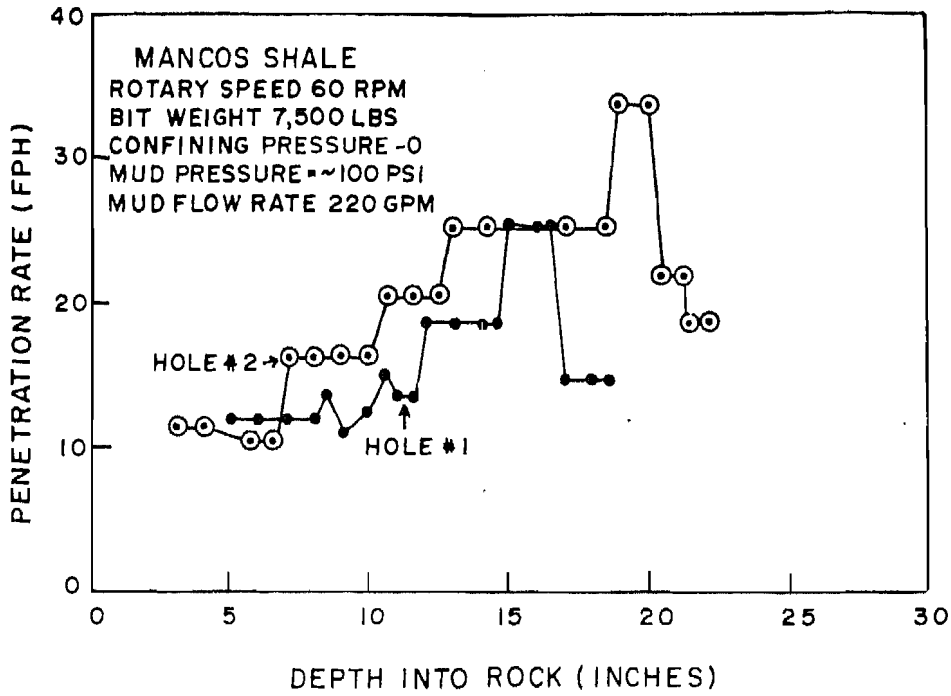

FIGURE 10
Uniformity Test of Mancos Shale. Entire Hole Drilled with Constant Drilling Parameters

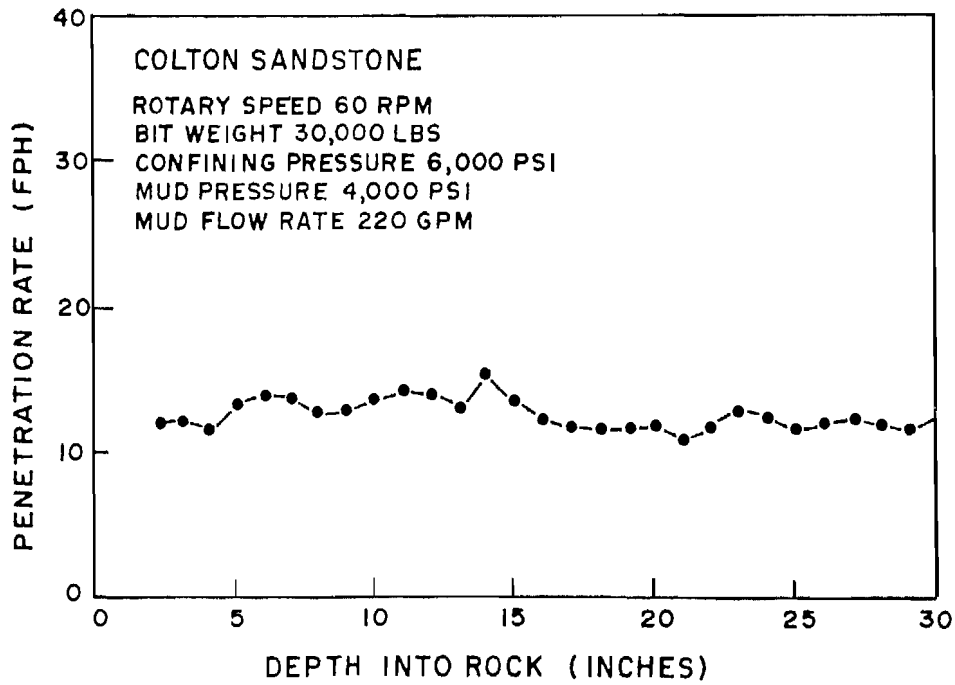

FIGURE 11

Uniformity Test of Colton Sandstone. Entire Hole Drilled with Constant Drilling Parameters

uniformity of the sample, it was decided to delete this shale sample from the test program. Funding limitations precluded obtaining further shale samples, so after consultation and direction by the ERDA Contract Coordinator, the program was continued without doing drilling tests in shale. Similar atmospheric drilling tests for uniformity in the dolomite samples showed it to be reasonably uniform, except for occasional vugs or defects. The dolomite was used, but if a defect was encountered during the drilling tests as evidenced by a sudden jump in drill rates, that data was deleted from the reported results.

DRILL BIT AND MUD SELECTION

The bits used were selected on the basis of recommendations solicited from the major bit manufacturers. The recommendations were obtained by first holding a meeting where the bit manufacturers were invited to learn about the program. The attending manufacturers were requested to make recommendations as to which bits should be used along with any other comments they might have on the program. Recommendations and comments were received from Reed Tool Company, Smith Tool Company, Hughes Tool Company, Dresser Industries (Security Division), and Christensen, Inc. A collection of the correspondence pertaining to the meeting and the subsequent replies is given in Appendix D. The recommendations were reasonably consistent and three manufacturers furnished bits at no charge for use in the drilling program. Based on a comparative analysis of the recommendations, the following bit types were selected for the program.

MANUFACTURER	TYPE*	RECOMMENDED FOR
Smith Tool	F3	Sandstone or Shale
Reed Tool	FP52	Sandstone or Shale
Security	M89TF	Sandstone or Dolomite

* Manufacturers specifications for these bits are tabulated in Appendix D.

The bit size selected, also based on the recommendations, was 7 7/8 inches. This size is very popular for the drilling of oil and gas wells for which this drilling program is simulating. Also, most experimental bits are made in this size and the results of this program will be directly comparable to much of the current research being done in the industry. The goal of this project was to study the drilling rates with currently available bits, consequently no experimental bits or bits not available from normal purchasing were considered.

The drilling fluid selected was to be typical of the fluid used in drilling oil and gas wells. Since muds are commonly used for well stability and pressure control, mud was selected for this program. A waterbase, weighted mud was selected to be representative of typical drilling. Table 2 tabulates the constituants and basic properties of the mud. Percentage compositions of the solids are not given since they changed throughout the drilling as drill solids accumulated and small additions of the other constituants were made from time to time to keep the weight, viscosity and gel properties reasonably constant throughout the test. The same mud was used for both the atmospheric drilling and the pressure drilling.

TABLE 2

MUD PROPERTIES

BASE: Water

PHASES: (i) Water
(ii) Solids
(a) Bentonite
(b) Barite
(c) Drill Solids

WEIGHT: 9.3 pounds/gallon

APPARENT VISCOSITY: ~12. cp

PLASTIC VISCOSITY: 7 cp

YIELD POINT: 10 pounds/100 square feet

INITIAL GEL: 5 pounds/100 square feet

10 MINUTE GEL STRENGTH: 14 pounds/100 square feet

pH: 7.85

API FILTRATE: 14.2 cc/30 minutes

EXPERIMENTAL METHOD

The tests were performed with the Drilling Research Laboratory drill rig. For atmospheric conditions, the drill rig was positioned over rock blocks placed in the drilling pit. Samples to be drilled under simulated downhole conditions were first cored from the large quarried blocks with a 13 5/8 inch thin-walled core drill and then fitted with a urethane jacket and steel end caps prior to placement in the pressure vessel.

To simulate downhole stress conditions, the overburden, or vertical stress gradient was assumed to be 1.0 psi per foot and the horizontal stress was assumed to be 70% of the vertical stress. These are typical values, for normally pressured reservoirs, although local conditions in specific wells may be somewhat different. For the laboratory tests, the pore pressure was essentially zero.

One of the critical aspects of the experimental procedure was to determine what combinations of confining pressure, axial pressure, and borehole pressures could be exerted on the rock specimens to both simulate downhole conditions and not cause the specimen to fail. To accomplish this, a model predicting specimen failure was developed (Appendix E) and used as a guide in specifying the test conditions. The final selection of the operating conditions and the test matrix was made under the direction of the ERDA contract coordinator. The various parameters were chosen to be typical of actual field conditions and to provide a basic set of data. In the selection of conditions, some emphasis was placed on mud pressure in addition to rotary speed and thrust (weight) on the bit.

The actual drilling of the samples was done using the servocontrolled equipment so that the drilling conditions could be rapidly changed and then held constant. With this arrangement, it was possible to obtain many data points on each three foot long specimen. Changing from one set of conditions would then take only a few minutes. During these stabilized drilling periods, the computerized data acquisition program would be invoked to gather a set of digitized data in addition to the continuous strip chart record being made throughout the test. Some of the data reduction and analysis was done with the digitized data and computer programs.

