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DRAFT

FINAL REPORT

TURBODRILL TESTING PROJECT

PHASE I

July 1980

For

MORGANTOWN ENERGY TECHNOLOGY CENTER
DEPARTMENT OF ENERGY

Under

METHANE RECOVERY FROM COALBEDS PROJECT
Contract No. DE-AC21-78MC08089

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EXECUTIVE SUMMARY

This report describes Phase I and shakedown testing and the results obtained in the bench testing of the 5-3/8 inch Maurer turbodrill. This work was performed under Contract No. DE-AC21-78MC08089 for the Methane Recovery from Coalbeds Project of the Morgantown Energy Technology Center (METC) of the Department of Energy (DOE). The turbodrill was built by Maurer Engineering, Inc. (MEI) under Contracts EY-77-C-21-8093 and EW-78-C-21-8380 with DOE/METC. Phase I testing was conducted at TRW Mission Manufacturing Company in Houston, Texas, according to the Test Plan appended to this report.

Two versions of the turbodrill have been developed by MEI because of different downhole applications. The physical distinction relates only to the design of the bearing package and not to the turbine section of the assembly. For typical oilfield applications when drilling with mud, a sealed bearing pack configuration is used; when drilling with water in a hot geothermal well, a flow-through bearing pack design is employed.

The overall goals of the Testing Project are (1) to determine operational characteristics of the 5-3/8 inch turbodrill and (2) to demonstrate applicability to directionally drilled methane drainage boreholes in horizontal coalbeds (or possibly in steeply-dipping coal seams).

The objective of Phase I testing was to determine baseline performance characteristics prior to field testing. This test was run on clean drilling mud in an above-ground, bench testing mode with no applied axial loads to the turbodrill. A Phase II test was designed to determine both straight-hole and directional drilling performance characteristics using mud as the driving fluid, penetrating known formations. The objective in Phase III will be to determine the feasibility of placing methane drainage boreholes in a horizontal coal seam from a vertical position at the surface.

Prior to Phase I testing, MEI had completed shakedown testing in December 1978, which consisted of bench tests with no axial loads applied to the turbodrill. Both the sealed bearing pack and flow-through versions of the turbodrill were run with water as the working fluid. Teardown and inspection of the drill motor following individual tests revealed some design problems in

the sealed bearing pack version. In response, MEI instituted design modifications to the turbodrill, but adequate pressure seals could not be developed. DOE/METC exercised the option to proceed into formal Phase I testing with the flow-through bearing package version of the turbodrill running on drilling mud.

Formal Phase I testing was completed in February 1979. Analysis of the test data shows characteristic torque, power, efficiency, and rotary speed relationships. However, rotary speeds and pressure drops through the turbine appear to be considerably higher than design values.

It is recommended that the project proceed into Phase II controlled field testing at Gearhart-Owen in Fort Worth, Texas. Prior to Phase II field testing, however, it is recommended that a reasonably accurate and reliable turbodrill tachometer be developed to aid the operator on a drilling rig monitor rotary speed downhole. This would be beneficial in avoiding overspeeding and extend drill bit life; detecting stall to keep from getting stuck in the hole; better matching of bit-weight and speed for stable operation; and maximizing rate-of-penetration for a truer indication of turbodrill potential drilling performance.

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1. INTRODUCTION

1.1 BACKGROUND

The Department of Energy (DOE) is engaged in many efforts to increase resource recovery and supplies of fossil energy. At the Morgantown Energy Technology Center (METC), one of these is directed toward exploring the use of downhole drilling motors and directional drilling techniques to improve the efficiency and reduce the costs of drilling in coal. The application is to place long methane drainage boreholes in horizontal coalbeds in advance of active mining operations (or possibly in unmined or steeply-dipping coal seams). A major advantage in using downhole drilling motors is to significantly increase penetration rates compared to conventional, rotary drilling techniques. Another major advantage of downhole drilling motors is reduction of friction between drill string and wellbore, which is very important, especially in drilling directional wells. This can result in less rig trip time and smoother drilling operations because of reduced possibilities of "twist-offs".

1.2 THE TEST PROJECT

The Test Project was established to test the Maurer Engineering (MEI) 5-3/8 inch turbodrill as part of the ongoing drilling technology development effort at DOE/METC. (The scope and detailed objectives of the test project are discussed in Section 2.) The overall goal of the Test Project is to demonstrate applicability of the turbodrill for drilling long, horizontal methane drainage boreholes in coal seams at depths to 1,000 feet, which appears consistent and attainable with today's directional drilling technology. The boreholes will be designed to be drilled vertically at the surface and horizontally at coal seam depth.

The test project was divided into distinct steps or elements and structured in the following phases:

<u>Phase I</u>

Bench testing in Phase I was performed in a horizontal, above-ground test mode, using the clean drilling mud circulation system (discussed in Section 3) at TRW Mission Manufacturing Company in Houston, Texas. The objective was to

determine baseline performance profiles at zero applied bit-end pressure drops and with no axial thrust loads (weight-on-bit force) applied to the motor. Preliminary indications of wear on internal parts also were to be ascertained from the test. Bit-end pressure drops were not applied in Phase I testing because of the unavailability of pressure seals that could tolerate sustained elevated pressure drops of 500 to 1,000 psi. Axial loading in Phase I was not considered because no equipment was available to conveniently perform that function. The test was performed in a horizontal mode because it was relatively quick and inexpensive, and met the requirements for generating baseline performance data. The effects of vertical position, axial loading, and elevated bit-end pressure drops can be determined in subsequent Phase II testing on a drilling rig.

Phase II

Phase II testing will evaluate the effects of the conditions not applied in Phase I (vertical position, axial loads, and bit-end pressure drops). Phase II is a controlled field test to be performed on a drilling rig at Gearhart-Owen Industries. The test site is located at the wireline crew training facility in Fort Worth, Texas. The formations encountered in drilling at this site have been penetrated numerous times for training purposes in the past, and reliable data are available on straight-hole drilling rates using conventional, rotary drilling equipment to evaluate turbodrill performance. A distinct advantage of this site is that downhole geology is known *a priori* to minimize potential hole problems.

Phase III

Phase III is a drilling technology test directed specifically at the coalbed methane resource. Phase III requires drilling a directional well from vertical at the surface to horizontal into a coalbed at depth or into a steeply-dipping coal seam. The site will be selected to reflect methane drainage drilling conditions evident in more rugged field applications.

1.3 TURBODRILL DESIGN

Figure 1-1 gives a sectional view of the MEI turbodrill which consists of a turbine section and a separate bearing package. The driving fluid can be either drilling mud or water. All blades and vanes are contained in the turbine section, and all bearings (both thrust and radial) are housed in the bearing pack. The turbine package contains 50 stages of blades and vanes. The bearing package is designed in two versions: a sealed bearing

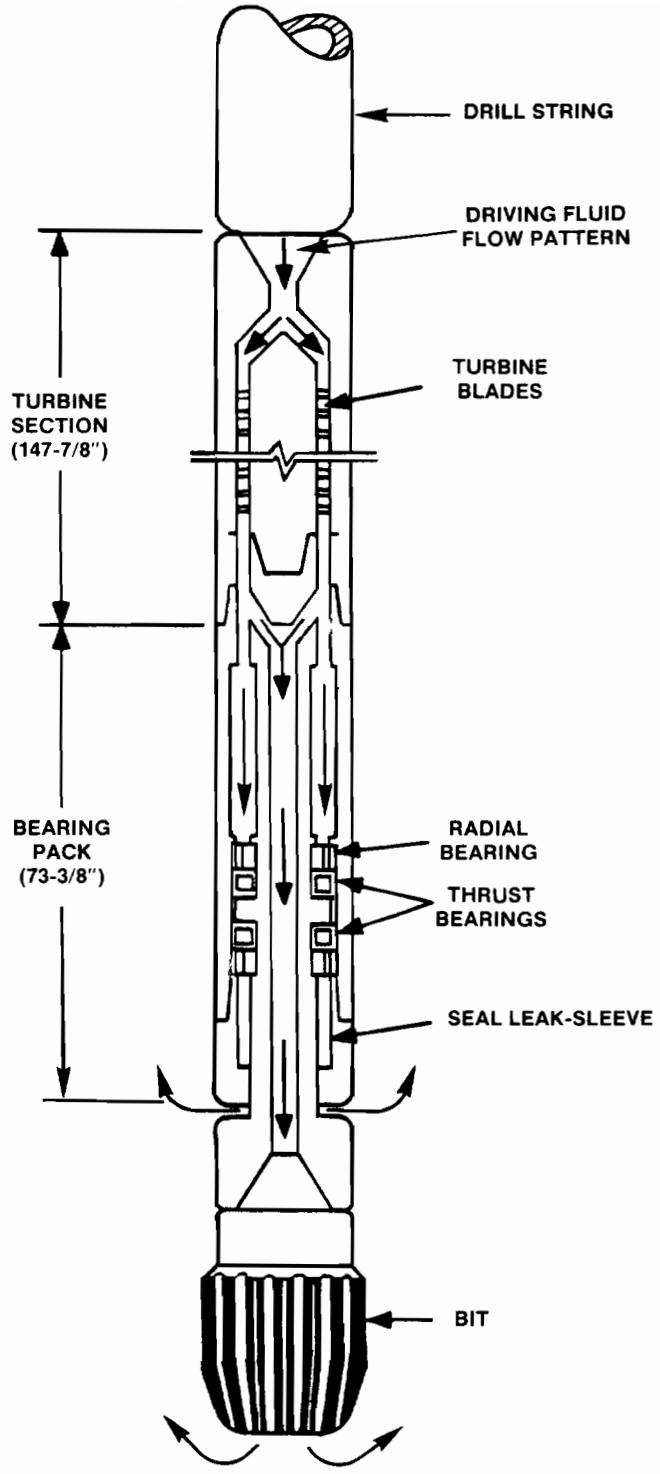


Figure 1-1. Cross Section of Turbodrill with Flow-Through Bearing Package

pack for use in drilling with muds containing solids and cuttings, and the flow-through pack for use primarily with water as the drilling fluid. The sealed bearing pack has application for directional and straight-hole drilling in conventional oil and gas fields and is shown in Figure 1-1 of Appendix A of this report. The flow-through bearing pack version, shown in Figure 1-1 of this section, is designed for use with water in geothermal applications and in coal seam methane drainage requiring directional drilling. Water passing through the bearing section is intended to cool and lubricate the bearings. In addition, the flow-through bearing package may offer the advantage of longer service intervals when drilling in formations where water can be used as the drilling fluid.

Both the sealed bearing pack and flow-through versions were tested during pre-Phase I shakedown runs. Difficulties were experienced continually with integrity of the pressure seals at the bit-end of the sealed bearing pack turbodrill. The problem of stopping fluid losses proved insurmountable, and only the flow-through bearing pack turbodrill was used in later Phase I testing. Further details are presented in Section 4.

There are two major pressure drops in the turbodrill itself: one across the stage assembly of blades and vanes in the turbine section (to overcome resistance to rotation, counteract fluid friction, and provide power); and the other in the bearing package across the seal leak-sleeve or pressure seal assembly at the bit-end. The pressure drop across the bit, in turn, depends upon the pressure drop across the bit-end of the turbodrill. The bit pressure drop is important for proper bottomhole hydraulic cleaning of cuttings from the rock face by counteracting chip hold-down.

In rotary drilling the weight normally applied to a bit to increase penetration rates produces an upward-acting force on the drill string at the bottom of the hole and is called the bit-reaction force. In downhole turbines there is an additional force exerted, which acts downward, opposite to the bit-reaction force. This force results from the pressure drop acting across the annular flow area of the turbine blades. Called the hydraulic downthrust, this force is internal to the turbodrill, whereas the bit-reaction force is external to the downhole motor.

Weight-on-bit (WOB) and the hydraulic thrust force are transmitted to the bearings via the rotor shaft and axial compression spacer rings mounted on the shaft. In all there are seven spacers, three sets of radial roller bearings, and two sets of roller thrust bearings. The bearing pack is designed to maintain a thrust bearing preload to take advantage of the hydraulic downthrust of the turbine in counteracting the upward acting, bit-reaction force on the bearings, and this results in less dynamic load on the thrust bearings. The net effect is that considerably greater weights can be applied to the bit when operating on a drilling rig to increase penetration rates while maintaining relatively lower loads on the bearings in the turbodrill. The thrust bearing preload also serves to eliminate roller bearing "chatter" when temporarily operating under low-load or no-load conditions, such as during startup. The bearings offer insignificant resistance to rotation and are commercial, off-the-shelf items.

2. TEST PLANNING

2.1 SCOPE OF PHASE I TESTING

In this report, Phase I includes all initial testing of the 5-3/8 inch turbodrill at MEI's Kor-King facility and formal testing at TRW Mission Manufacturing Company's plant in Houston, Texas in above-ground, bench tests. Bench testing refers to operation with the turbodrill mounted in a stationary test fixture, as opposed to actual well drilling.

The scope of Phase I of the Test Project was defined as follows:

- Phase I testing and the preliminary shakedown tests represent the first attempts to determine performance characteristics of the MEI 5-3/8 inch turbodrill in a systematic manner.
- The testing reported herein does not constitute qualification testing or any performance verification effort.

The Test Plan presented in Appendix A governed all activities connected with Phase I operations. Considerable detail is included in that plan to provide coordinated planning, testing requirements, detailed test procedures, and supporting information for the series of tests that will determine performance and wear characteristics of the Maurer 5-3/8 inch turbodrill in an above-ground, bench testing mode. The major thrust of the effort in the Test Plan was to establish the turbodrill's basic performance characteristics. The baseline performance data determined in Phase I are required to provide performance characteristics against which to assess the data resulting from subsequent active well drilling tests. Wear and other degradation information also were desired to aid in estimating reliability, preliminary tool maintenance requirements, and component life expectancy for future test planning.

2.2 OBJECTIVES

The purpose of Phase I testing was to determine performance and wear characteristics of the Maurer Engineering 5-3/8 inch turbodrill in an above-ground, bench testing mode.

Specific objectives of Phase I testing were:

- Determine performance characteristics, i.e., turbodrill speed, torque, and power as functions of mud flow rate, inlet pressure, and pressure drop across the turbine.
- Determine the leakage rates of drilling fluid at different bit-end pressure drops through the bearing package.
- Ascertain wear characteristics experienced in rotary operation under simulated torque conditions in bench tests.
- Acquire data for use in determining reliability and component service life expectancies.

When it became apparent that the turbodrill was an early prototype model and had little actual Maurer in-house testing prior to the Phase I test, it was agreed that the wear and reliability tests would be premature at this point in the development cycle. Therefore, the wear measurement requirement was eliminated.

3. TEST FACILITY AND EQUIPMENT

The test facility was at TRW Mission Manufacturing Company's plant in Houston, Texas. The test setup schematic and equipment layout is represented in Figure 3-1. The drilling mud circulation system provided driving energy to the turbodrill: typically 250 gpm flow rate and 3,000 psi maximum inlet pressure. Flow rates of driving fluid were regulated using two Thornhill-Craver adjustable chokes, which diverted part of the pump discharge to the mud holding tanks. This capability was required because the output of the mud pump was greater than the throughputs required by the 5-3/8 inch turbodrill.

The driving fluid used in Phase I testing was clean drilling mud that never had been used in well drilling operations. The mud properties were controlled and kept constant for use in production testing TRW Mission Manufacturing's fluid-end oilfield pump parts and valve assemblies. No conventional oilfield mud conditioning equipment, such as desilters/desanders or shale shakers, were required.

The turbodrill was installed in the above-ground, bench testing configuration shown in Figure 3-1. Test equipment and installation required to generate the baseline turbodrill performance characteristics are described in detail in the Test Plan presented in Appendix A to this report. The Phase I Test Plan was approved by project participants prior to commencement of test operations and governed all activities connected with performing the tests. Test instrumentation and ancillary equipment included in the test setup are described in Sections 2 and 5 of Appendix A. Test procedures also are described in Section 5 of Appendix A. Calibration curves for primary sensing instruments are presented in Appendix B.