EXPERIMENTAL DATA AND RESULTS

The experimental data obtained is tabulated in Tables 3 and 4. Actually, considerably more drilling was done than is reported in Tables 3 and 4, but lack of homogeneity in some of the test samples, particularly the dolomite, and some operational problems resulted in some bad tests or unreliable data. The questionable results were thus omitted from the reported results.

For the Colton Sandstone tests, the penetration rate as a function of rotary speed, weight on bit, borehole mud pressure, mud flow rate, confining pressure and overburden pressure is shown in Figures 12 to 18. The data were generally fit to a power curve ($y = ax^b$) for these plots. From these curves, it is readily apparent that the penetration rate is highly dependent on rotary speed, weight on the bit and borehole mud pressure. Mud flow rate had a small influence whereas confining pressure and axial pressure had an apparent negligible effect. These results are in accord with expectations based on drilling theory.

The borehole mud pressure was particularly significant in controlling the drilling rate. As the mud pressure was raised, the drilling rate dropped rapidly until the pressure reached about 2,000 psi. At borehole mud pressure above this value, the increased pressure had a small effect. Evidently, the chip hold-down and imperfect cleaning effects resulting from the differential between the mud and pore pressures tended to reach a critical level. Once this critical level was reached, the drilling rate was then dependent primarily on bit weight. Neither rotary

TABLE 3
EXPERIMENTAL DATA FOR COLTON SANDSTONE

BIT	CONFINING PRESSURE (psi)	AXIAL PRESSURE (psi)	MUD PRESSURE (psi)	MUD FLOW (gpm)	ROTARY SPEED (rpm)	BIT WEIGHT (1000 lbs)	DRILLING RATE (ft/hr)	TORQUE (ft. lbs)
SMITH F-3 7 7/8 Inch w/3- 11/32 Nozzles	Atmos.	Atmos.	100	220	40	5	6.1	400
						10	20.6	830
						15	30.1	1320
						20	36.4	1950
						25	47.0	- -
						30	57.5	- -
						35	64.5	- -
					60	5	8.0	400
						10	23.8	800
						15	41.0	1200
						20	53.0	1800
						25	70.0	- -
						30	77.5	- -
					80	5	12.0	350
						10	30.5	730
						15	52.0	1070
						20	75.5	1380
					100	5	14.1	230
						10	37.3	580
						15	65.0	960
						20	93.5	1240
	1500	σ_1 = 2140	275	220	60	10	7.7	440
						20	22.2	1000
						30	31.8	1600
						40	44.9	- -
			500	220	60	10	7.4	420
						20	15.8	1000
						30	27.4	1700
						40	35.4	2200
			1000	220	60	10	5.3	400
						20	9.9	940
						30	16.9	1600
						40	21.3	2100
	3000	σ_1 = 4285	1000	220	60	10	4.8	400
						20	9.2	880
						30	17.6	1440
						40	22.6	2040
			2000	220	40	10	3.4	400
						20	6.5	900
						30	9.0	1480
						40	17.8	2280
					60	10	3.9	380
						20	7.8	840
						30	10.4	1400
						40	14.6	2000
					80	5	5.4	200
						10	9.0	400
						20	11.5	880
						30	19.0	1460

Table 3 Continued

BIT	CONFINING PRESSURE (psi)	AXIAL PRESSURE (psi)	MUD PRESSURE (psi)	MUD FLOW (gpm)	ROTARY SPEED (rpm)	BIT WEIGHT (1000 lbs)	DRILLING RATE (ft/hr)	TORQUE (ft. lbs.)
SMITH F-3 7 7/8 Inch w/3-11/32 Nozzles	3000	σ_1 = 4285	2000	220	80	40	27.4	2160
					100	5	5.8	200
						10	7.6	400
						20	14.1	880
						30	20.5	1400
						40	28.0	2000
				80	60	10	7.1	400
						20	9.9	950
						30	11.6	1500
						40	16.9	2150
				150	60	10	4.8	440
						20	9.1	950
						30	13.8	1560
						40	17.8	2200
				220	60	10	7.9	400
						20	11.1	840
						30	13.8	1500
						40	20.2	2100
		σ_1 = 3330	2000	220	60	20	9.8	900
						40	21.6	2150
		σ_1 = 4000	2000	220	60	20	11.8	1000
						40	22.0	2200
		σ_1 = 4660	2000	220	60	20	9.7	940
						40	19.8	2150
	6000	σ_1 = 8570	2000	220	60	5	3.2	200
						10	3.6	400
						10	4.8	400
						20	11.0	840
						20	7.8	1000
						30	12.8	1600
						30	14.6	1500
						40	22.7	2200
						40	21.7	2200
			4000	220	40	5	3.2	230
						5	2.7	--
						5	3.6	240
						10	5.1	400
						10	5.2	480
						15	4.8	650
						20	6.1	900
						20	8.0	960
						30	11.2	1440
						40	13.8	2000
					60	5	3.0	200
						5	4.0	--
						10	4.7	--
						10	4.6	400
						20	7.1	800
						20	9.0	--
						30	10.6	1400
						30	12.8	--
						30	12.5	1600

Table 3 Continued

BIT	CONFINING PRESSURE (psi)	AXIAL PRESSURE (psi)	MUD PRESSURE (psi)	MUD FLOW (gpm)	ROTARY SPEED (rpm)	BIT WEIGHT (1000 lbs)	DRILLING RATE (ft/hr)	TORQUE (ft lbs)
SMITH F-3 7 7/8 Inch	6000	σ_1 =8570	4000	220	60	40	13.8	2000
					100	5	3.5	200
						10	5.1	400
						20	8.6	820
						30	12.7	1360
						40	17.8	1900
	9000	σ_1=12860	4000	220	60	10	4.6	400
						20	9.6	800
						30	11.4	1500
						40	18.7	2100
			5000	220	60	10	9.2	480
						20	10.7	1000
						30	12.9	1550

TABLE 4

EXPERIMENTAL DATA FOR BONNE TERRE DOLOMITE

BIT	CONFINING PRESSURE (psi)	AXIAL PRESSURE (psi)	MUD PRESSURE (psi)	MUD FLOW (gpm)	ROTARY SPEED (rpm)	BIT WEIGHT (1000 lbs)	DRILLING RATE (ft/ hr)	TORQUE (ft lbs)
SECURITY M89TF 7 7/8 Inch w/3 - 11/32 Inch Nozzles	Atmos.	Atmos.	50	220	40	5	3.8	90
						10	12.6	320
						20	33.4	800
					60	5	4.2	70
						10	14.2	260
					80	5	6.4	70
						10	20.7	260
					100	5	8.4	70
						10	26.6	260
	3000	σ_1 = 4285	1000	220	60	10	16.0	360
						20	41.1	800
						30	67.5	1200
			1500	220	60	5	5.3	100
						10	13.8	300
						20	33.0	750
						30	58.3	1220
						40	82.5	1800
			2100	220	60	5	3.9	100
						10	8.9	310
						20	27.0	780
						29	54.7	1200
						38	70.5	1800
	6000	σ_1 = 8570	4100	220	40	5	4.8	220
						5	4.7	260
						10	10.1	400
						10	10.4	500
						20	24.5	940
						20	25.1	1100
						30	37.8	1490
					60	5	6.6	--
						5	6.9	300
						5	6.6	310
						10	14.6	--
						10	14	430
						10	13.5	430
						20	34.2	1020
						20	34.0	900
						28	54.6	1430
						28	53.6	1540
					80	5	7.4	100
						10	17.2	390
						20	37.8	820
						26	52.3	1220
					100	5	7.0	180
						10	16.4	440
						21	50.3	600
						26	59.0	880

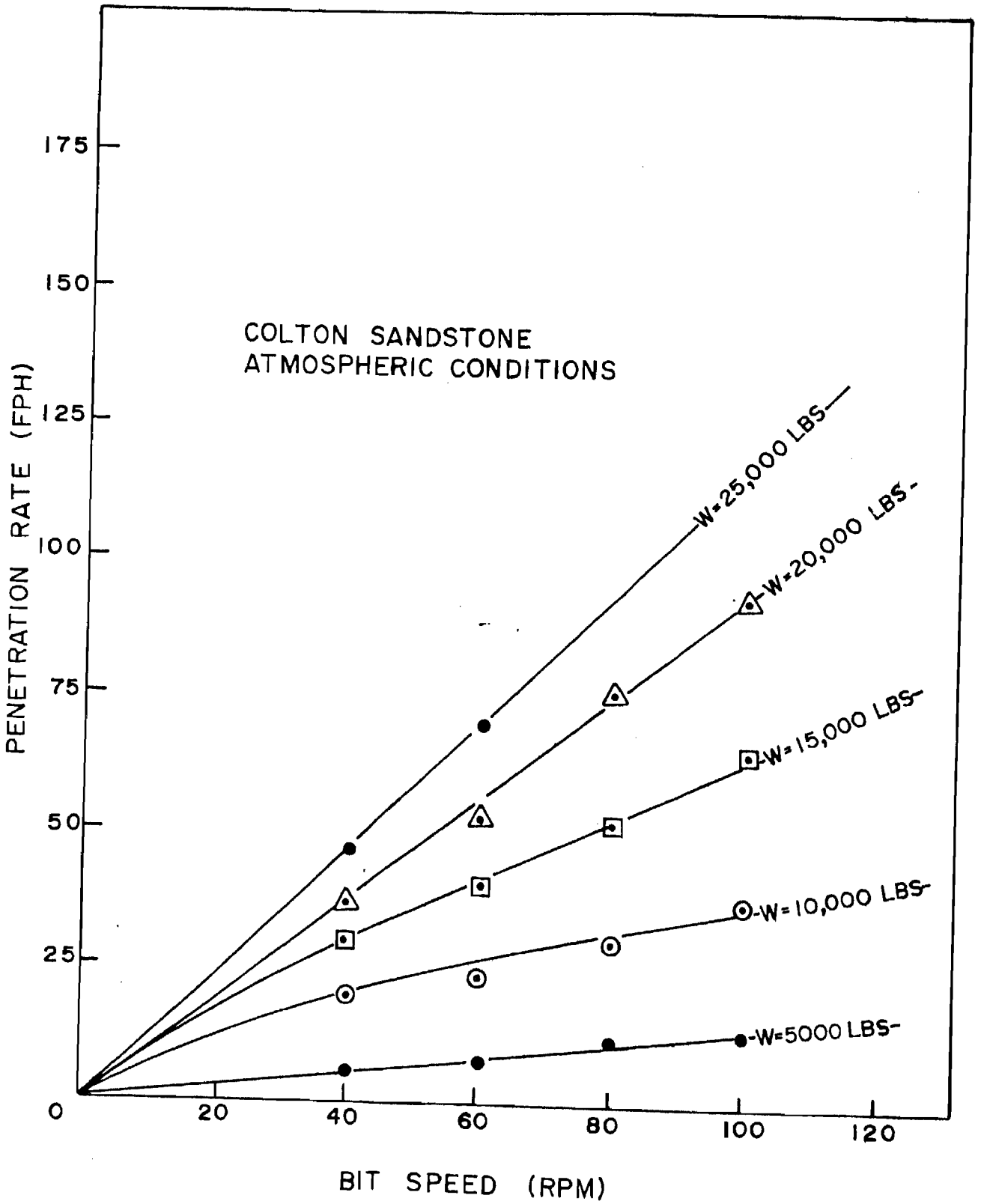

FIGURE 12

Penetration Rate versus Bit Weight and Rotary Speed for Colton Sandstone at Atmospheric Conditions

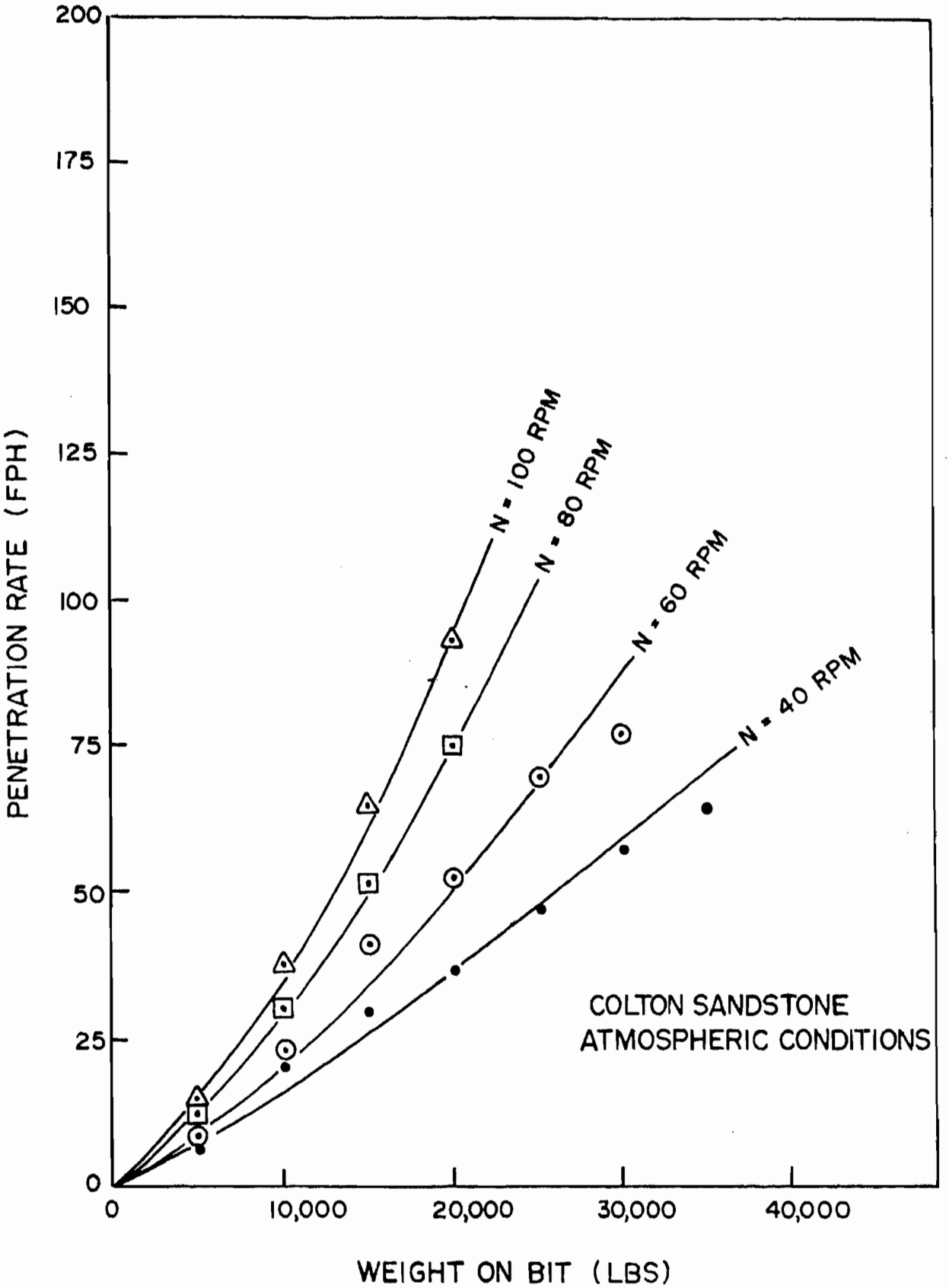

FIGURE 13

Penetration Rate versus Bit Weight and Rotary Speed for Colton Sandstone at Atmospheric Conditions

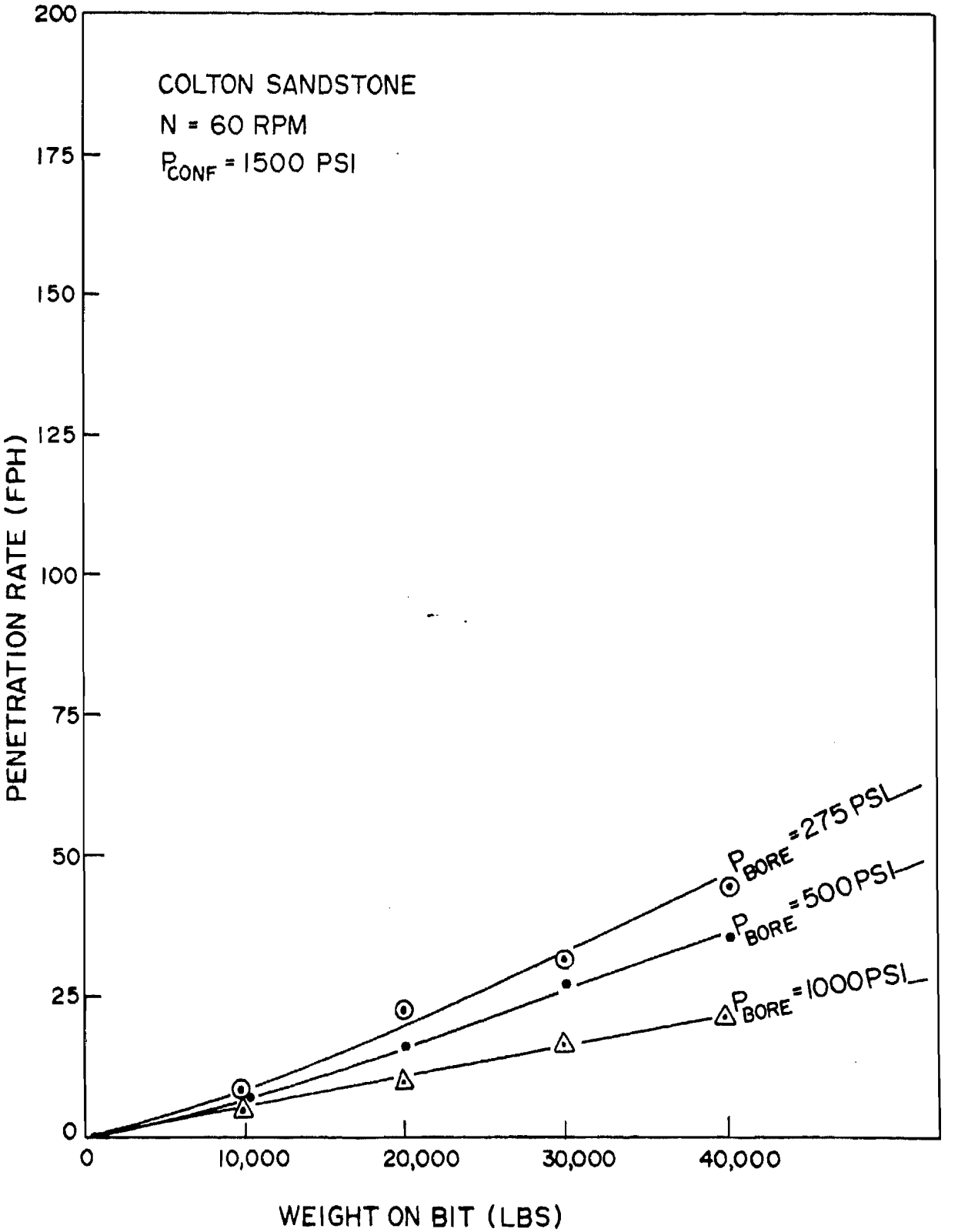

FIGURE 14

Penetration Rate Versus Bit Weight and Mud Pressure for Colton Sandstone at Confining Pressure of 1,500 psi and Rotary Speed of 60 RPM