Torque loading was introduced by means of a dynamometer mounted with a short shaft (with two universal joints) on the front-end of the turbodrill. The dynamometer was manufactured by AW Dynamometer Company of Chicago, Illinois (Model NEB 600). It performed satisfactorily during shakedown testing except for inconsistent measurement of applied torque values. This was attributed to hydraulic losses due to variation of friction coefficient of

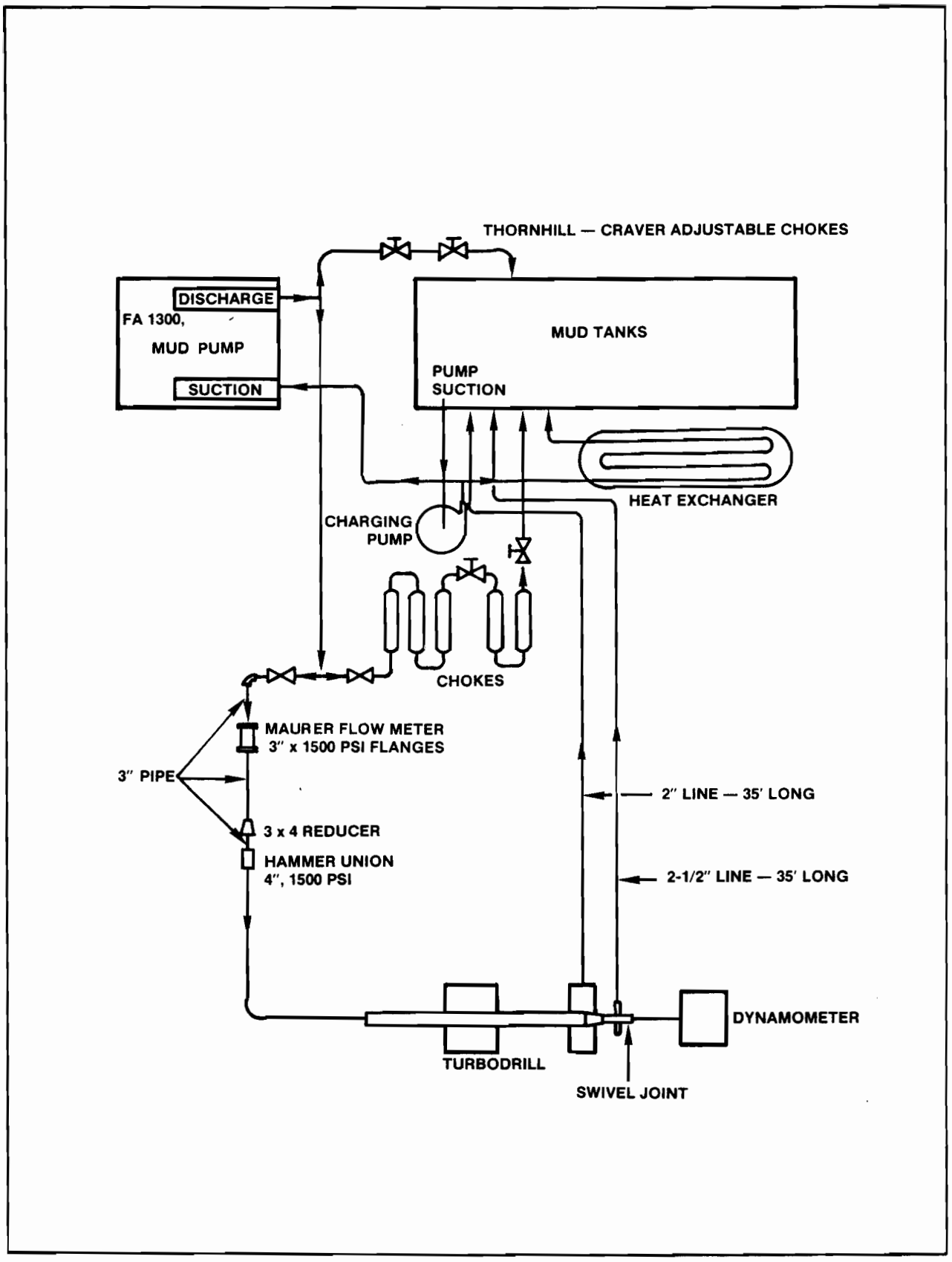


Figure 3-1. TRW Mission Test Facility Layout

the dynamometer fluid under dynamic conditions, and to mechanical losses in the dynamometer and in the front-end swivel joint.

Consideration of the dynamometer losses noted above indicates that measurement of total reactive torque developed by the turbodrill would be significantly more accurate and reliable than relying on the dynamometer itself. The reactive torque measuring system shown in Figure 3-2 was designed by MEI to indicate the required total reactive torque developed by the turbodrill and compensate for the dynamometer losses. In that system the turbodrill was mounted on the supports of the test fixture with commercial roller bearings to minimize torque resistance. The remaining test equipment was used as discussed in the Test Plan in Appendix A, in the performance of the tests at TRW Mission.

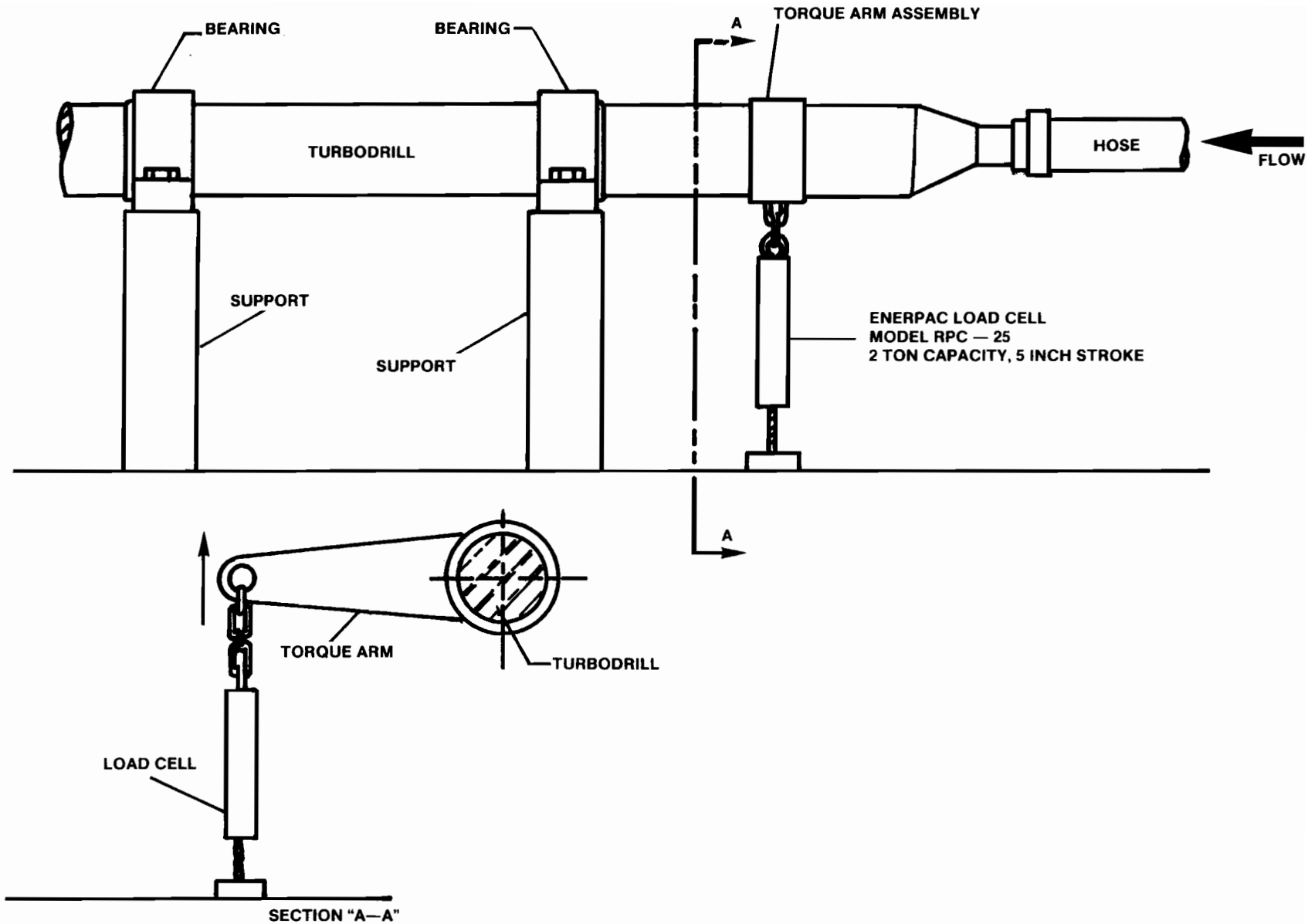


Figure 3-2. Turbodrill Reactive Torque Measuring System

4. SHAKEDOWN TESTING

Preliminary testing of the turbodrill was not part of the original plan presented in Appendix A. However, the opportunity arose, and MEI elected to perform a series of short-duration, inexpensive, shakedown tests to essentially "de-bug" the motor and testing procedures to be used in the official Phase I test program. Shakedown testing also presented an opportunity to make minor turbodrill design modifications, as required, besides providing additional data to aid in evaluating Phase I turbodrill performance, with relatively little time loss and without committing the TRW Mission test facility to additional test time.

Shakedown testing of the 5-3/8 inch turbodrill was performed by MEI at its Kor-King warehouse facility in Houston, Texas. Shakedown testing was done using water as the driving fluid in a bench testing mode very similar to the Phase I test setup described in Section 3. Both the sealed bearing package and flow-through bearing package versions were run in shakedown tests.

Torque responses obtained at a driving fluid flow rate of 250 gallons per minute (gpm) in the several shakedown tests are presented in Figure 4-1. Some degree of difference among the several curves perhaps may be ascribed to "breaking-in" of the turbodrill, but no consistent trend can be established.

A comparison of shakedown performance to turbodrill design performance is presented in Table 4-1. In each case, torque and power output are below design values. Pressure drops measured across the turbine, which indicate the pumping power required to drive the motor, are considerably greater than design and are the primary reason for the relatively low values of efficiency obtained with this motor. The pressure drop across the motor is not highly dependent on rotary speed, as can be seen in Figure 4-2. However, the pressure drop does depend on flow rate as can be inferred from the data presented in Table 4-1.

Design problems that surfaced during shakedown testing of the sealed bearing package version of the turbodrill were (1) mechanical problems stemming from interferences from tight fits between rotating/mating parts and

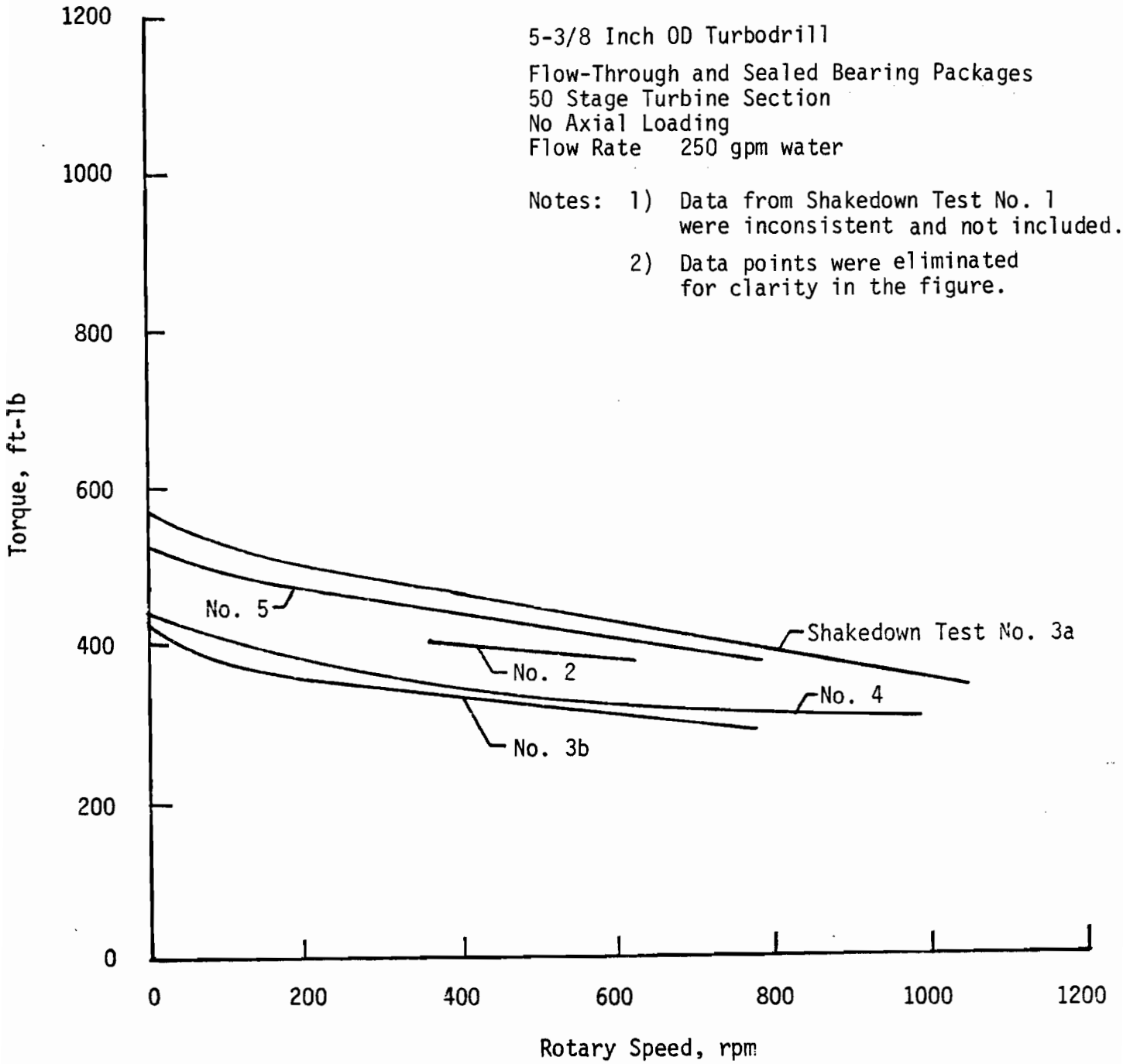


FIGURE 4-1. Turbodrill Performance in Shakedown Tests

TABLE 4-1.

COMPARISON OF PRE-PHASE I TURBODRILL PERFORMANCE TO DESIGN PERFORMANCE

		Flow Rate gpm	Rotary Speed rpm	Pressure Drop Across Turbine psi	Output Torque ft-lb	Power Output hp	Efficiency Power out/Power in
Design Values	Roller Cone Bits	250	200	377	867	33	0.60
	Diamond Bits	250	800	872	501	76	0.60
Shakedown Test No. 1* (sealed bearing package)		N/A	N/A	N/A	N/A	N/A	N/A
Shakedown Test No. 2 (sealed bearing package)		276 275	236 816	1330 1480	600 475	27 74	0.13 0.31
Shakedown Test No. 3a (flow-through)		251 248	177 772	1120 1332	505 395	17 58	0.10 0.30
Shakedown Test No. 4 (sealed)		249 245	244 730	855 950	408 336	19 47	0.15 0.34
Shakedown Test No. 5 (flow-through)		251 249	192 788	1030 1200	486 377	18 57	0.12 0.32

*Note: Shakedown Test No. 1 did not produce consistent data and the data are not applicable (N/A).