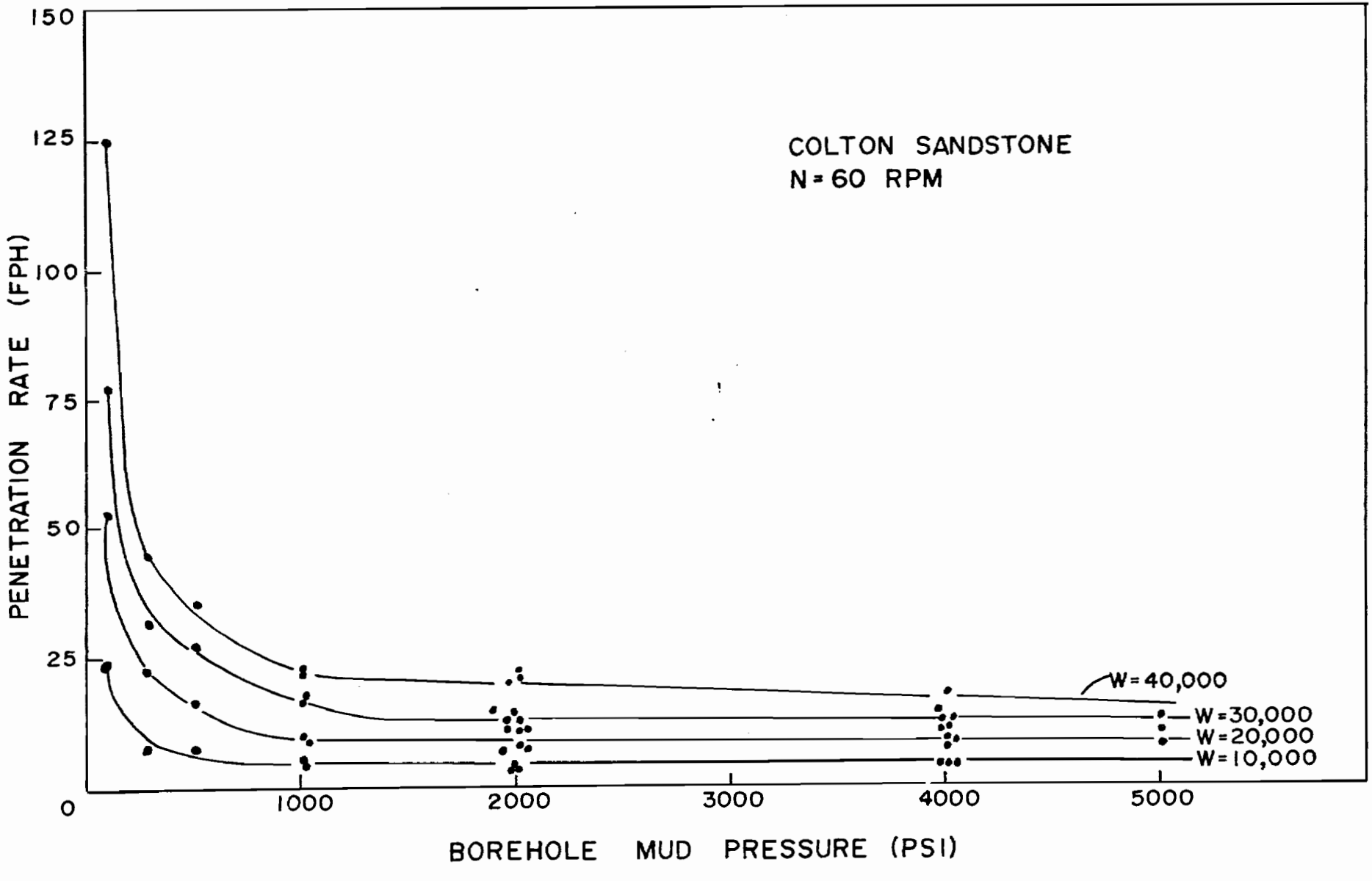

FIGURE 15

Penetration Rate Versus Mud Pressure and Bit Weight for Colton Sandstone at Simulated Downhole Conditions

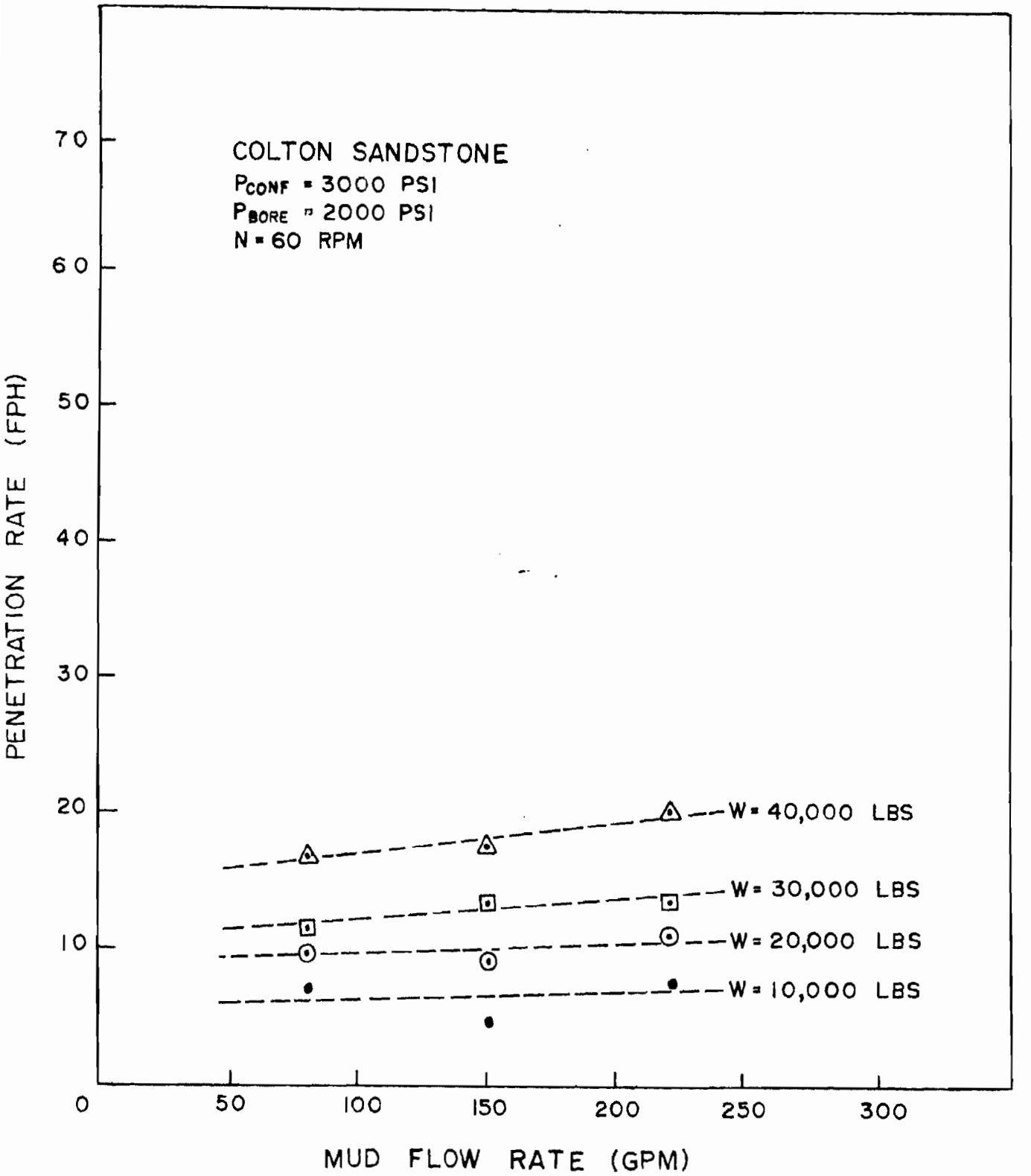

FIGURE 16

Penetration Rate versus Mud Flow Rate and Bit Weight
for Colton Sandstone at Simulated Downhole Conditions

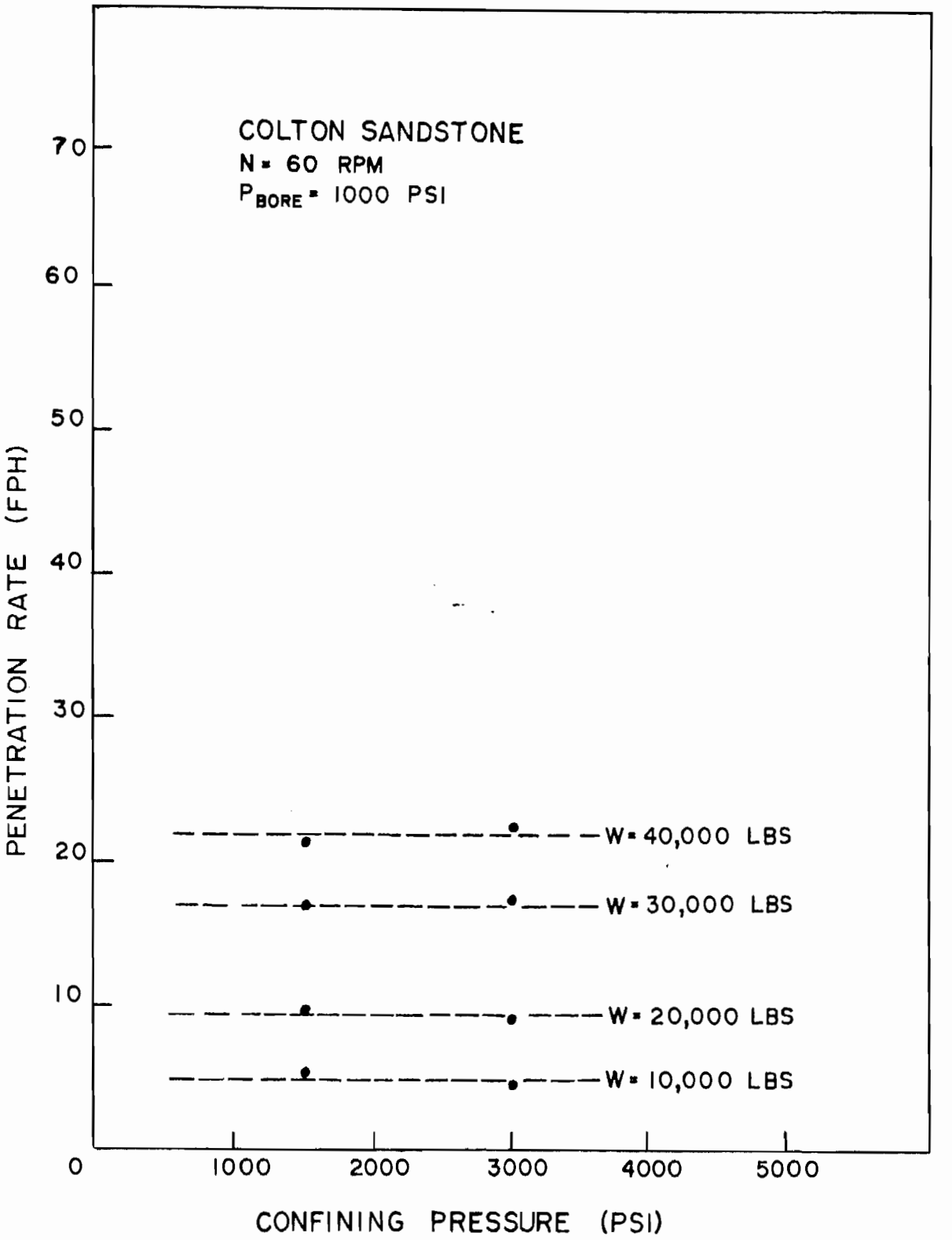

FIGURE 17

Penetration Rate versus Confining Pressure and Bit Weight for Colton Sandstone at Simulated Downhole Conditions

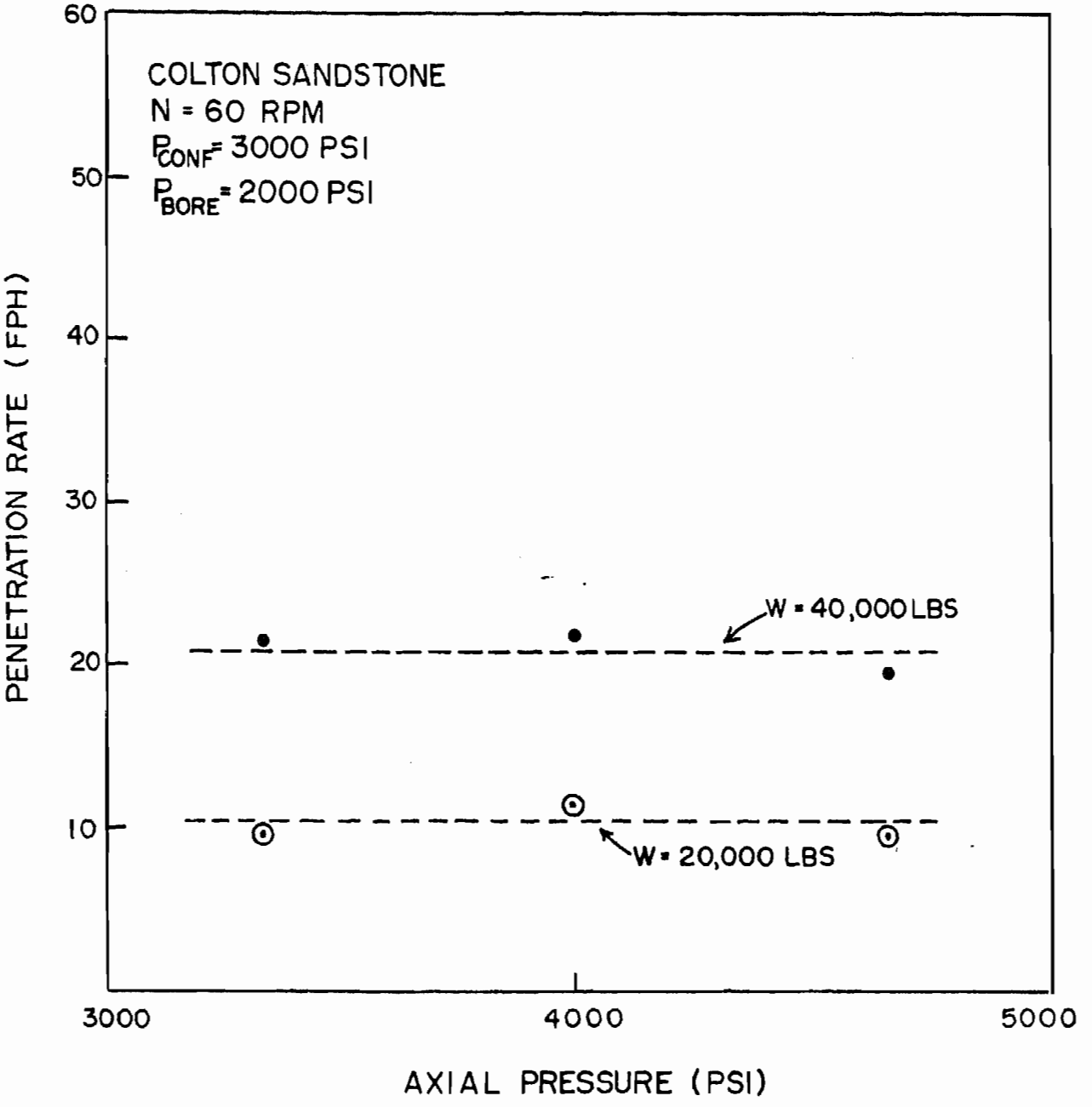

FIGURE 18

Penetration Rate versus Axial Pressure (Overburden) and Bit Weight for Colton Sandstone at Simulated Downhole Conditions

speed nor mud pressure have the degree of effect on penetration rate as they did when the mud pressure was below the critical value.

For the Bonne Terre Dolomite, plots of penetration rate as functions of the other parameters are shown in Figures 19 to 21. From these curves it is also seen that the qualitative results of the Dolomite drilling are similar to the Sandstone drilling. The effect of the borehole mud pressure is less in the Dolomite than in the Sandstone, however.

Although the stress state in the rock being drilled was well below the failure point and presumably in the elastic range as seen in Figure 9, the bottomhole drilling pattern for Sandstone drilled at high pressures visually appeared to have been ductilly deformed. No detailed examination of the chips or the drill patterns was made, however. Figure 22 is a photograph of one of the Colton Sandstone bottomhole patterns after drilling at pressure and Figure 23 is a similar photograph for a Bonne Terre Dolomite sample.

An indication of drilling efficiency was made by plotting the penetration rate/rotary power as a function of bit weight and borehole pressure in Figures 24 and 25. This shows that the drilling efficiency drops significantly between atmospheric conditions and downhole pressure conditions. Also, the Dolomite is behaving somewhat differently than the Sandstone.