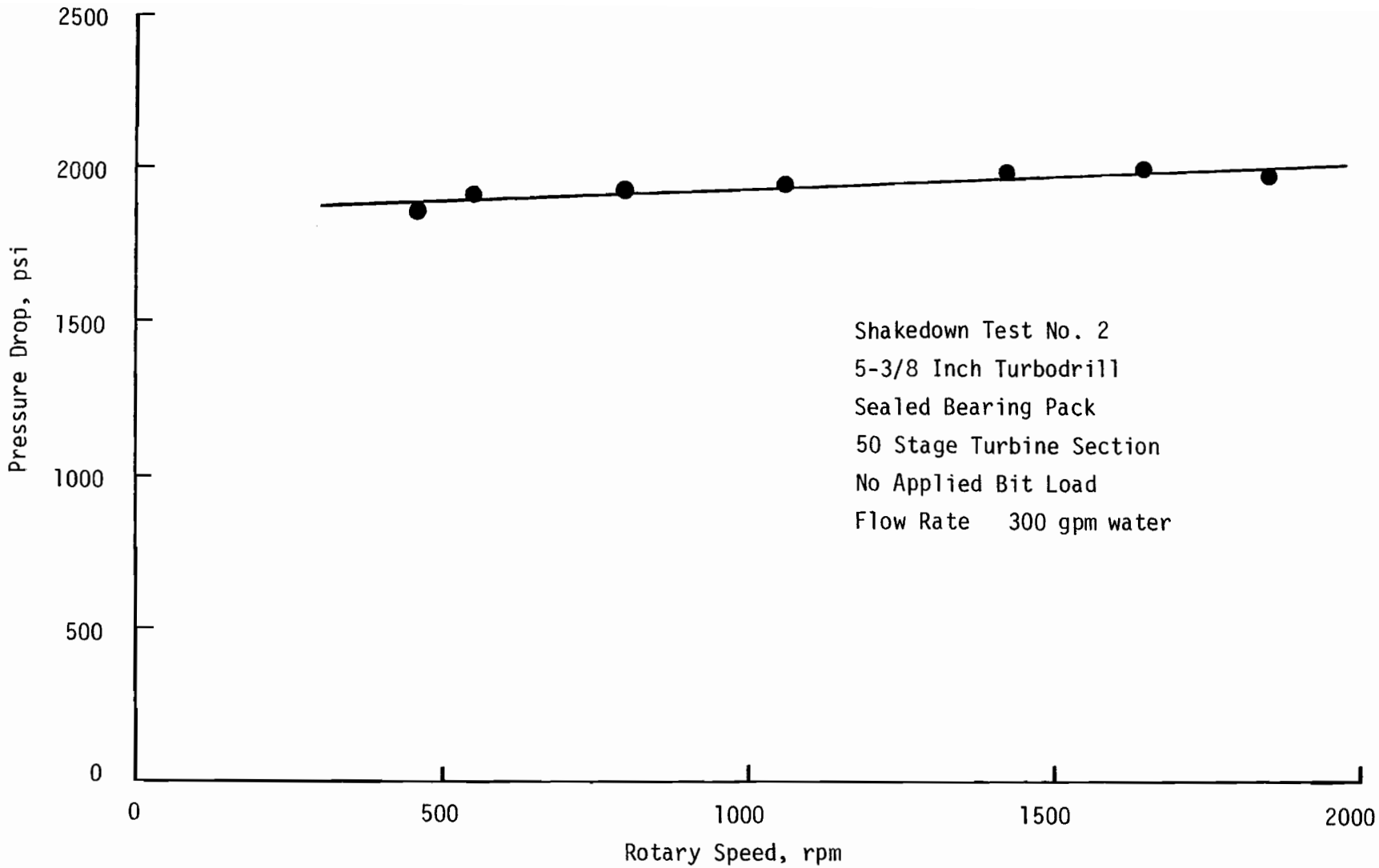


FIGURE 4-2. Pressure Drop Across Turbodrill

(2) seal problems resulting from inadequate design and material failure. The mechanical interference problems were corrected by opening up tolerances on some internal parts in the bearing package.

The major problem area requiring attention prior to the start of Phase I testing of the sealed bearing package turbodrill was the pressure seal assembly at the bit-end of the drill motor, shown in Figure 1-1 of Appendix A. The seal assembly consists of a series of three bronze journal bearings (called seal spacers) with two sets of three Uneepac seals sandwiched between them. The seal elements are manufactured in a "W"-configuration, and the two sets are oriented to seal in opposite directions: one against mud intrusion from outside the turbodrill through the bit-end; and the other against loss of synthetic bearing lubricant from the oil reservoir. In addition, the seal spacers are designed to act as journal bearings by supporting a portion of the lateral loads sustained during normal directional drilling. (See Figure 1-1 in Appendix A.)

The seals run in shakedown tests were commercial off-the-shelf items. The Uneepac seals were made from Buna-N elastomer impregnated with about 30 percent cotton-duck reinforcing material. During shakedown tests, the seals vulcanized, became exceedingly brittle, disintegrated, mixed with bearing lubricant, and were extruded from the front-end of the bearing package. During these tests, rotary speeds ranged up to 2,000 rpm and pressure drops across the pressure seal assemblies were less than 200 psi. Calculations performed by MEI personnel have shown that temperatures in the individual seal elements reached up to 535°F during these tests. Most synthetic rubber or elastomer rotating seals deteriorate rapidly above 350°F operating temperature.

The recurring problems with deterioration of the main pressure seals tested led to abandonment of the sealed bearing pack version of the turbodrill for testing in Phase I of the project. Seal development is reportedly being pursued in another project.

5. PHASE I TEST DATA

Phase I test data were measured and recorded according to procedures contained in the approved Test Plan appearing in Appendix A of this report. The only deviation from this requirement was in the case of reactive torque measurements. The raw data have been transcribed in the prescribed format onto Table 5-1 with appropriate annotated remarks.

Reactive torque raw data were measured and recorded in values of millivolts of the torque arm load cell transducer output. Conversion to ft-lbs was accomplished straightforwardly as the first step in the data reduction process by means of the following equation (developed by MEI) characteristic of the MEI load cell used in the test:

$$\text{Torque} = 227(\text{millivolts} - 0.28) \text{ in ft-lb}$$

The derivation of this equation is presented in Appendix C.

The test proceeded smoothly except for premature termination immediately after obtaining the final data point on the 300 gpm speed profile. At that time the bearing housing temperature escalated rapidly and leak-flow through the bearing package ceased abruptly, indicating a problem internal to the turbodrill. Repeated attempts were made to correct the problem and restart the test to obtain data on the 350 gpm speed line; however, these failed and Phase I testing was terminated.

TABLE 5-1. PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Reactive Torque		Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
						mv*	ft-lb			
2/20/79										
1	11:15am	-	-	-	-	-	-	-	-	Start Up
	11:24	250	980	132	0	2.26	449	4.0	118	
	11:28	250	1090	130	197	2.31	461	6.1	119	
	11:31	252	1060	132	103	2.40	481	6.0	120	
	11:32	250	1150	130	308	2.27	452	6.1	119	
	11:35	248	1160	130	402	2.17	429	6.0	121	
	11:37	249	1200	128	492	2.10	413	6.1	120	
	11:38	248	1220	128	600	2.01	393	5.0	121	
	11:42	249	1300	126	804	1.87	361	5.8	120	
	11:44	250	1310	126	920	1.77	338	5.5	120	
	11:46	249	1350	125	1030	1.70	322	5.8	121	
	11:48	249	1360	128	1131	1.67	316	5.3	122	
	11:50	249	1370	128	1216	1.61	302	4.2	121	
	11:55	-	-	-	-	-	-	-	-	Stop

*millivolts

TABLE 5-1. (cont'd) PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Reactive Torque mv	Reactive Torque ft-lb	Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
2/20/79										
2	12:45pm	-	-	-	-	-	-	-	-	Startup to Obtain Check Data Points
	12:52	251	980	130	0	2.36	472	4.6	118	
	12:53	250	1070	120	278	2.19	434	5.0	117	
	12:53	247	1190	120	550	2.02	395	5.3	117	
	12:57	100	130	32	0	0.52	54	0.0	118	Changed Flow Rate to 100 gpm
	1:04	150	340	52	0	1.24	218	0.0	117	Changed Flow Rate to 150 gpm
	1:05	146	350	50	104	0.97	157	0.0	117	
	1:10	146	360	50	225	0.93	148	0.0	117	
	1:14	150	450	55	619	0.83	125	0.0	118	
	1:15	155	420	55	311	0.97	157	0.0	118	
	1:16	152	430	55	404	0.88	136	0.0	118	
	1:17	152	440	55	489	0.87	134	0.0	117	
	1:18	151	450	53	607	0.83	125	0.0	117	
	1:19	147	460	53	702	0.77	111	0.0	117	

TABLE 5-1. (cont'd) PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Reactive Torque		Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
						mv	ft-lb			
2/20/79										
3	1:22pm	200	640	90	0	1.42	259	2.5	118	Changed Flow Rate to 200 gpm
	1:23	198	660	82	165	1.49	275	2.2	118	
	1:25	200	710	82	235	1.52	281	2.3	119	
	1:27	200	710	82	281	1.48	272	2.9	118	
	1:29	203	750	85	387	1.45	266	3.0	118	
	1:31	202	780	83	445	1.40	254	3.0	118	
	1:33	201	800	85	567	1.35	243	2.7	119	
	1:35	201	810	83	670	1.28	227	0.0	119	
	1:37	205	840	85	756	1.29	229	2.7	119	
	1:39	202	850	85	778	1.27	225	3.4	119	
	1:40	201	860	87	905	1.15	197	4.1	120	
	1:42	199	900	87	1201	1.14	195	3.6	120	
	1:43	201	900	80	1302	0.85	129	3.3	121	

TABLE 5-1. (cont'd) PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Reactive Torque mv	Reactive Torque ft-lb	Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
2/20/79										
4	1:47 pm	250	990	110	0	2.19	434	4.3	120	Changed Flow Rate to 250 gpm
	1:49	252	1050	110	103	2.24	445	4.9	120	
	1:51	252	1080	110	207	2.20	436	4.7	121	
	1:52	252	1120	110	305	2.20	436	4.9	121	
	1:53	249	1150	108	401	2.15	424	5.3	121	
	1:54	249	1200	110	505	2.06	404	5.2	121	
	1:55	252	1250	110	624	2.02	395	5.5	121	
	1:56	253	1290	110	750	1.97	384	5.5	122	
	1:57	252	1290	110	807	1.92	372	5.6	122	
	1:59	250	1300	110	889	1.86	359	5.6	122	
	2:00	251	1340	110	1005	1.80	345	5.6	123	
	2:01	257	1460	115	1145	1.81	347	5.7	123	
	2:02	254	1410	118	1210	1.69	320	5.7	123	
	2:04	254	1420	120	1302	1.65	311	5.9	123	

TABLE 5-1. (cont'd) PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Reactive Torque mv	Reactive Torque ft-lb	Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
4	2:05	258	1430	120	1402	1.42	259	5.8	123	
	2:07	254	1420	118	1411	1.53	284	6.0	124	
2/20/79						Dynamometer Torque ft-lb *				
5	2:20pm	300	1400	172	0	720		5.7	121	Changed Flow Rate to 300 gpm
	2:21	303	1520	172	96	680		7.7	122	*Load Cell on Reactive Torque Arm Jumped Calibration
	2:22	305	1590	172	205	680		7.6	124	
	2:23	309	1710	180	292	685		7.9	125	
	2:24	302	1510	168	199	680		7.6	125	
	2:26	299	1550	162	292	660		7.8	124	
	2:27	303	1650	166	400	650		7.8	124	
	2:29	300	1650	160	483	640		8.2	125	
	2:30	305	1800	170	608	640		8.6	125	
	2:33	300	1610	160	452	615		7.6	126	
	2:35	303	1800	170	665	610		7.8	127	

TABLE 5-1. (cont'd) PHASE I TEST DATA - MAURER ENGINEERING 5-3/8 INCH TURBODRILL

Date / Test Run	Time	Mud Flow Rate gpm	Inlet Mud Pressure psig	Exit Pressure psig	Rotary Speed rpm	Dynamometer Torque ft-lb	Mud Leak Rate gpm	Bearing Housing Temperature °F	Remarks
2/20/79	2:36	300	1800	165	789	585	7.9	127	
5 (cont'd)	2:38	305	1820	165	874	570	7.7	126	
	2:39	297	1850	162	1090	510	8.0	128	
	2:41	298	1860	161	1179	500	8.4	128	
	2:42	296	1900	160	1361	440	7.2	129	
	2:45	290	1940	162	1421	400	6.8	131	Shut Down to Check Out Zero Leak Flow & Elevated Bearing Temperature
	2:48	310	1560	183	0	500	0.0	198	
	3:40 pm	-	-	-	-	-	-	-	Terminate Test Due to Lack of Leak-Flow Through Bearing Package

6. ANALYSIS OF PHASE I TEST DATA

Phase I bench testing at the TRW Mission facility was conducted on February 19 and 20, 1979. The flow-through bearing package version of the 5-3/8 inch diameter turbodrill was run on lightweight (9.35 pounds per gallon, 11 cp viscosity) drilling mud for a total of approximately five hours. Baseline performance data were obtained at five individual flow rates ranging from 150 to 300 gpm in 50 gpm increments. Data at 350 gpm were not obtained due to failure of the lower thrust bearing after data were collected at the high speed end of the 300 gpm performance curve. In general, analysis has shown that baseline performance of the turbodrill (at no imposed bit-end pressure drop and no axial load) was comparable to that exhibited earlier during shakedown testing.

Performance characteristics calculated from the data obtained during Phase I of the Turbodrill Testing Project are presented in Figures 6-1, 6-2, and 6-3. The plotted points in Figures 6-1, 6-2, and 6-3 are tabulated in Table 6-1. The mechanical power output, hydraulic power input, and turbodrill overall efficiency values appearing in Table 6-1 were calculated using the Phase I test data presented in Table 5-1 and the following standard equations pertaining to rotating hydraulic machinery:

$$P_{out} = \frac{2\pi}{33{,}000} \text{(Torque)(Speed) in horsepower, hp}$$

$$P_{in} = \frac{1}{1714} \text{(Flow Rate)(Pressure Drop across Turbine) in hydraulic horsepower, hhp}$$

$$\text{Efficiency} = \frac{P_{out}}{P_{in}}$$

The solid curves drawn in Figures 6-1, 6-2, and 6-3 were obtained from results of regression analyses performed on Phase I test data. The dashed curves correspond to Shakedown Test No. 5 data (which were not processed through regression analysis), for which data points do not appear in the figures. The shakedown test data used for performance comparison purposes are presented in Table 6-2. No data points were obtained beyond 1500 rpm because of turbodrill operating instability and possible destruction.