To make a preliminary evaluation of the functional relationships between the variables, a few regression analyses were made on selected portions of the data. Table 5 gives the coefficients determined for penetration rate as a function of rotary speed and bit weight for different conditions of confining pressure and mud pressure. Note that in the Colton Sandstone, the coefficients for both RPM and bit weight are drastically

reduced as the combined confining and mud pressures are increased. This contrasts with the same coefficients for the Bonne Terre Dolomite which remain about the same with a similar change in confining and mud pressure.

TABLE 5

Coefficients from Multiple Linear Correlation Analyses

Drilling Rate = $C_o + C_1 x(RPM) + C_2 x(Bit\ Wt.)$

	C_o	C_1	C_2	R^2 Correlation
Colton Sandstone				
Atmosphere Conditions	-39.3	.592	.00271	.86
3,000 psi confining 2,000 psi mud	-11.2	.159	.00053	.90
6,000 psi confining 4,000 psi mud	- .05	.0325	.00032	.95
Bonne Terre Dolomite				
Atmosphere Conditions	-16.8	.171	.00223	.95
6,000 psi confining 4,100 psi mud	-18.7	.228	.00194	.95

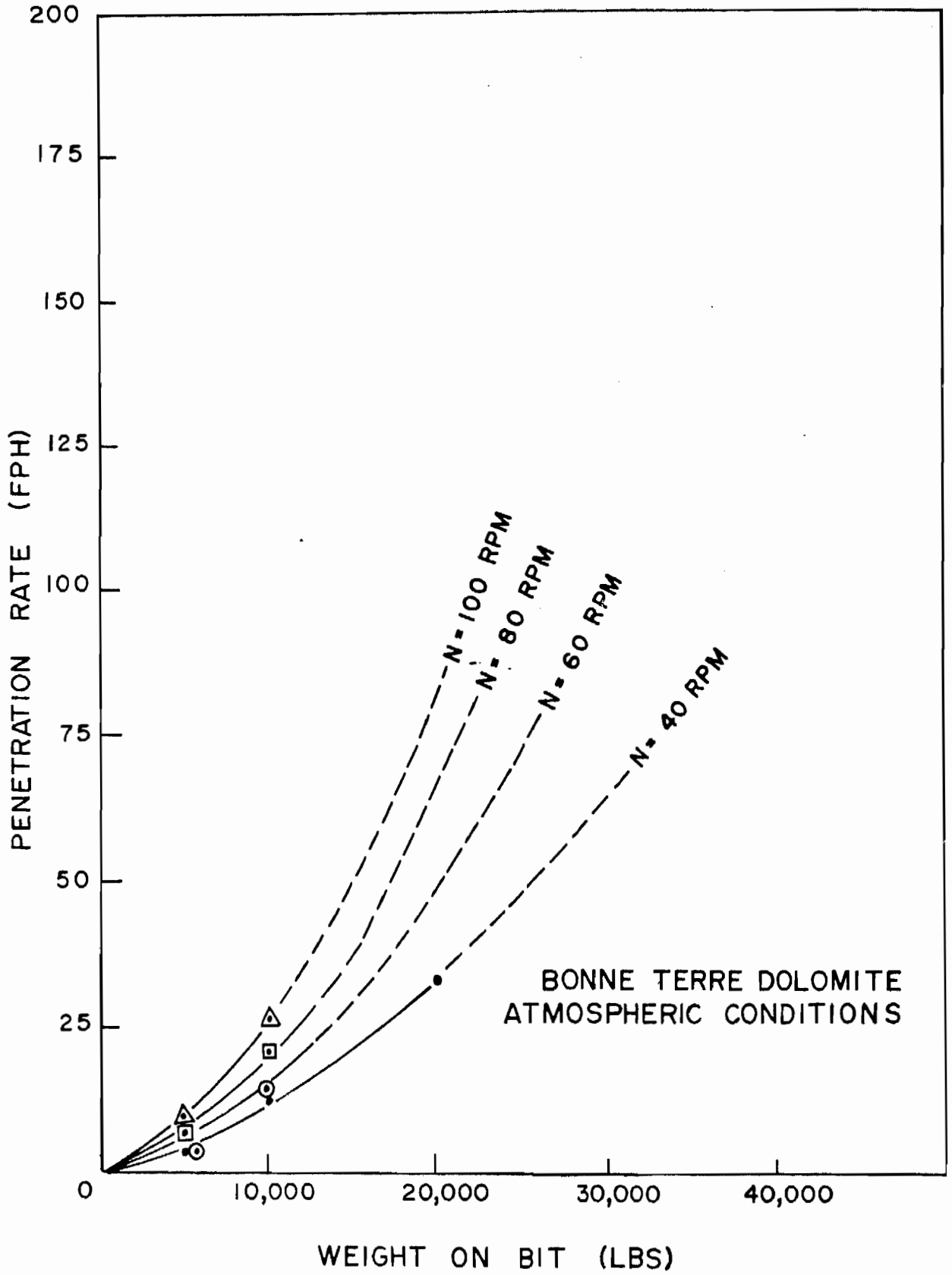

FIGURE 19

Penetration Rate versus Bit Weight and RPM for
Bonne Terre Dolomite at Atmospheric Conditions

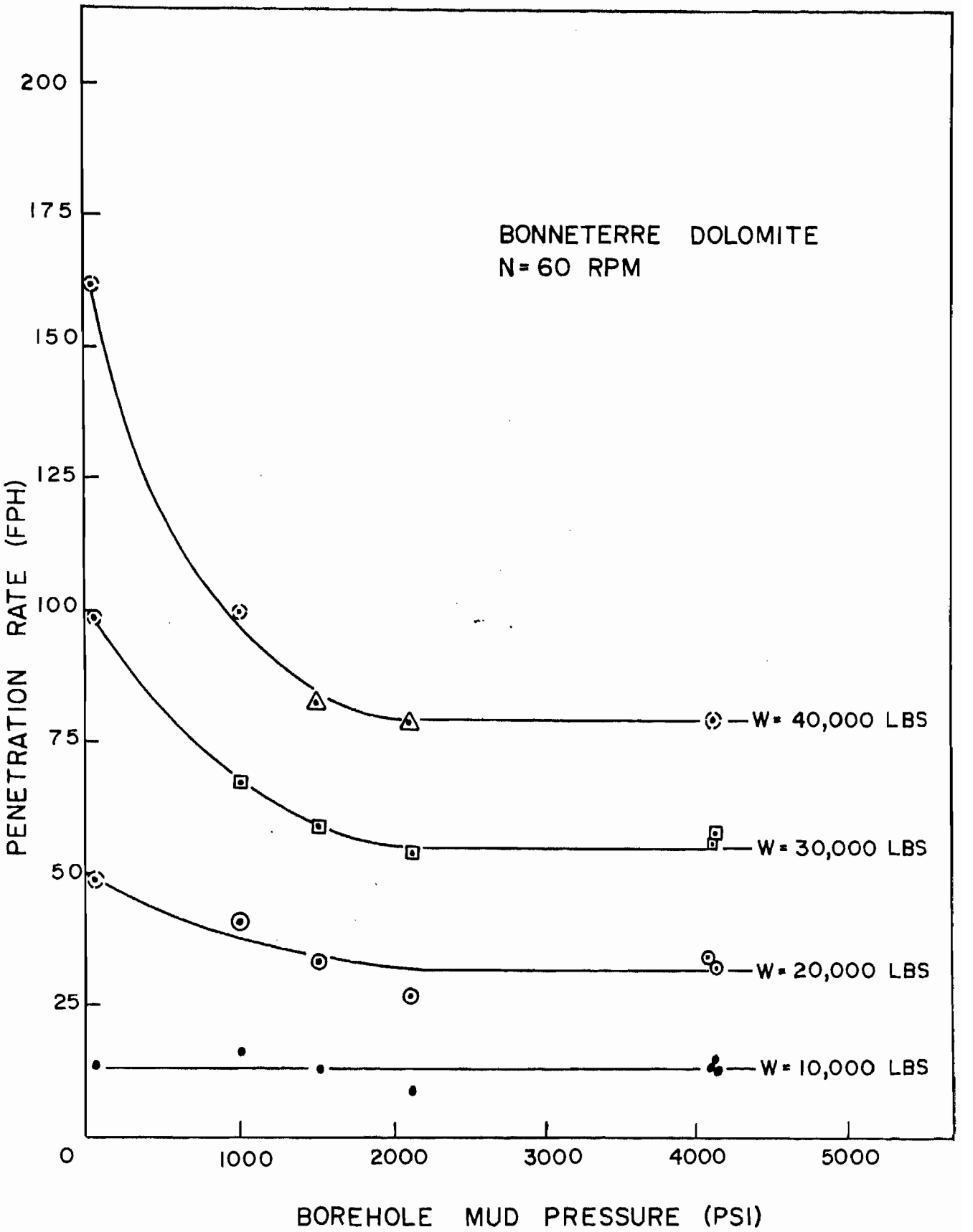

FIGURE 20

Penetration Rate versus Mud Pressure and Bit Weight for
Bonne Terre Dolomite at 60 RPM and Simulated Downhole Conditions

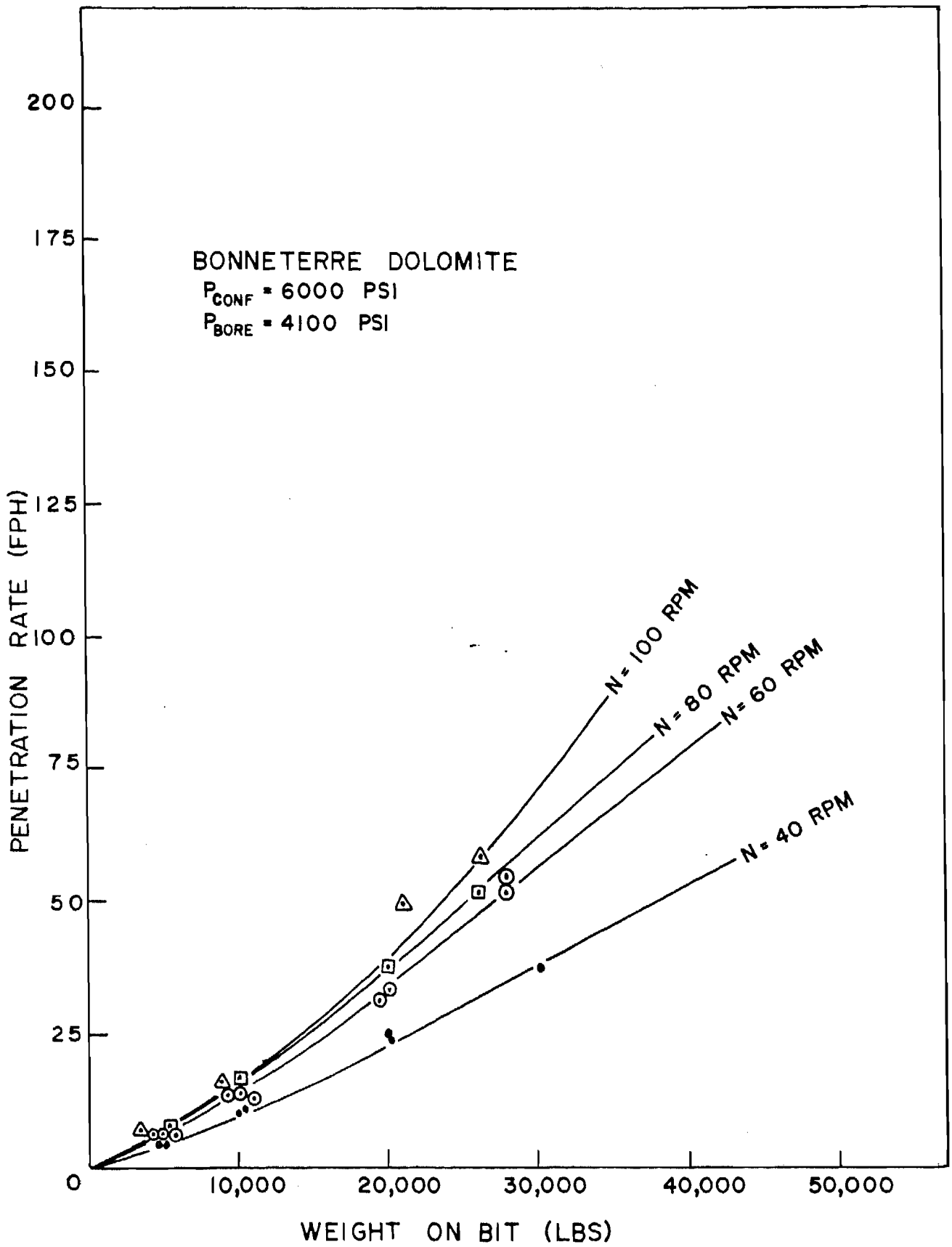

FIGURE 21

Penetration Rate versus Bit Weight and Mud Pressure for Bonne Terre Dolomite at 60 RPM and Simulated Downhole Conditions

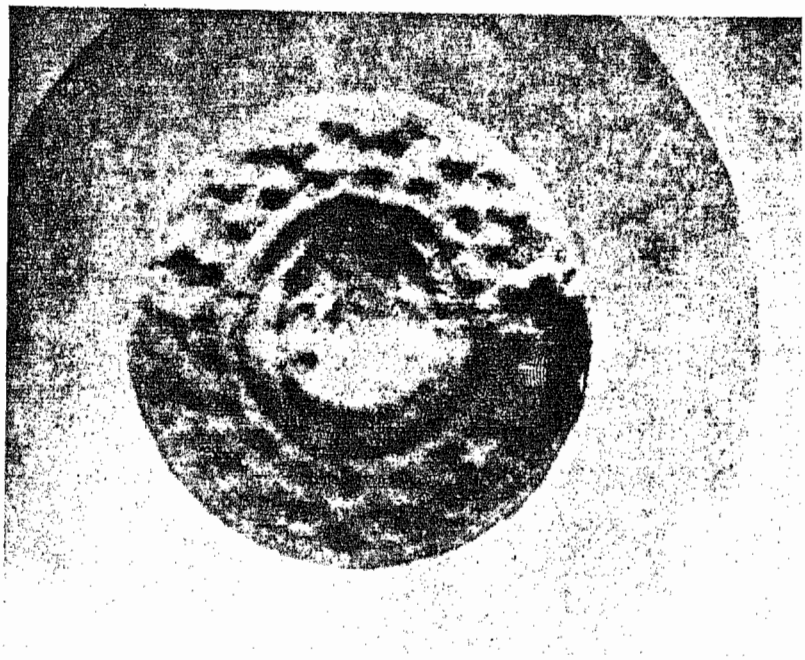

FIGURE 22

Bottomhole Patterns of Colton Sandstone after Drilling at Simulated Downhole Conditions

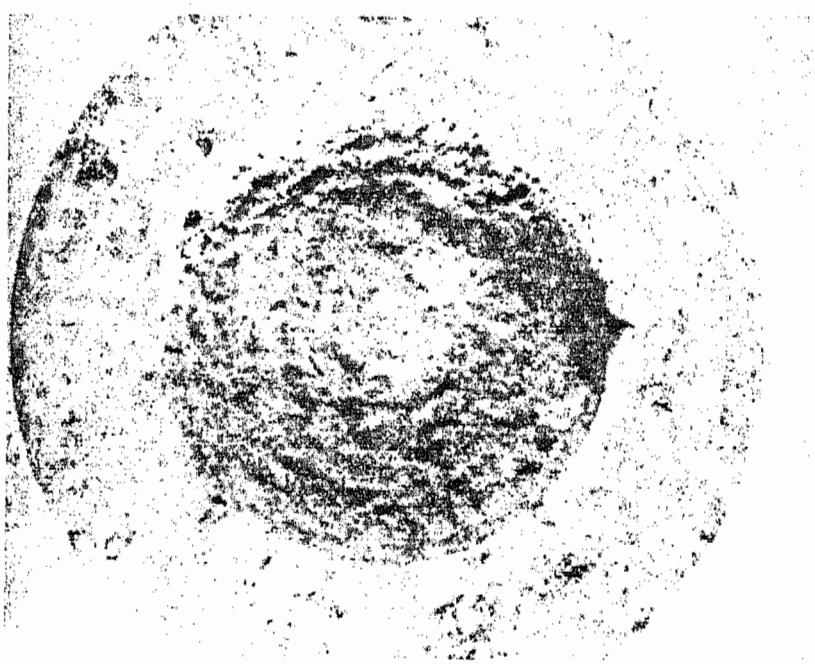

FIGURE 23

Bottomhole Patterns of Bonne Terre Dolomite after Drilling at Simulated Downhole Conditions