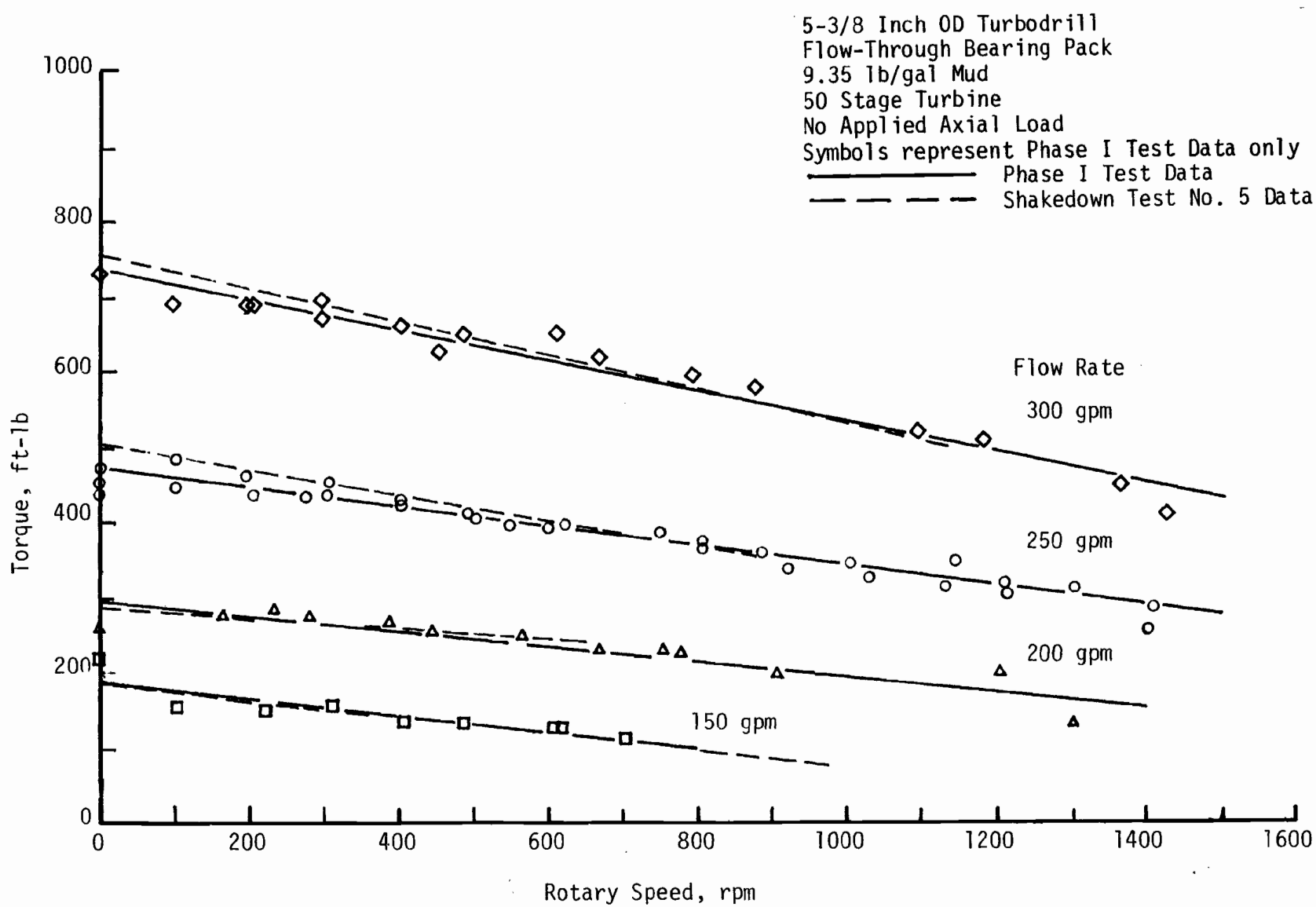


FIGURE 6-1. Phase I - Performance Data

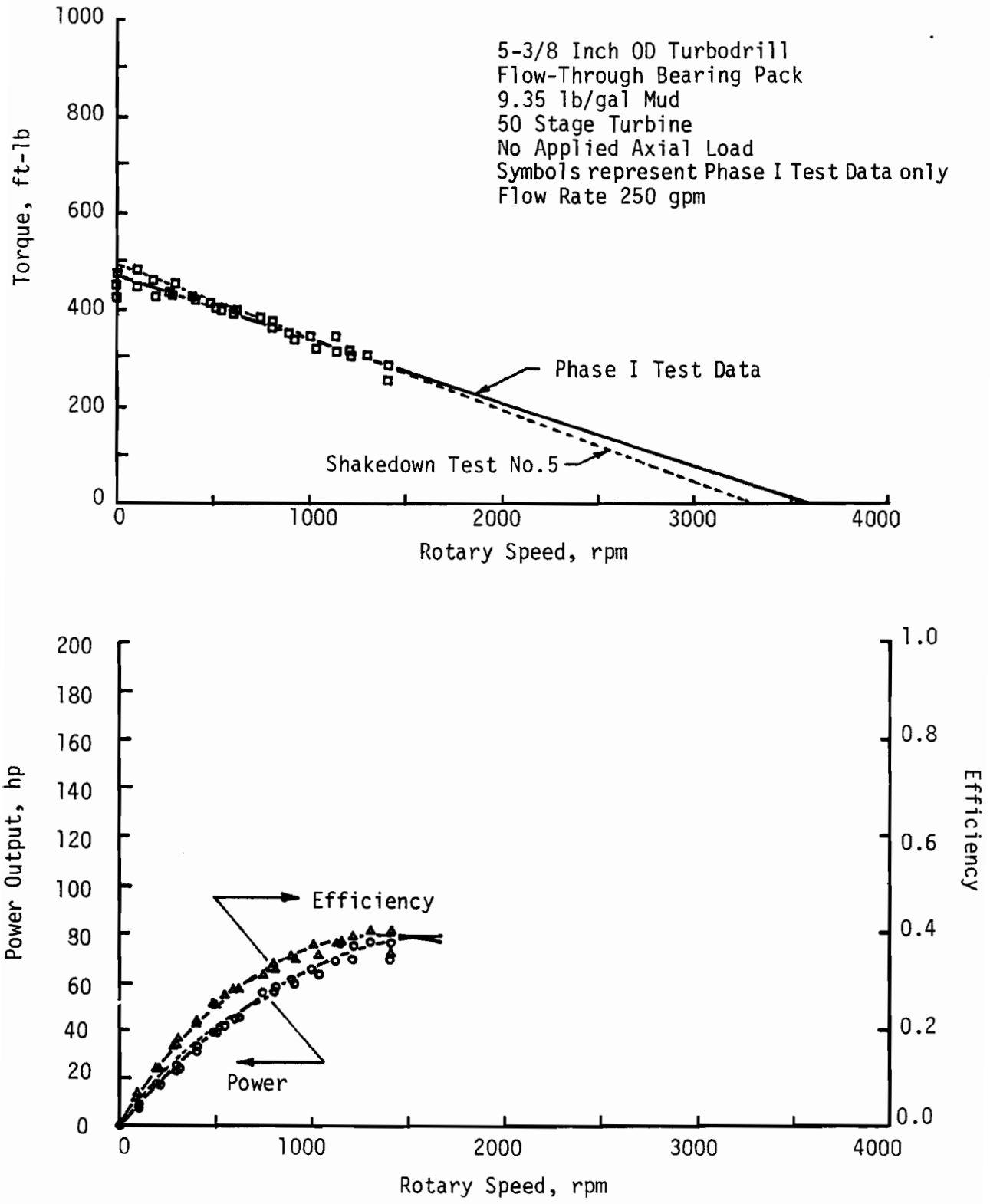
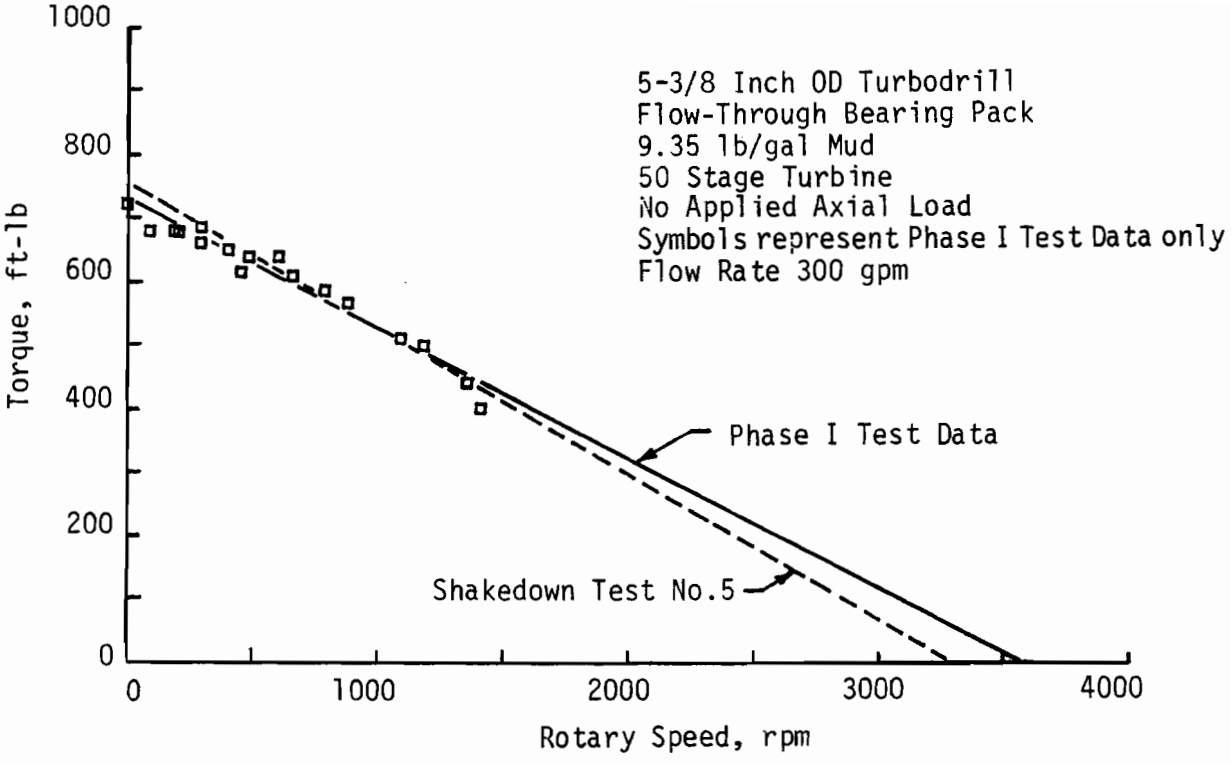


FIGURE 6-2. Phase I - 250 gpm Performance



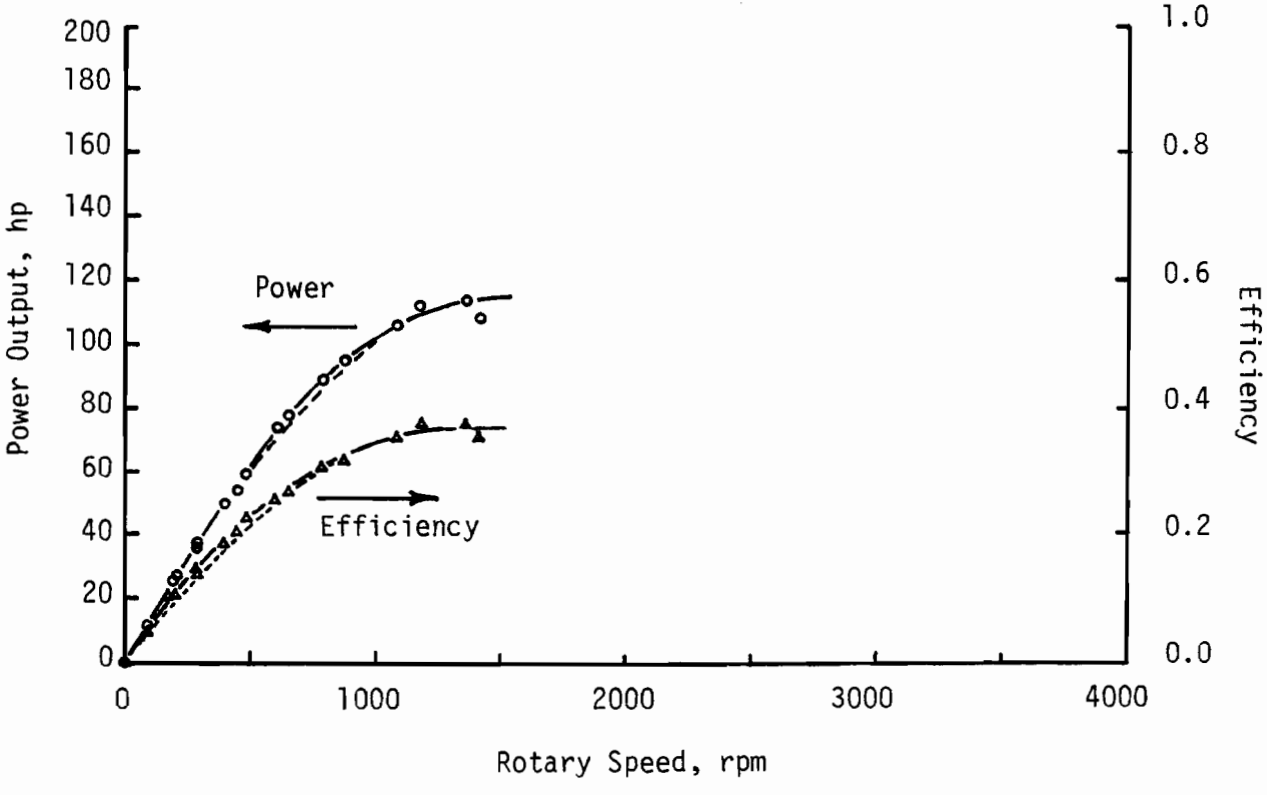


FIGURE 6-3. Phase I - 300 gpm Performance

TABLE 6-1. PHASE I TEST DATA ANALYSIS RESULTS

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP psi *	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
250	0	449	848	124	0	0
250	197	461	960	140	17	0.12
252	103	481	928	136	9	0.07
250	308	452	1020	149	27	0.18
248	402	429	1030	149	33	0.22
249	492	413	1072	156	39	0.25
248	600	393	1092	158	45	0.28
249	804	361	1174	171	55	0.32
250	920	338	1184	173	59	0.34
249	1030	322	1225	178	63	0.35

*ΔP between intake and outlet of turbine motor

TABLE 6-1. (cont'd) PHASE I TEST DATA ANALYSIS RESULTS

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP psi	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
249	1131	316	1232	179	68	0.38
249	1216	302	1242	180	70	0.39
251	0	472	850	124	0	0
250	278	434	950	139	23	0.17
247	550	395	1070	154	41	0.27
250	0	434	880	128	0	0
252	103	445	940	138	9	0.06
252	207	436	970	143	17	0.12
252	305	436	1010	148	25	0.17
249	401	424	1042	151	32	0.21

TABLE 6-1. (cont'd) PHASE I TEST DATA ANALYSIS RESULTS

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP psi	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
249	505	404	1090	158	39	0.25
252	624	395	1140	168	47	0.28
253	750	384	1180	174	55	0.31
252	807	372	1180	173	57	0.33
250	889	359	1190	174	61	0.35
251	1005	345	1230	180	66	0.37
257	1145	347	1345	202	76	0.38
254	1210	320	1292	191	74	0.39
254	1302	311	1300	193	77	0.40
258	1402	259	1310	197	69	0.35

TABLE 6-1. (cont'd) PHASE I TEST DATA ANALYSIS RESULTS

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP psi	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
254	1411	284	1302	193	76	0.40
300	0	720	1228	215	0	0
303	96	680	1348	238	12	0.05
305	205	680	1418	252	27	0.11
309	292	685	1530	276	38	0.14
302	199	680	1342	236	26	0.11
299	292	660	1388	242	37	0.15
303	400	650	1484	262	50	0.19

TABLE 6-1. (cont'd) PHASE I TEST DATA ANALYSIS RESULTS

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP psi	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
300	483	640	1490	261	59	0.23
305	608	640	1630	290	74	0.26
300	452	615	1450	254	53	0.21
303	665	610	1630	288	77	0.27
300	789	585	1635	286	88	0.31
305	874	570	1655	295	95	0.32
297	1090	510	1688	292	106	0.36
298	1179	500	1699	295	112	0.38
296	1361	440	1740	300	114	0.38
290	1421	400	1778	301	108	0.36
310	0	500	1377	249	0	0

TABLE 6-2. COMPARISON DATA FROM SHAKEDOWN TEST NO. 5

FLOW RATE gpm	ROTARY SPEED rpm	OUTPUT TORQUE ft-lb	PRESSURE DROP * psi	HYDRAULIC POWER IN hhp	POWER OUTPUT hp	OVERALL EFFICIENCY
254	0	550	970	144	0	0
251	192	486	1030	151	18	0.12
255	0	531	960	143	0	0
251	146	472	1010	148	13	0.09
247	296	441	1050	151	25	0.16
241	565	382	1070	150	41	0.27
254	0	527	960	142	0	0
252	154	463	1010	148	14	0.09
248	388	418	1060	153	31	0.20
249	788	377	1200	174	57	0.32
256	523	436	1210	181	43	0.24
248	0	495	900	130	0	0

*ΔP between intake and outlet of turbine motor

Figure 6-1 shows the linear relationship of developed torque to rotary speed for flow rates of 150, 200, 250, and 300 gpm. The torque data were subjected to linear regression analysis (least-squares fitting) and were found to exhibit high correlation coefficients (0.89 to 0.98) to linear variation with speed, as shown in Figure 6-1. Figures 6-2 and 6-3 show additional performance profiles for mud flow rates of 250 and 300 gpm, respectively. Non-linear regression analysis was applied to the calculated power and efficiency values, and these were found to be highly correlated to second-order dependence on speed as evidenced by the high resultant correlation coefficients (0.97 to 0.99). The curves in Figures 6-2 and 6-3 obtained by fitting with the regression procedure are characteristically parabolic in shape and attain maxima in the range of 1,300 to 1,700 rpm. These results are consistent with the torque data reported in Figure 6-1 that indicate power and efficiency should attain maxima at approximately 1,800 rpm, which is one-half the runaway speed. This can be seen from Figure 6-4 which presents theoretical performance characteristics for a typical downhole turbine. The curves in Figure 6-4 represent typical turbine response to throughput of driving fluid. As can be seen in the figure, the output torque increases linearly from zero at runaway speed (under no-load conditions) to maximum value at zero rotary speed. Maximum power output and efficiency occur theoretically at one-half the runaway speed. Resultant efficiencies tend toward maximum values of about 40 percent for both the 250 and 300 gpm mud flow rates in Figures 6-2 and 6-3. These efficiencies would tend to be higher in actual drilling practice, however, due to relief of the bearing loads induced by hydraulic downthrust with the application of bit-weight, as discussed previously in Section 1.3.

The data presented show turbodrill performance with mud to be consistent with previous test results obtained with water. The results in Figures 6-1, 6-2, and 6-3 compare favorably with corresponding values obtained in previous shakedown testing (see Tables 4-1 and 6-2). Shakedown Test No. 5 was selected to provide direct performance comparison data in Table 6-2 because the reactive torque measuring system used in Phase I was also used in that particular shakedown test but not in the others. The reactive torque measuring system provided consistent data in all runs during Phase I

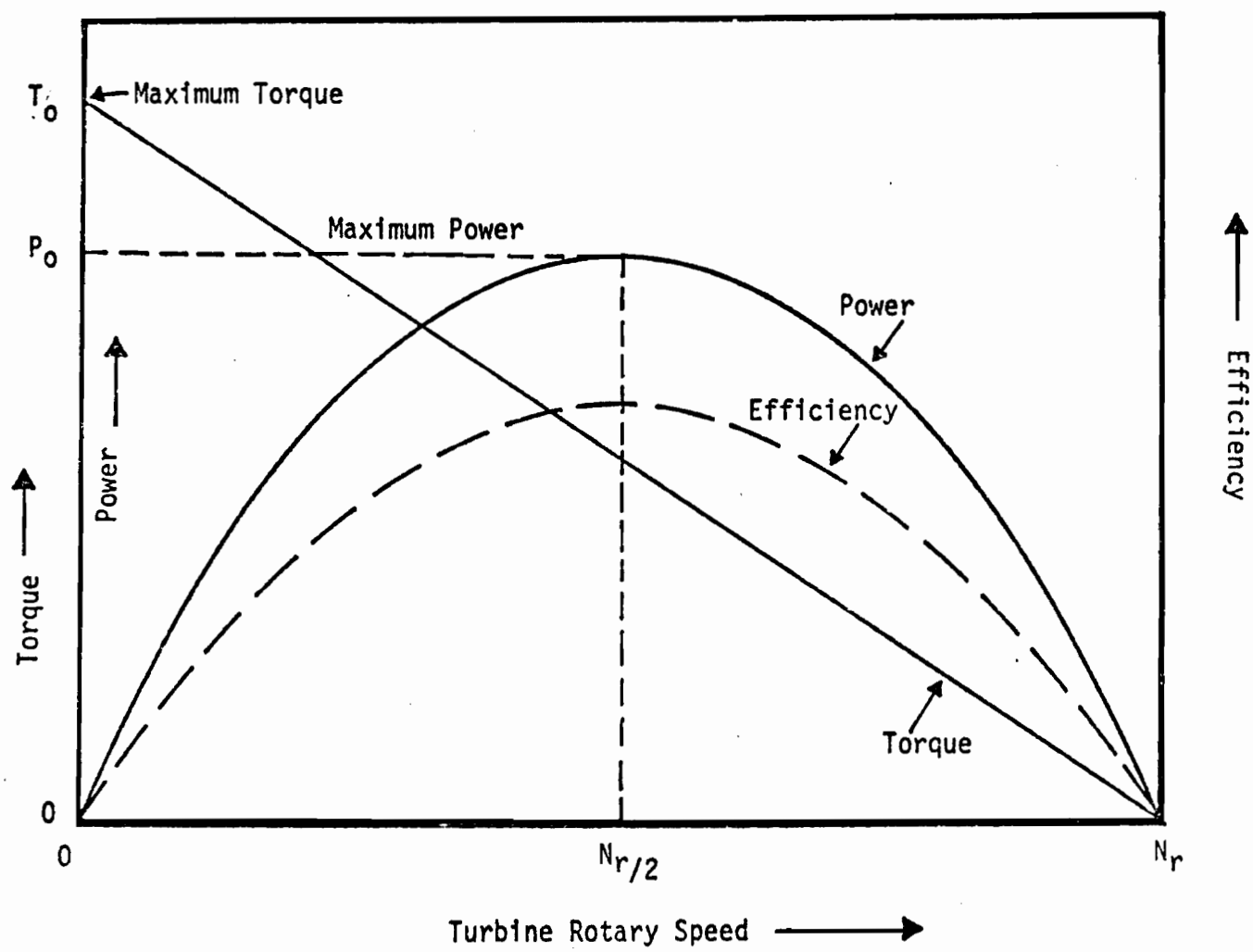


FIGURE 6-4. Typical Turbodrill Performance Curves

testing except the last, taken at 300 gpm. In that run (No. 5 in Table 5-1) the load cell apparently deviated from calibration for no known reason. This fact became readily apparent upon comparison of reactive torque values with previous reactive torque values obtained during Shakedown Test No. 5. It was found that the reactive torque values recorded in Run No. 5 were consistently biased by an increase of 100 to 120 ft-lbs in each case for the 300 gpm speed profile. The power and efficiency curves in Figures 6-2 and 6-3 generated from Phase I test data and from Shakedown Test No. 5 data are virtually indistinguishable. This indicates that running the motor on a lightweight mud or water tends to make little difference in performance, even though the mud used in this case is 12 percent denser than water and 11 times as viscous as water. No conclusions can be drawn at this time relative to performance characteristics to be expected when running the turbodrill on significantly heavier drilling muds.

Table 6-3 presents a performance comparison of the Maurer turbodrill with other prominent designs. The power and efficiency performance values presented in Table 6-3 for the Maurer turbodrill are the peak values obtained from Figure 6-3. The torque value of 425 ft-lb corresponds to the speed at which maximum power and efficiency occur. It is significant to note that the positive displacement Moineau motors tend to exhibit efficiencies in excess of 60 percent. The Maurer turbodrill exhibits lower operational efficiencies, primarily due to frictional effects from internal fluid slip-flow and possibly to hydraulic downthrust loading on the bearings.

Leak flow rates through the bearing section of the turbodrill were measured during testing (see Table 5-1) and ranged from zero to 9 gpm. These values represented from zero to 3 percent of the total flow through the turbine. The leak flow rates through the turbodrill bearing package had been intended by MEI to be on the order of 10 to 15 percent of the total volumetric throughput. The turbodrill was originally designed to support a bit-end pressure drop of 1000 to 1500 psi. The achievement of the relatively low leak rates is due primarily to the low pressure differentials sustained across either the pressure seals or seal leak-sleeve (on the order of 200 psi, as indicated by approximately 400 psi measured in the oil reservoir and about 200 psi in the flow exit line) in Phase I and shakedown testing.

TABLE 6-3. COMPARISON OF MAURER TURBODRILL PERFORMANCE WITH PERFORMANCE OF OTHER DRILLING MOTORS

Manufacturer (type)	Outside Diameter (in)	Overall Length (ft)	Flow Rate (gpm)	Rotary Speed (rpm)	Pressure Drop Across Turbine (psi)	Output Torque (ft-lb)	Power Output (hp)	Motor Efficiency
Maurer Engineering (50 stage turbodrill)	5.38	18.4	300	1500	1780	425	115	0.37
Eastman Whipstock D-89 (75 stage turbodrill)	6.75	N/A*	300	628	272	239	28.5	0.60
Eastman Whipstock D-92 (3 stage Moineau)	6.5	22.6	300	391	250	561	41.8	0.96
Christensen Navi-Drill (Moineau)	6.25	25	425	510	580	940	92	0.64
Baker (Moineau)	6.75	19.9	350	175	250	1200	40	0.78
Allegheny Ludlum - Garrison Motordrill (flexible-vane)	6.25	12	275	375	1000	1875	134	0.83

Notes:

1. Performance data on the Eastman Whipstock downhole motors were obtained from Drilling Contractor, May 1979, pp. 54-57.
2. Reference data on Christensen Navi-Drill were obtained from Drilling Contractor, May 1979, pp. 80-84.
3. Performance data on the Baker Downhole Drilling Motor were obtained from published Baker Service Tools literature.
4. Data on Garrison Motordrill were obtained from Petroleum Engineer, March 1966, pp. 76-79.

*Not available

Teardown of the turbodrill bearing package after Phase I testing revealed that the lower roller thrust bearing failed due to excessive hydraulic downthrust loading (discussed in Section 1.3). This condition persists whenever the tool is run without normal bit-weights experienced with a drilling rig. The lower thrust bearing failure most likely was due to the compounded effects of three factors:

- Excessive hydraulic downthrust loading (The calculated load was approximately 25,000 pounds.)
- Rotary speeds in excess of 1,000 rpm
- Use of drilling mud that was 12 percent denser and 11 times more viscous than water

The scenario of events that led to bearing failure probably was as follows:

- Due to the effects of the above three factors, the rolled wire-mesh backup ring employed as the lower thrust bearing race seat deformed under load in such a manner as to impose uneven loading on the bearing race.
- As a result, the lower race cracked circumferentially in the middle and induced uneven loading on the bearing rollers to the extent that each roller appeared to crack in two places and subsequently disintegrated.
- In the final stage of failure, the two bearing races were sandwiched with the roller cage and then ground to a halt, cutting off the mud flow, with deep scoring and metal discoloration indicating severe local heat generation.

The MEI modification designed to alleviate the problem was to install six Belleville springs to back up each roller bearing in the bearing package. The design modification was made and Phase I testing was scheduled to be resumed. However, this effort was terminated by a management decision to begin preliminary Phase II testing activities at TerraTek and Los Alamos. The results of these activities will be discussed in the report on Phase II testing.

Wear measurements on the parts designated prior to testing were not obtained by MEI after teardown of the turbodrill following Phase I testing. As a result, no determination of wear rates or assessment of tool repair requirements was made.

7. CONCLUSIONS

The following conclusions were drawn from analysis of Phase I test data:

- The primary objective of this phase of the Test Project (to determine baseline performance characteristics) was accomplished.

- Some design modifications to the 5-3/8 inch turbodrill must be considered. The turbodrill in its present design configuration exhibits a number of operational and design problems. This is true of both the flow-through and the sealed bearing package versions of the turbodrill. The two major problem areas are (1) excessive pressure drops through the turbine section and (2) maximum power output and efficiency that are attained only at very high rotary speeds.

The turbine blade design is such that, although high torques are developed by the turbodrill, excessive pressure drops result when driving the turbine. This phenomenon may be associated with the fact that the fluid turning angle through the blades and vanes in the turbine section is relatively large compared to other turbodrill designs (according to MEI). The major disadvantage of the large pressure drops (on the order of 2,000 psi) is that the turbodrill will require large capacity rig pumps to drive it downhole, and that the power requirements of these large pumps will necessitate the use of large drive engines in the field. Thus, general field application of the turbodrill could be limited by escalated operating costs compared to conventional rotary drilling and by the unavailability of large mud pumps in some areas.

The tendency of the turbodrill to develop maximum power and efficiency at relatively high rotary speeds is detrimental to drill bit life. In tests run to date, maximum power occurs at approximately 1,500 rpm. Special high-speed, roller-cone bits are limited to about 375 rpm in continuous drilling, and conventional diamond bits are limited to about 500 rpm to achieve reasonably long bit life and not contribute substantially to operating costs on a rig.

Mitigation of these problems may require redesign of the turbine blades themselves and perhaps modification of other components in the turbodrill as well.

8. RECOMMENDATIONS FOR FUTURE TESTING

It is recommended that the project proceed into Phase II controlled field testing at Gearhart-Owen in Fort Worth, Texas. However, prior to Phase II field testing, it is further recommended that a reasonably accurate and reliable turbodrill tachometer be developed to aid the drilling rig operator by monitoring rotary speed downhole. This would be beneficial in avoiding overspeeding in order to extend drill bit life, detecting stall conditions to keep the bit and motor from becoming stuck in the hole, to better match bit-weight and speed for stable operation, and to maximize rate-of-penetration for a truer indication of turbodrill potential drilling performance.

The scope of this test project does not include redesign of the turbodrill to minimize or eliminate the major problems of large pressure drops and excessive rotary speeds. Neither does it involve retesting the new design to determine performance characteristics. Nonetheless, if warranted, it is recommended that these problems be addressed in a separate project.

APPENDIX A

TEST PLAN

This appendix contains the Test Plan that governed all test activities during Phase I at TRW Mission Manufacturing Company in Houston, Texas.

The Plan was reviewed and approved by project participants prior to initiation of Phase I test operations at TRW Mission.

TEST PLAN
for the
MAURER ENGINEERING 5-3/8 INCH TURBODRILL
Initial Bench Testing
at
TRW MISSION MANUFACTURING, INC.
Houston, Texas

by

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1.0 INTRODUCTION

This document establishes the Test Plan for initial bench testing of the 5-3/8 inch turbodrill developed by Maurer Engineering, Inc. (MEI) under Contract No. EY-77-C8093 for the Department of Energy (DOE), Morgantown Energy Technology Center (METC). The plan states test requirements and presents procedures to determine performance and wear characteristics of the turbodrill under controlled operating conditions. In this Test Plan, bench testing refers to operation with the turbodrill mounted in a stationary test fixture, as opposed to actual well drilling.

1.1 BACKGROUND

In one of many activities aimed at increasing supplies and production of energy, the DOE is exploring the use of downhole drilling motors and directional drilling techniques in present day coalbed methane and oilfield well drilling operations to improve efficiency and reduce drilling costs. The Maurer Engineering 5-3/8 inch diameter oilfield model turbodrill, shown schematically in Figure 1-1, incorporates several advanced features:

- High efficiency turbine blade design, providing greater torque with fewer stages and lower driving fluid volume throughput
- High load capacity roller thrust bearings, permitting greater bit weights (weight applied to the bit) and improved penetration rates
- Improved rotating seal design and materials, providing longer bearing life (interval between changeovers) and permitting greater pressure drops across the bit to flush out rock chips and cool the bit more efficiently.

A major advantage is low drill string and casing wear (due to minimal rotation requirements) which results in increased drilling rates and smoother operation due to decreased chances for "twist-offs" and other problems. The other version of the turbodrill (geothermal model) being developed is geared to high-temperature field applications and allows drilling fluid to flow through the bearing pack to cool and lubricate the bearings. This tool offers the advantages of longer service intervals when drilling in formations where water can be used as the drilling fluid.

The major thrust of the effort to be carried out in this test plan is to establish basic performance characteristics of the oilfield model turbodrill. Parallel development of the geothermal model turbodrill is also

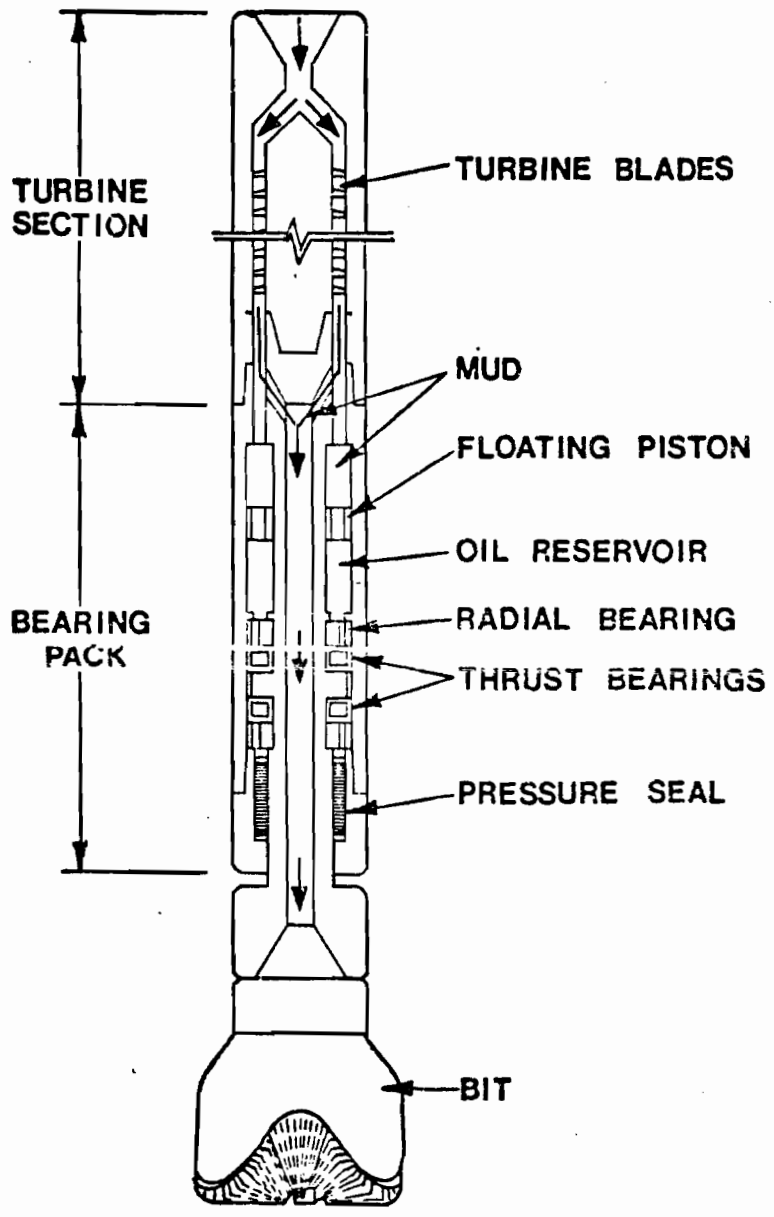

Figure 1-1. Turbodrill - Oilfield Model

being supported by Government funding in another project. A relatively small amount of test work in the form of bearing package leakage tests that are germane to the geothermal model turbodrill is included herein. The incremental cost of the additional test effort is minimal compared to the cost to the Department of Energy to run the tests on their own at another time.

Turbodrills have been manufactured, but have not been tested for performance and reliability. Performance and wear testing to determine operating and durability characteristics is to be done in Phase I of the testing project. From tests described in this plan, performance characteristics will be determined under controlled conditions, prior to drilling tests into previously drilled formations whose characteristics are well known. These tests will be performed at another test facility in the field as Phase II of this project. Phase III of the testing project will demonstrate the turbodrill at a field site drilling into formations whose properties are not well known a priori.