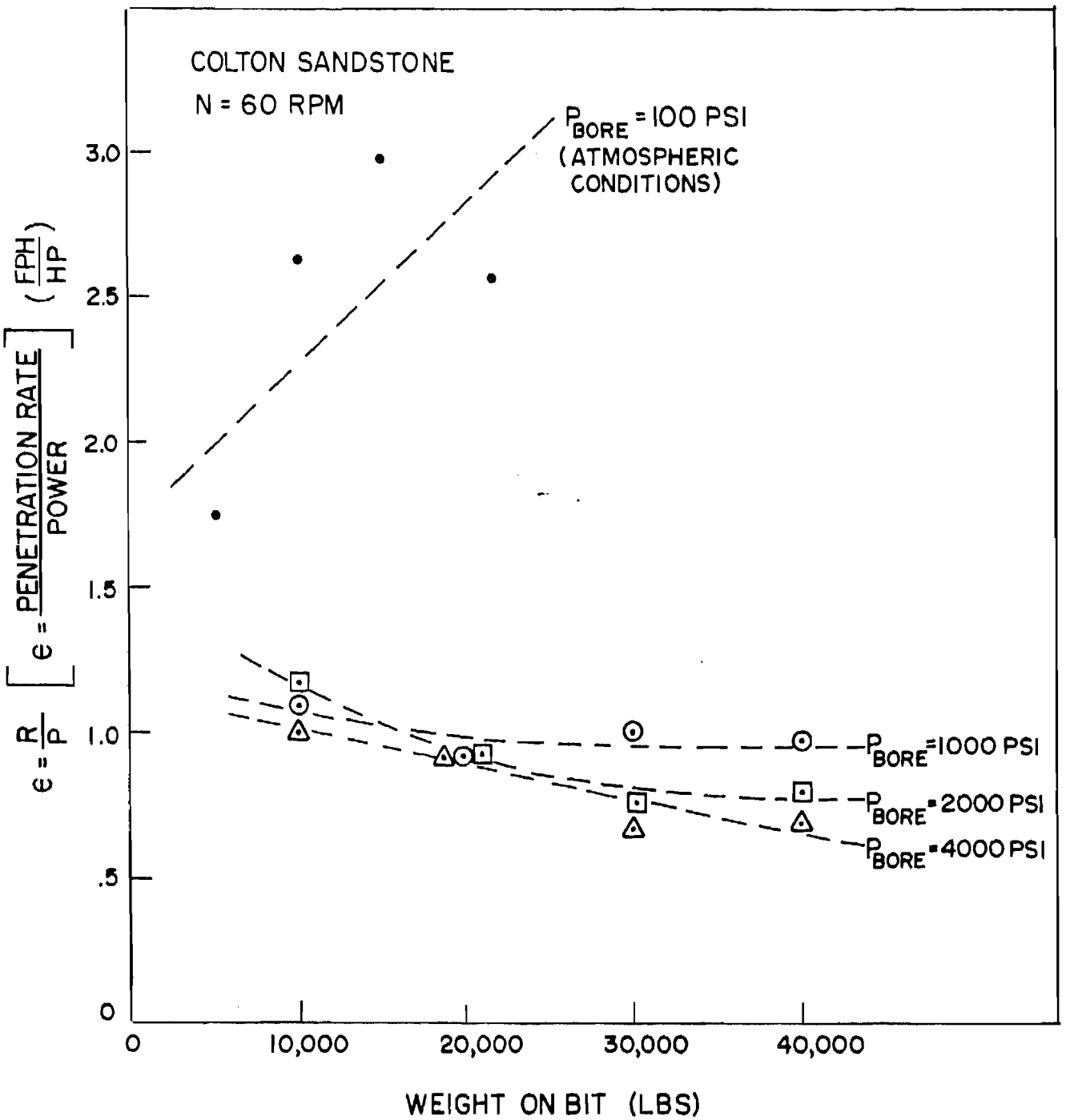

FIGURE 24

Efficiency of Drilling Rate versus Bit Weight and Mud Pressure for Colton Sandstone at 60 RPM and Simulated Downhole Conditions

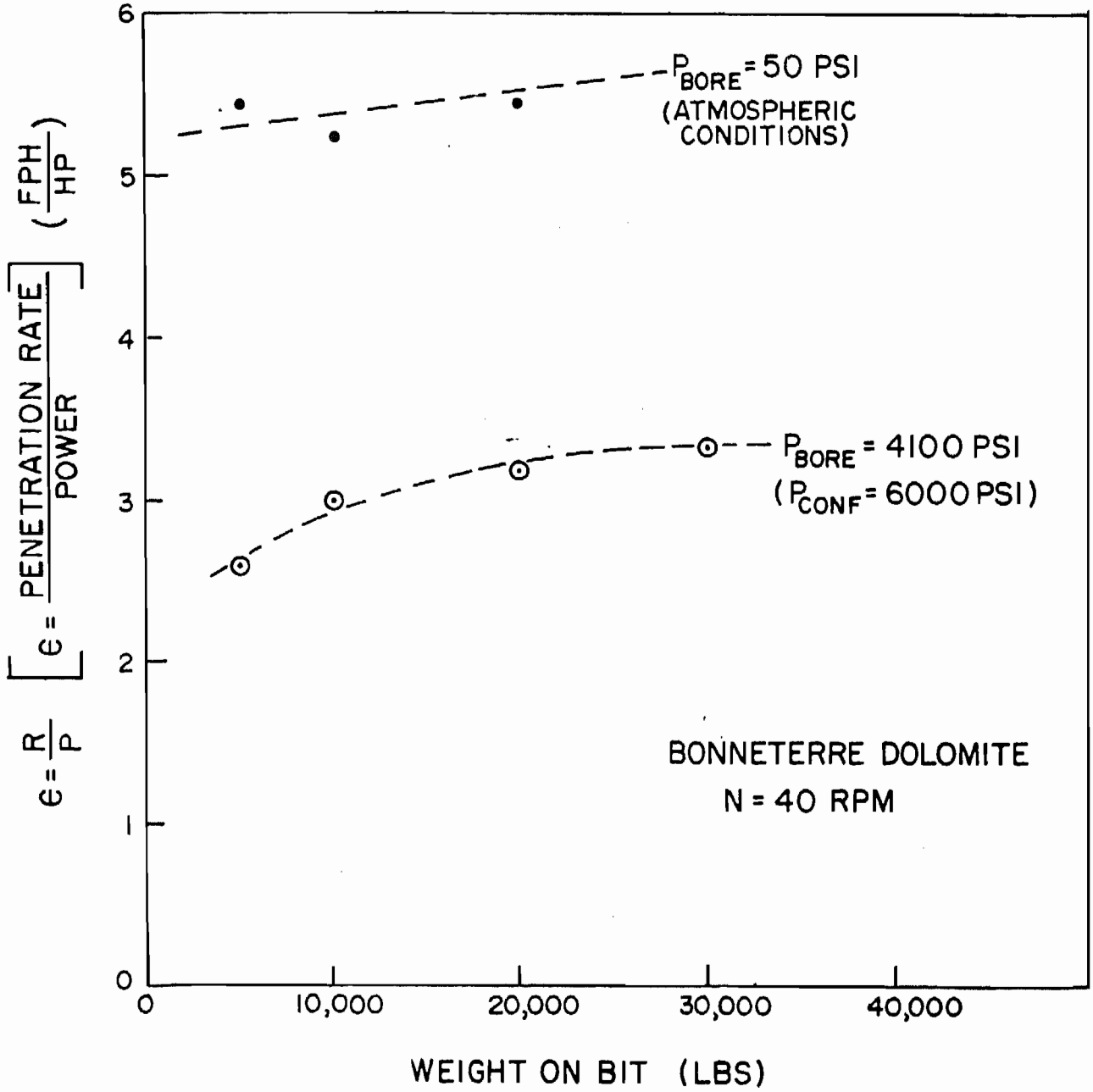

FIGURE 25

Efficiency of Drilling Rate as a Function of Bit Weight and Mud Pressure for Bonne Terre Dolomite at 40 RPM and Simulated Downhole Conditions

CONCLUSIONS

The goals of the project to select rocks typical of deep oil and gas wells and drill them under full-scale simulated downhole pressures were accomplished. The amount of special effort needed to make the equipment operational for the simulated downhole conditions did limit somewhat the number of tests that could be performed within the time and budgetary constraints. A significant amount of data was, nevertheless, obtained to provide an important base for future full-scale drilling tests.

The study to determine typical rocks for deep gas wells in the United States identified four different types; Shales, Sandstones, Limestones and Dolomites. From examination of the physical properties of these rock types in the major petroleum provinces in the United States, particular varieties of each of these rock types were selected as typical of their rock type. From the typical varieties, selections were made where large blocks could be obtained for the laboratory tests. The rocks selected were Colton Sandstone, Bonne Terre Dolomite and Mancos Shale. The Shale samples received were too inhomogeneous, so the program was completed using only the Sandstone and Dolomite.

Commercially available bits were selected based on manufacturers' recommendations. The bit size of 7 7/8 inch was selected because of its common use and the fact that most new experimental bits are made this size.

The drilling fluid was a water based mud selected to be typical of fluids commonly used to drill oil and gas wells. The drilling parameters

were selected to cover the ranges of rock stresses, borehole pressure, rotary speeds, and weight on bit that are typical of actual drilling conditions. The results obtained thus provide data on the functional relationships of the basic drilling parameters and are a basic body of data.

The drilling penetration rate was found to be primarily dependent on the rotary speed, weight on the bit and borehole fluid pressure. There was a small dependency on mud flow rate. The dependence on the mud pressure was particularly significant since the penetration rate decreased rapidly until the differential mud pressure reached approximately 2,000 psi. Above this value, additional mud pressure and rotary speed had only a minor effect on penetration rate. The effect was more pronounced in the Sandstone than the Dolomite. Visual examination of the rock bottomhole pattern under the bit after drilling at simulated downhole conditions revealed much ductility in the Sandstone and more chipping and cratering in the Dolomite. The stress state in the undrilled rock ahead of the bit was well within the elastic response range so that the only non-elastic deformations were those of the bit action on the rock. The confining stresses, within the range of these tests, had no apparent effect on the drilling rate.

ACKNOWLEDGMENTS

Acknowledgment is given to John Sandstrom, Gordon Tibbitts, Jim Wilson and Gary Wright for their effort in getting the equipment operational and in running the tests and to the ERDA Contract Coordinator, C. Ray Williams, for his positive comments which were a significant part of making this test program a success. Acknowledgment is also given to William Maurer and others at Maurer Engineering for their assistance in this program.