The baseline data (determined in Phase I) will provide performance characteristics against which to assess the data resulting from subsequent active well drilling tests. Wear and other degradation information is also desired to aid estimation of preliminary tool maintenance requirements and component life expectancy for future test planning. In the past, turbodrills have received limited application due to bearing and seal failures. Bearing pressure seals are especially critical to tool changeover requirements. Evaluation of alternate pressure seals having varying configurations and made of differing materials is important in order to improve seal performance and to provide backup capability.

1.2 OBJECTIVES

The purpose of this test plan is to provide coordinated planning, test requirements, detailed test procedures, and supporting information for a series of tests that will provide performance and wear characteristics of the Maurer Engineering 5-3/8 inch turbodrill in an above-ground, bench testing mode.

Specific objectives of the Phase I tests are:

- To determine performance characteristics; i.e., nominal turbodrill speed, torque, and power as functions of mud flow rate, mud pressure, and pressure drop across the bit

- To ascertain wear characteristics experienced in rotary operation under simulated load conditions in bench tests
- To acquire data for use in determining component service life expectancies
- To determine the leakage rates of drilling fluid at different bit pressure drops through the geothermal model bearing package
- To investigate the applicability of alternate pressure seal designs and materials.

1.3 SCOPE

This test plan governs and provides guidelines for all initial bench testing of the Maurer 5-3/8 inch turbodrill at TRW Mission Manufacturing, Inc. facilities in Houston, Texas. This plan covers all Phase I activities of the Maurer turbodrill testing project.

2.0 REQUIREMENTS

Test procedures and operations shall be designed and implemented to provide data to determine the performance and wear characteristics of the turbodrill. Wear and other degradation of components critical to sustained operation of the turbodrill will be observed, measured, and recorded to the extent required to determine design adequacy and service requirements for field testing. A preliminary assessment of turbodrill operating performance and service life expectancy is required.

Test requirements reflecting the above general objectives are specified in this section. Designated responsible personnel, equipment configurations, test prerequisites, and safety considerations along with other test conditions, procedures, and data requirements are stated. Detailed test procedures for satisfying these requirements are presented in Section 5.

2.1 PERSONNEL

Planning and implementation of the planned tests requires a coordinated effort between METC, MEI, and TRW. These organizations shall function in the capacities listed below. The individuals noted, or a designated alternate, shall be the point of contact for purposes of this test, contractual matters excepted.

Test Controller	Morgantown Energy Technology Center R. L. Wise, Project Manager
Test Director	TRW Energy Systems Group R. S. Ottinger, Manager, Energy Resources
Test Conductor	Maurer Engineering, Inc. W. C. Maurer, President
Test Facility and Support	TRW Mission Manufacturing, Inc. S. L. Collier, Manager of R&D

The test crew shall be provided by MEI who shall perform test operations in accordance with test procedures approved by METC.

2.2 TEST CONFIGURATION

The test facility and equipment configuration supplied by Maurer Engineering is shown in Figure 2-1. The turbodrill, test stand, dynamometer,

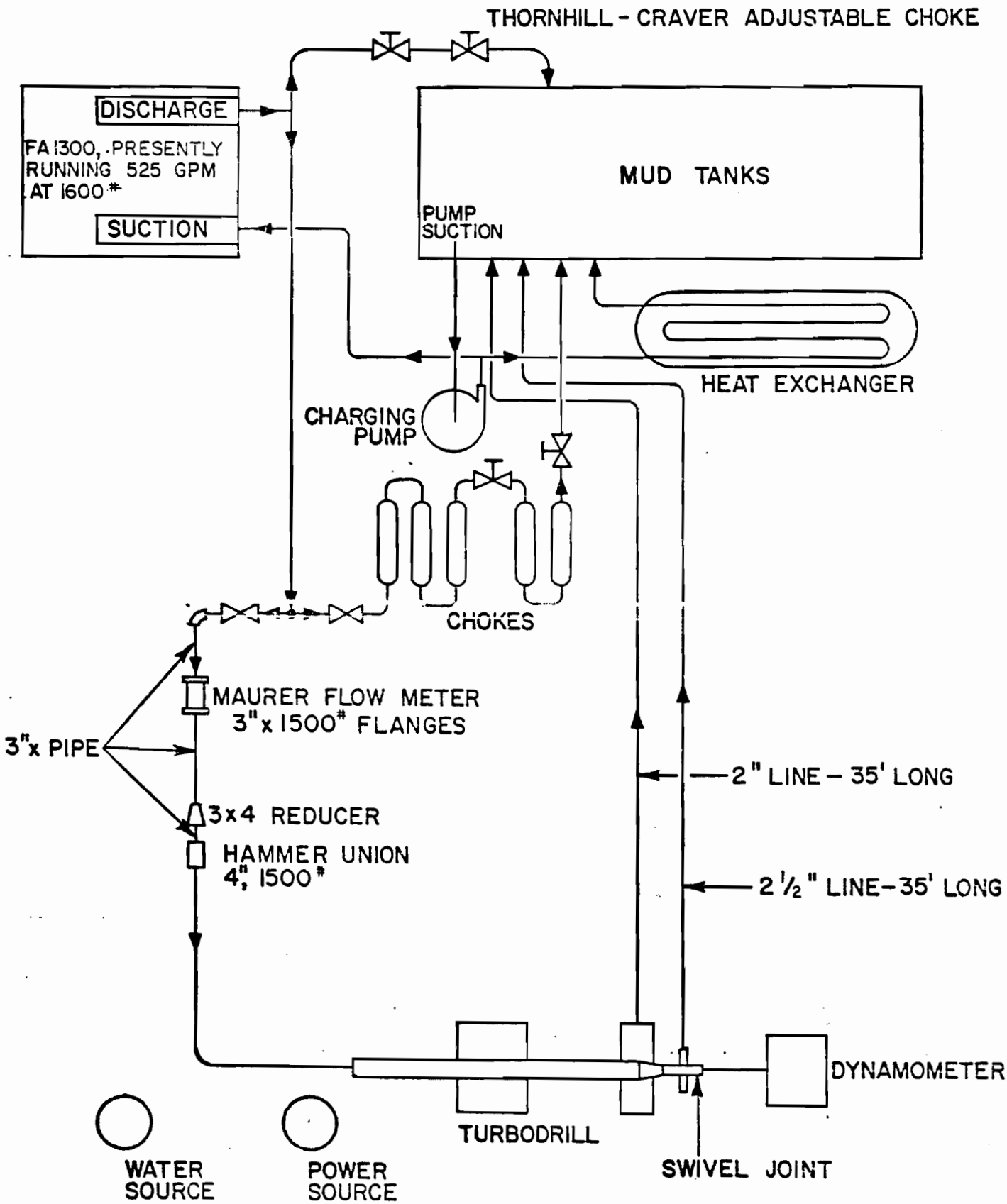

Figure 2-1. TRW Mission Test Facility Layout

instrumentation, and related equipment shall be provided by MEI and installed in a TRW Mission Manufacturing facility equipped with the mud handling and circulating equipment noted in the figure. The leadtime required to change-out the inoperative valves (3 inch and 4 inch) is within the time available prior to testing. In that case, they will be removed, repaired, and placed back in service before testing commences.

The turbodrill shall be transported, assembled, installed in the test stand, prepared for testing, operated/serviced/maintained, and deactivated by MEI after testing is completed.

The test facility and support shall be provided, prepared to support testing, and operated/serviced/maintained by TRW Mission during the testing program.

Equipment and operating requirements not specifically defined shall be provided by MEI and TRW Mission by mutual agreement determined before testing begins. Test configuration and planning shall be supported and reviewed for technical adequacy by TRW Energy Systems Group. METC shall have final approval of all plans and procedures. Test equipment requirements include the following major equipment and related auxiliary and incidental items:

MEI
- Test stand (Modified MEI Assembly Stand)
- Turbodrill assembly equipment
- Dynamometer
- Instrumentation - generally items installed on MEI equipment or provided to measure/record turbodrill and dynamometer operating parameters.

TRW Mission
- Mud pump and drive engine
- Mud and mud holding tank
- Mud piping and valving
- Instrumentation - generally items installed on TRW Mission equipment or provided to control/record mud flow parameters.

2.3 TEST PREREQUISITES

2.3.1 Instrumentation Calibration and Certification

All instruments and recording equipment used in these tests will be calibrated according to accepted, standard industrial procedures by the

supplier prior to delivery to the test facility. Certification stickers stating date, responsible party, duration of effectiveness, and standards used shall be affixed to the instrument.

2.3.2 Prerequisite Testing

Prior formal testing of the turbodrill is not required.

2.3.3 Test Setup and Readiness

The turbodrill and all test equipment and test support requirements shall be prepared and verified ready to support testing prior to start of test operations. Test participants shall verify readiness, and no operation shall be started without specific direction of the Test Director.

2.4 SAFETY

Test personnel shall strictly adhere to published safety practices in accordance with the documents and directives of the organizations listed below:

- OSHA safety regulations/standards
- City of Houston Electrical Code
- TRW Mission Health and Safety Manual.

Safety hazards associated with the planned turbodrill operations involve high pressures, rotating equipment, and electric shock. Appropriate controls and safeguards for these hazards are documented above. All test planning and operations shall be done cognizant of these safety requirements. Special, or unusual, hazards shall be noted during test operations prior to each point where they occur.

It shall be the responsibility of the Test Conductor to assure compliance with safety precautions and approved controls and safeguards during test operations.

2.5 TEST PROCEDURES

Test operations shall be performed in accordance with procedures described herein and designed to satisfy the test requirements described in this section. Test procedures are required to:

- Determine mud pressure drops across the drill bit, rotary speeds, and torque responses as functions of mud flow rates

- Measure and determine wear rates of thrust bearings, radial bearings, marine (sleeve) bearing seal, pressure seals, turbine blades, and stator vanes.

The test procedures shall be designed for performance in an orderly manner with data logged/recorded as each step/event/milestone occurs. All procedures, including those for emergency operations, shall be prepared by the Test Conductor and approved by the Test Director unless precluded by time limitations. Handwritten procedures developed during the course of a test due to unforeseen difficulties are acceptable, but must have Test Conductor and Test Director approval prior to implementation.

In emergency situations or if equipment damage is imminent, and where time is of the essence, the Test Conductor shall assume a single point of command and report his actions to the Test Director as soon as practical. In the event that deviation from previously approved procedures occurs, a written report shall be made to the Test Director after the test is terminated.

In the event of a procedural error or an unplanned test interruption, Test Conductor and Test Director agreement must be obtained prior to error correction or test restart.

Successful test procedure completion is signaled when all required data have been acquired and are in apparent good order.

2.6 DATA REQUIREMENTS

Expected test parameters, other required data, and required instrument response characteristics are covered in the test procedures in Section 5.

One copy of the test procedures, Section 5 of this test plan, shall be designated the "Data Master Copy." Data entries, record of procedure deviations and other annotations shall be made on this master copy to help avoid recording errors and omissions and to assure accurate, precise, and complete test data use and reporting.

3.0 TEST STRATEGY

An overview of the test strategy, rationale, and planned testing activities is described in this section. Detailed procedures and test conditions are presented in Section 5.

3.1 STRATEGY ELEMENTS

Specific strategy elements to achieve the test objectives in Section 1.2 are:

- Verify prior to test operations that instrumentation meets prescribed requirements and calibrations are valid for the test period. Obtain pre-test and post-test calibrations, where appropriate
- Obtain and log/record data for operating parameters to establish baseline performance characteristics at zero pressure drop across the bit
- Obtain data on performance characteristics at elevated bit pressure drops and perform endurance tests under steady-state simulated operating conditions
- Obtain leakage rates through marine bearings used in the bearing package of the flow-through (geothermal) version of the turbodrill
- Obtain and record measurements to determine wear rates of components critical to sustained drill motor operation
- Evaluate the performance of an alternate bearing seal.

3.2 TEST DESCRIPTION AND RATIONALE

This subsection describes how each strategy element will be carried out and the reasons behind performing each element.

Prior to test operations, the exact configuration of the turbodrill will be identified with 8" x 10" photographs and documented to serve as a basis for subsequent wear measurements. All component part numbers and critical dimensions will be recorded. The condition of seals, bearings, and finished surfaces will be noted. Clearances at critical locations will be measured. Assembly details such as sequence, tightness of fit, assembly torques, and lubrication will be described and recorded. The turbodrill will be mounted in a test stand provided by MEI by modifying its assembly stand. Special clamps and equipment are required to provide reaction torque and to limit bending moments on the turbodrill during test operations.

In preparation for testing, a dynamometer is installed to provide external loading, simulating the resistance encountered during actual well drilling. Calibrated instrumentation is installed/connected, and determined to be in good working order. Thermocouples will be installed on the bearing pack outer housing to monitor temperature responses throughout the course of the tests and to give early warning of the possible onset of bearing malfunction or failure.

The driving fluid is drilling mud, and the turbodrill is operated by pumping mud through it at a constant flow rate specified for each test run. Standard oil field (constant weight) drilling mud will be used in these tests. In actual well drilling operation, the mud flows down the drill string, through the turbodrill and up through the annulus between the drill pipe and the borehole. For these tests, however, the return flow bypasses the external surfaces of the turbodrill, and the mud is returned directly to a large holding tank for recycling. Samples of mud will be obtained and analyzed for composition and properties (weight or density, viscosity, sand content, and filtrate analysis).

The base line performance characteristics of the turbodrill will be established in the first series of test runs. For the first test run, the mud pump will be adjusted to deliver a constant flow rate through the turbodrill with no dynamometer load applied to the turbodrill and zero bit pressure drop. This will produce maximum (runaway) turbodrill bit rotary speed (N_r, on the order of 1800 rpm), which is recorded. See Figure 3-1. The dynamometer torque will be increased and the rotary speed will decrease in incremental steps (described in Section 5) until the turbodrill stalls (at maximum torque, T_0 in Figure 3-1). Torque and speed are recorded at each step. After this sequence, one set of data will be obtained by stepping up two speed points to check for reproducibility. From this data the turbodrill power output and efficiency (see Figure 3-1) will be calculated for each incremental speed at the given mud flow rate. This procedure will be repeated in steps for increasing mud flow rates and all data recorded to fill out the performance curves. Upon completion of this test series, mud flow rate will be stepped down two increments from the high end and a set of data obtained to check previous data. Maximum power output and efficiency of the drill motor occur theoretically at one-half the runaway speed, $N_{r/2}$. (See Figure 3-1.)

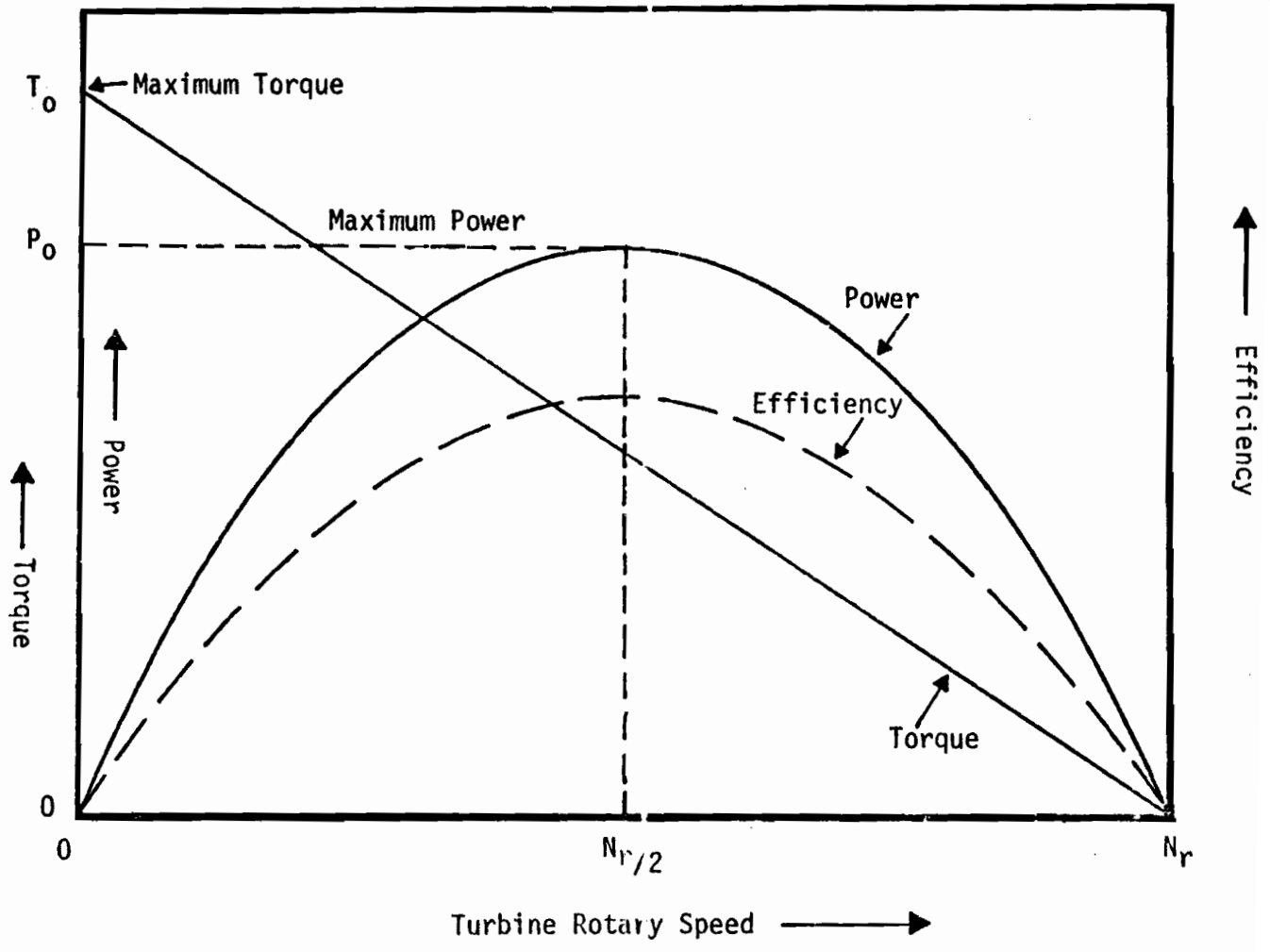

Figure 3-1. Typical Turbodrill Performance Curves

After the baseline data are obtained at the various mud flow rates, leakage rates of drilling mud through the bearing package will be determined. This is done by changing out the bearing package with one in which the pressure seal in the bottom of the bearing pack is a marine bearing type of flow constrictor. The constrictor acts as a partial seal and provides controlled leakage of drilling fluid through the bearings to cool and lubricate them. This will allow sustained use of turbodrills in high-temperature environments.

After obtaining data on the leakage rates of drilling mud through the bearing package, tests will be performed with the differential pressure drop across the turbodrill bit section increased to two different levels to simulate operation with a drill bit. Details are discussed in Section 5. Bench testing will not involve use of a drill bit. However, the use of one can be simulated. The mud discharge flow will be restricted to simulate the pressure drop caused by the jetting action in a drill bit. This will be done by inserting a flow restrictor in the exit channel of the turbodrill rotor assembly. An endurance test will be run at each of the prescribed bit pressure drops. Details of the test conditions are presented in Section 5.

The packing seal used in the bearing package in the previous test work is a Johns-Manville Uneepac seal. The Uneepac rotating seal is fabricated in the form of a series of "W"-shaped overlapping elements. However, the availability of an alternate seal would enhance reliability and applicability of the turbodrill. For this reason, a final four-hour endurance test will be run using a Utex Industries chevron packing seal. This seal consists of a series of "V"-shaped overlapping rotating elements. This type of seal has been widely used in other applications and would provide a readily available backup in the field if tests prove its acceptability.

The turbodrill will be disassembled, inspected, and wear measurements taken. In addition, the tool will be serviced, when necessary, at four points during the test program described above. These are:

- After completion of the baseline data runs
- After the measurements of mud leakage rates through the bearing pack using the flow constrictor. Specifically, the wear rate of the marine bearing will be determined

- After the series of two initial endurance tests at different bit pressure drops
- After the final endurance test using an alternate type of pressure seal in the bearing package.

The information obtained from observations and measurements of wear at these four intervals will allow determination of component life expectancies and establish presecribed service intervals when the drill motor is tested in field operations in Phases II and III of the test program.

4.0 ROLES AND RESPONSIBILITIES

Implementation of this test plan will involve several organizations whose roles and responsibilities are identified below:

4.1 TEST DIRECTION AND CONTROL

DOE — Programmatic responsibility, allocation of top level funding and delegation of project implementation authority. Assigned to the Fossil Energy Office, DOE.

METC — Project implementation and field management. Responsibilities include the preparation of budgets and schedules, coordination with related projects and monitoring of activities to assure technical adequacy and achievement of project objectives.

4.2 TEST PLANNING, INTEGRATION, AND RESULTS ANALYSIS

METC — Overall control and responsibility for test planning and integration.

TRW — Detailed test planning and integration of technical requirements, assigned to TRW Energy Systems Group, Energy Systems Planning Division. This work includes review of test procedures and analysis of results.

MEI — Test planning and analysis support; test procedure preparation and support.

4.3 TEST PERFORMANCE

METC — Test Controller

TRW — Test Director

MEI — Test performance is assigned to MEI, who will act as Test Conductor. This activity includes pre-test preparations, support equipment modifications, preparation of the turbodrill for testing, and "hands on" test operations. MEI will procure required instrumentation equipment, install, and operate this equipment and log/record test data. MEI will also be responsible for obtaining instrumentation with valid calibration for the test period and certification thereof. All performance data recording and running time logging will be done by MEI.

4.4 TEST FACILITIES SUPPORT

TRW — TRW Mission Manufacturing, Inc. will provide the test facility and associated support at its Houston, Texas, location.

4.5 TEST EVALUATION AND REPORTING

TRW Energy Systems Group will coordinate and publish reports with METC approval.

5.0 PROCEDURES

Procedures are presented in this section for bench testing the Maurer Engineering 5-3/8 inch turbodrill at TRW Mission Manufacturing facilities in Houston, Texas. Specific procedures have been developed to implement the elements of the testing strategy presented in Section 3.1.

5.1 TEST PROCEDURE

The sequence of activities to be performed corresponding to the test strategy elements in Section 3.1 is:

(1) Pre-Test Activities

(2) Baseline Data Acquisition

(3) Degradation Inspection and Wear Measurements

(4) Marine Bearing Leakage Rate Tests

(5) Degradation Inspection and Wear Measurements

(6) Endurance Tests

(7) Degradation Inspection and Wear Measurements

(8) Alternate Bearing Seal Design Test

(9) Degradation Inspection and Wear Measurements

5.2 TESTING SCHEDULE

Figure 5-1 presents the schedule for performing the sequence of activities in Section 5.1. Required activities prior to testing as well as subsequent data analysis and reporting are included.

5.3 IMPLEMENTATION

The pertinent performance parameters to be either measured or monitored during testing are mud flow rate, inlet mud pressure, pressure drop across the drill bit, rotary speed, and output torque. The key instrumentation required to obtain these quantities is presented in the following list showing the type of instrument and required ranges corresponding to each variable or parameter:

- Volumetric flow rate of the mud - turbine flow meter (60-500 gpm capacity)

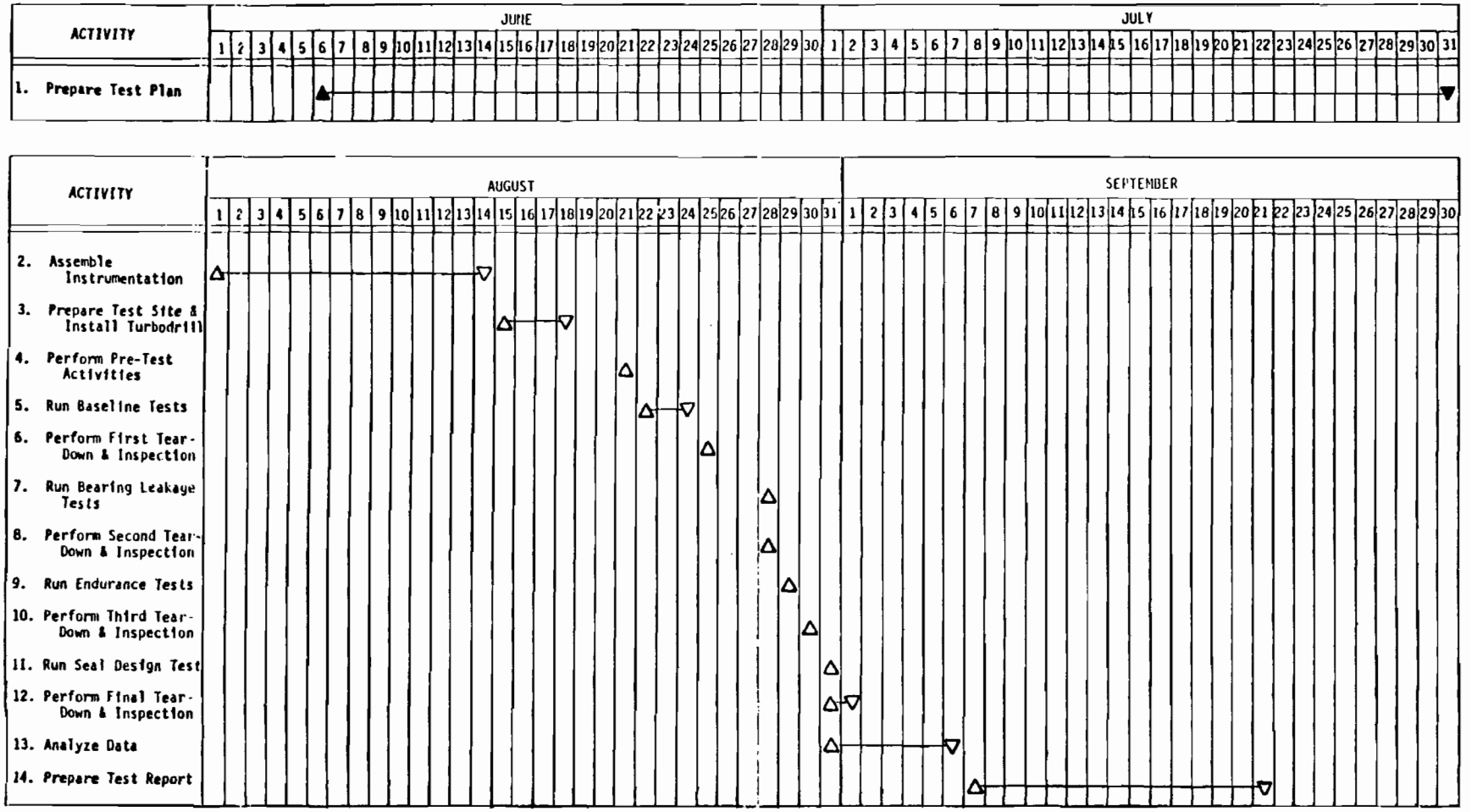

Figure 5-1. TRW Mission Testing Schedule

- Volumetric flow rate of the mud - turbine flow meter (15-200 gpm capacity)
- Inlet mud pressure - dial pressure gauge (0-3000 psi)
- Pressure drop across the drill bit - two dial pressure gauges (0-1000 psi)
- Rotary speed - tachometer (0-2000 rpm)
- Output torque - torque meter (0-3000 ft-lb).

Required accuracies of the above instruments are as follows:

Turbine flow meter - ± 2 percent full capacity

Dial pressure gauges - ± 2 percent full scale

Tachometer - ± 2 percent full range

Torque meter - ± 2 percent full capacity.

The instrumentation is located at the sensing points marked in Figure 5-2.

The raw data are recorded on strip chart recorders. This type of recorder requires conversion of physical data to electronic signals in order to record. This requirement is filled by electronic signal conditioning equipment.

Besides being recorded every fifteen minutes by hand (see the sample data sheet in Table 5-1), the volumetric flow rate of mud, for example, is converted to an electronic signal by a flow sensor in the mud line near the turbine flow meter leading to the drill motor. The flow sensor is a separate electronic device that emits pulses for every incremental volume of fluid that passes by the sensing point and is converted to a dc signal on a continuous basis. The volume depends on instrument design and the calibration. The instrument is calibrated in terms of pulse per fluid volume. An electronic counter is used to accumulate the counts and provide an integral value of fluid volume per unit time. Such an instrument is made by Anadex. The signals are changed to a variable time base dc signal for recording volumetric flow rate in engineering units with 1 to 2 percent accuracy. The signal is converted to a variable dc voltage to read out flow rate on a meter to check the response from the turbine flow meter.

It is important that the turbine flow meter be calibrated using a mud slurry similar to the drilling mud in the TRW Mission mud tank. Standard calibrations are done with water, and this would introduce an additional error

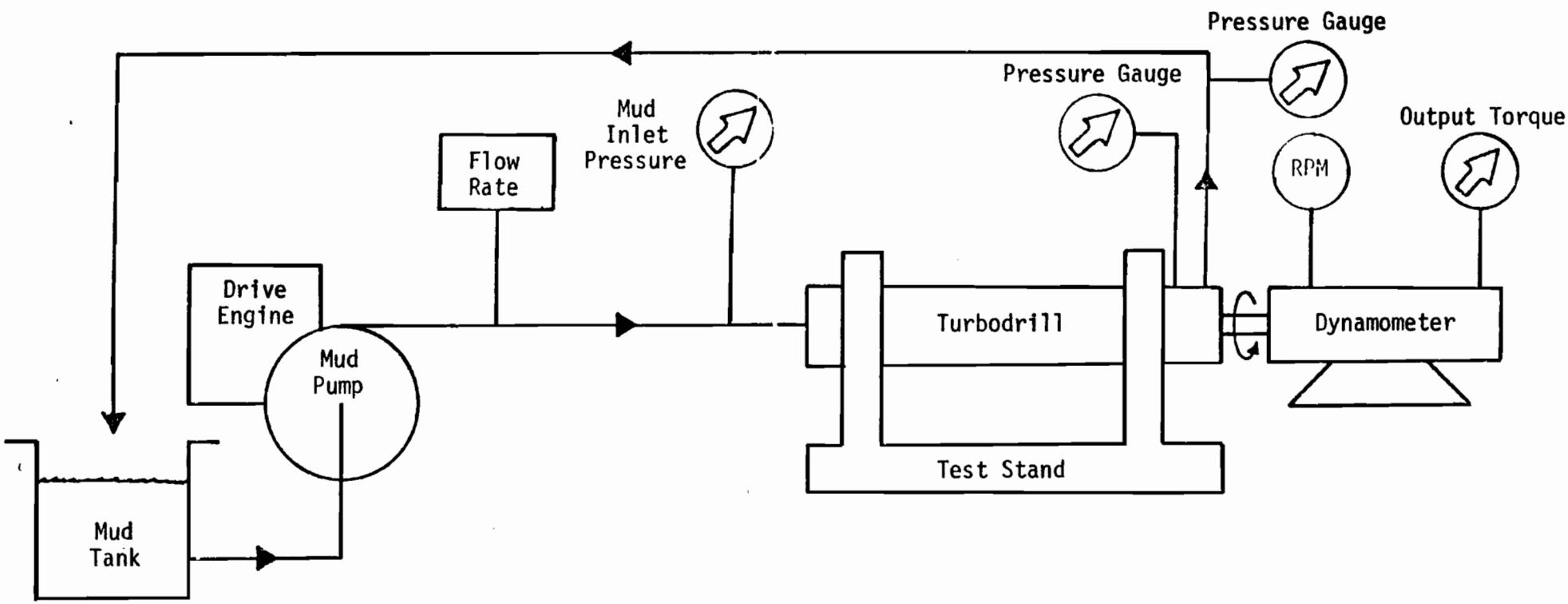

Figure 5-2. Turbodrill Bench Test Setup

Table 5-I. Sample Data Sheet

Maurer Engineering 5-3/8 Inch Turbodrill

TRW Mission Bench Tests

Date / Run No.	Time	Mud Flow Rate gpm	Inlet Mud. Pressure psig	Mud Pressure at Bit Exit - psig	Rotary Speed rpm	Dynamometer Torque ft-lb	Mud Leakage Rate gpm	Remarks

(to about 3 percent) in the data. Calibration with mud is expected to yield accuracy in the vicinity of 1.0 to 1.5 percent. The turbine flow meters used in these tests require stainless steel construction. Cox, Fischer & Porter and Halliburton make units of this type. Effects of drilling mud on instrument bearings are to be considered so as to ensure that instrument response quality does not deteriorate during the tests. A coarse wire-mesh screen will be installed in the mud line upstream of the turbodrill to keep any agglomerated particles from damaging the instrumentation. The turbine flow meter will be placed in the mud line at least 10 pipe diameters upstream of the turbodrill in the straight section of pipe.

Pressures are converted to continuous signals by means of transducers located in the proximity of the dial gauges at the sensing points in Figure 5-2. Suitable strain-gage transducers are manufactured by Endemco. This type of transducer requires a bridge-balance unit with a power supply for nulling and calibration purposes. These are available from B&F Instruments. The rotary speed response is generated and recorded using an electronic revolution counter. The revolution counter will provide direct response in rpm if a 60-tooth gear wheel is mounted on the dynamometer shaft or to the drill bit shaft of the turbodrill itself. Electro Products produces suitable revolution counters. The output torque is registered on the dynamometer using a conventional dial torque meter. A continuous torque signal is generated using a strain-gage device with associated equipment similar to that for pressure transducers.

Overall, combined maximum errors have been estimated for measured variables and quantities whose values depend on the primary, measured variables. Both random and systematic sources of error have been considered. These include response error inherent in the instrumentation, calibration error, electronic signal conditioning device error, recorder error, and human error in reading instruments. Results show the following maximum, combined errors associated with test variables and derived quantities:

Mud flow rate	± 6%
Inlet mud pressure	± 5%
Rotary speed	± 5%
Output torque	± 5%
Power output	± 8%
Efficiency	± 17%

Implementation of each activity in the test procedure is discussed individually in this section. Numeration corresponds to the activities listing in Section 5.1.

(1) Pre-Test Activities

As part of the pre-test activities, a complete set of turbodrill specifications for evaluation of wear will be recorded as per Table 5-2. Obtain 8" x 10" photographs of all parts to be measured and inspected for wear later. All of the electronic signal conditioning devices will be calibrated with respect to the recorders and ranges of values of the physical variables being measured. It is required that pre-test and post-test recorder responses to stepwise inputs be determined for calibration and to check for any drift that may have occurred during the testing period. Voltage regulation of the electrical power supply at the test facility will be determined, and a power supply regulator installed, if necessary.

(2) Baseline Performance Data Acquisition

The first series of tests in the second element in the testing strategy will be made at zero bit pressure drop to establish a base case. The independent variable is mud flow rate. The TRW Mission tests will concentrate on thoroughly establishing operating characteristics for the initial case of zero bit pressure drop. A portion of these tests will be repeated later at 500 and 1000 psi pressure drops (to be discussed) to expand the data base.

In the base case, the pump will be adjusted to deliver constant mud flow rate of 100 gpm with no torque applied to the drill motor. This will result in maximum or runaway rotary speed (in the vicinity of 1800 rpm). Data will be recorded manually (at 15 minute intervals) according to the sample data sheet and continuously on the recorder. Torque will be applied with the dynamometer until rotary speed stabilizes at 1500 rpm and the resulting torque recorded. Applied torque will then be increased incrementally to yield stable speeds of 1200, 1000, 800, 600, 400, and 200 rpm and data recorded. Finally, the stall

Table 5-2. Sample Specification Sheet

Maurer Engineering 5-3/8 Inch Turbodrill
TRW Mission Bench Tests

Part Name: Date:

Manufacturer:

Model No.:

Part No.:

	Nominal Dimension	Deviation	Remarks
Thrust Bearing Roller Diameter			
Radial Bearing Roller Diameter			
Johns-Manville Uneepac Seal Clearance			
Marine Bearing Clearance			
Utex Industries Chevron Seal Clearance			
Turbine Rotor Blades Nominal Mid-Length Thickness			
Nominal Tip Clearance			
Stator Vanes Nominal Mid-Length Thickness			

condition will be reached registering maximum torque at the given mud flow rate. This series will then be repeated at stable mud flow rates of 150, 200, 250, 300, 350, and 400 gpm and data re-recorded. For each set of data at a given mud flow rate, data will be obtained at the second point from the low end (at 600 rpm) as a check on reproducibility. At the conclusion of the entire set of runs at different mud flow rates, one run at a mud flow rate of 300 gpm will be repeated to check reproducibility. The maximum torque to be applied in these tests is 3000 ft-lb (the limiting dynamometer torque). All running time will be logged.

(3) Degradation Inspection and Wear Measurements

Upon completion of the baseline runs described above, remove the drill motor from the test stand. Disassemble the bearing pack and visually inspect parts for signs of wear and degradation. Obtain micrometer measurements of all critical dimensions of vital components, such as thrust and radial bearing rollers, and pressure seal clearances. Record all visual signs of erosion, pitting, scoring, or other degradation of metal parts on data sheets as per Table 5-2. Take 8" x 10" photographs of all parts showing signs of wear during each inspection.

(4) Marine Bearing Leakage Rate Tests

Upon completion of inspection and measurement, reassemble the drill motor. Replace the bearing pack containing the Johns-Manville Uneepac pressure seal in the bottom portion of the bearing pack with one having a marine (sleeve) bearing which acts as a flow constrictor. Run two tests for thirty minutes each at 250 gpm mud flow rate and 800 rpm rotary speed. The first test in this series will be at a bit pressure drop of 100 psi and the second at 200 psi. Measure and record the resulting leakage rates (flow rates) of mud through the bearings by placing a second turbine flow meter (15-200 gpm capacity) in the return line connected from the exit ports on the outside of the bearing pack housing to the mud tank. The leakage rates are expected to be within 10 to 20 percent of the mud flow rate to the turbodrill.

(5) Degradation Inspection and Wear Measurements

After bearing leakage tests are completed, tear down the drill motor again for visual inspection and measurement for wear in a manner identical to that described for the first teardown.

(6) Endurance Tests

Reassemble the bearing and turbine packs and run a four hour endurance test at 500 psi and another such test at 1000 psi simulated bit pressure drop and 800 rpm rotary speed. The bearing pack will contain the Johns-Manville Uneepac pressure seal. The mud flow will be set at 250 gpm in both cases.

(7) Degradation Inspection and Wear Measurements

After the endurance tests are completed, tear down the drill motor again for visual inspection and measurement for wear in a manner identical to that described for the first teardown.

(8) Alternate Bearing Seal Design Test

After completion of inspection and measurement activity, reassemble the drill motor and replace the Johns-Manville Uneepac seal with a Utex Industries chevron pressure seal. Run a four hour endurance test at a speed of 800 rpm, mud flow of 250 gpm, and 1000 psi bit pressure drop.

(9) Degradation Inspection and Wear Measurement

This is the final drill motor teardown and inspection/wear measurement to be performed in this test project. Especially careful examination will be made of all rotating and mating parts in the turbine and bearing packs. Wear characteristics will be noted. Disassemble the turbine pack and bearing pack, and visually inspect parts for signs of wear and degradation. Obtain micrometer measurements of all critical dimensions of vital components, such as thrust and radial bearing rollers, pressure seal clearances, turbine blade nominal (mid-length) thickness and tip clearance, and stator vane nominal (mid-length) thickness. Record all visual signs of erosion, pitting, scoring, or other degradation of metal parts on data sheets as per Table 5-2. Take 8" x 10" photographs of all parts showing signs of wear during each inspection.

In addition to other data obtained above to check reproducibility, a 30 minute run will be made after each intermediate teardown/inspection as part of the startup for the next tests to be done in items (4), (6), and (8) above. The conditions to be adhered to are: 250 gpm mud flow rate, 800 rpm rotary speed, and 1000 psi pressure drop.

6.0 TEST EVALUATION AND DELIVERABLES

6.1 DATA ANALYSIS AND REPORTING

Evaluation and reporting of the test results is the responsibility of TRW. Significant results shall be conveyed to METC and MEI verbally, by technical memoranda, and by written reports.

The report contents are as follows:

- Data analysis and test results pertaining to turbodrill operation, including the generation of performance curves
- Assessment of wear rates of critical components and determination of expected service life expectancies of these parts
- Recommendations concerning future turbodrill testing. Updating of Phase II and Phase III test planning, particularly parameter values to be used in Phase II field testing of the turbodrill on a drilling rig
- Assessment of the test results from a programmatic view. Correlation with the results of other projects. Recommendations for possible changes in project planning or adjustments in emphasis in other projects.

6.2 TEST PROJECT DELIVERABLES

Required deliverables are listed below:

- A draft final test report shall be submitted to METC and MEI for comment within thirty days after termination of the tests
- Three copies of the final test report shall be submitted to METC and two copies to MEI within thirty days after receipt of comments.

Phase I of the project will be considered complete when all of the test activities and reporting requirements listed in Subsections 5.1 and 6.1, respectively, have been accomplished.

APPENDIX B

CALIBRATION CURVES

The appendix contains the calibration curves obtained from data supplied by Maurer Engineering. The calibration data correspond to primary instrumentation and display equipment provided by MEI for Phase I testing at Mission Manufacturing. The period of effectiveness in all cases was one year.

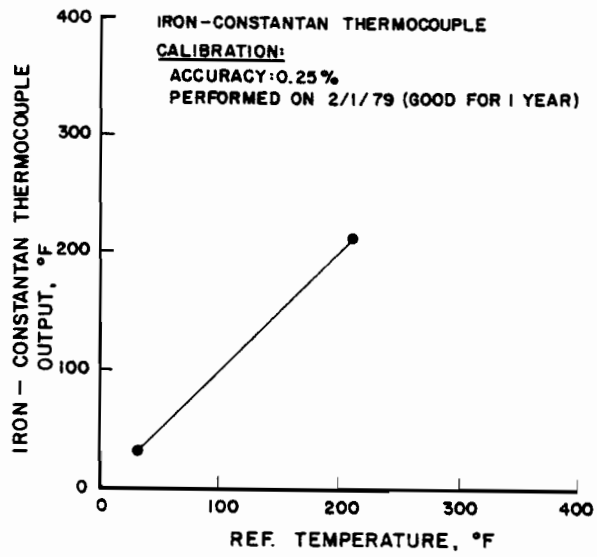

Figure 1. Iron-Constantan Thermocouple Calibration

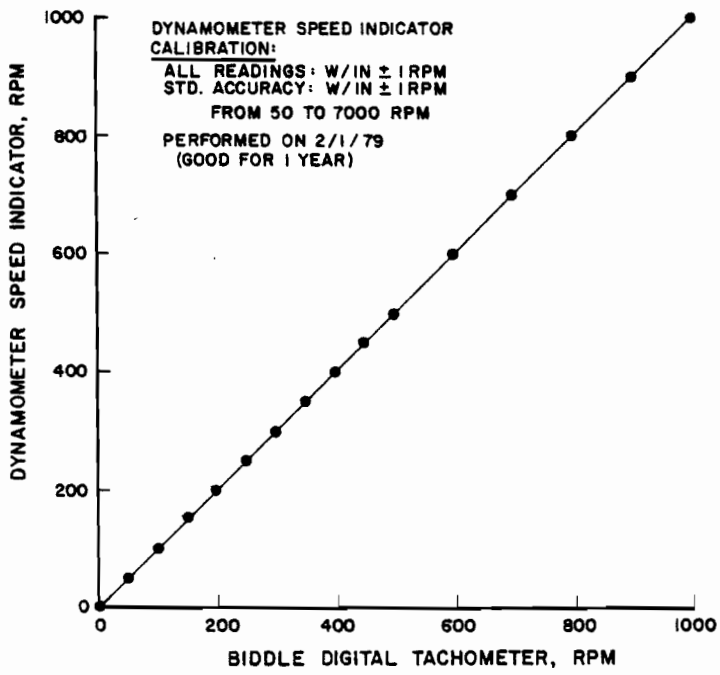

Figure 2. Dynamometer Speed Indicator Calibration

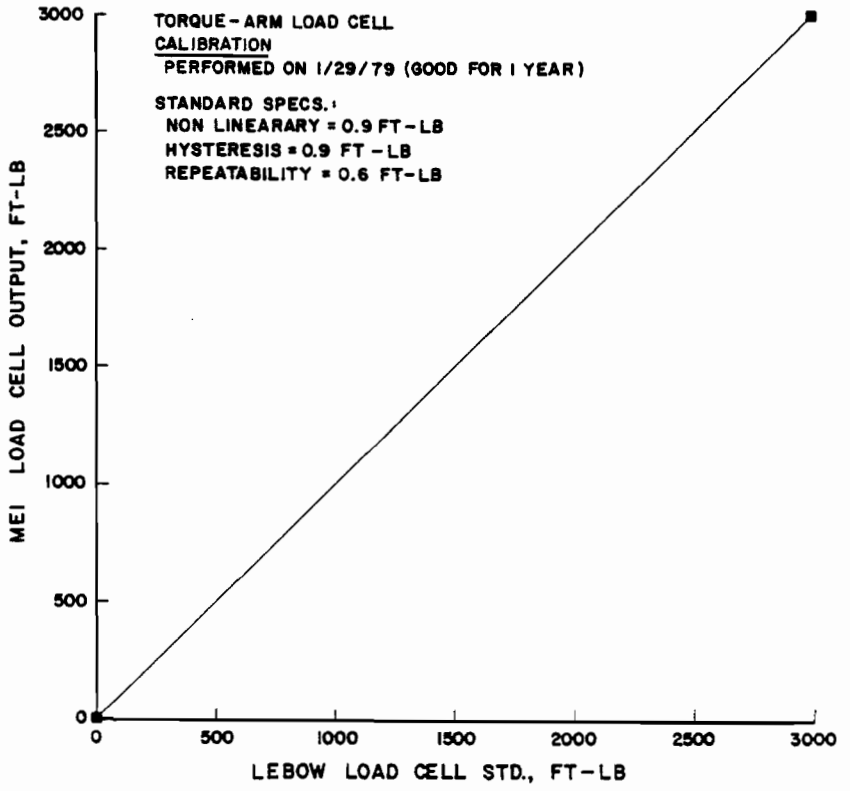

Figure 3. Torque-Arm Load Cell Calibration

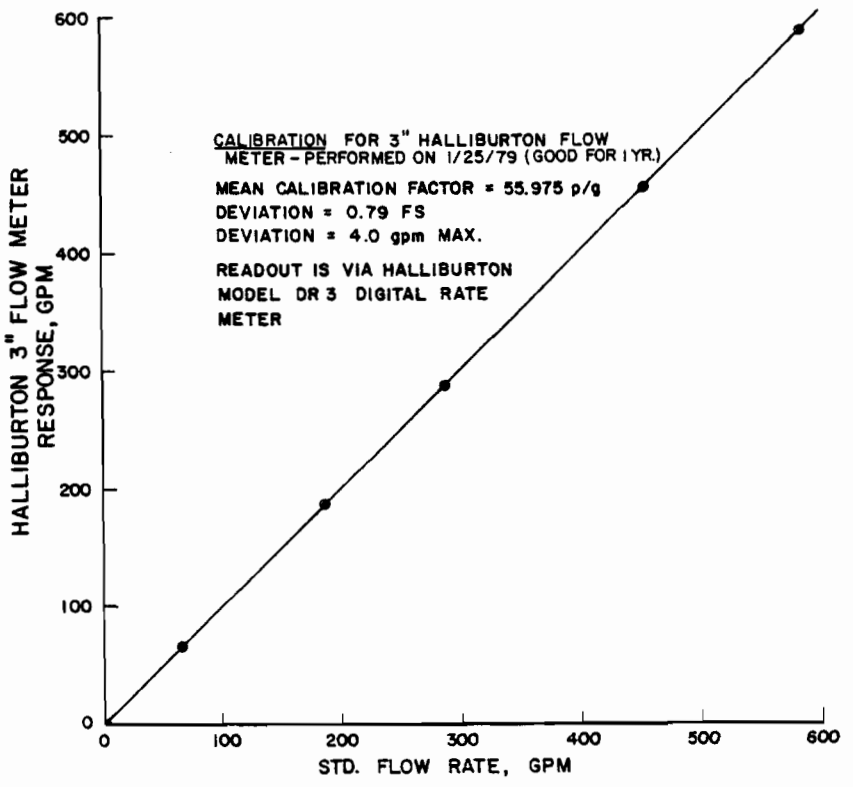

Figure 4. Calibration for 3 Inch
Halliburton Flow Meter

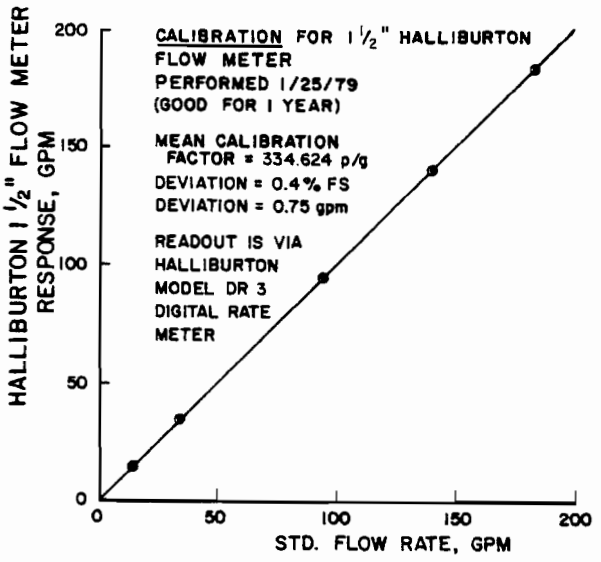

Figure 5. Calibration for 1-1/2 Inch Halliburton Flow Meter

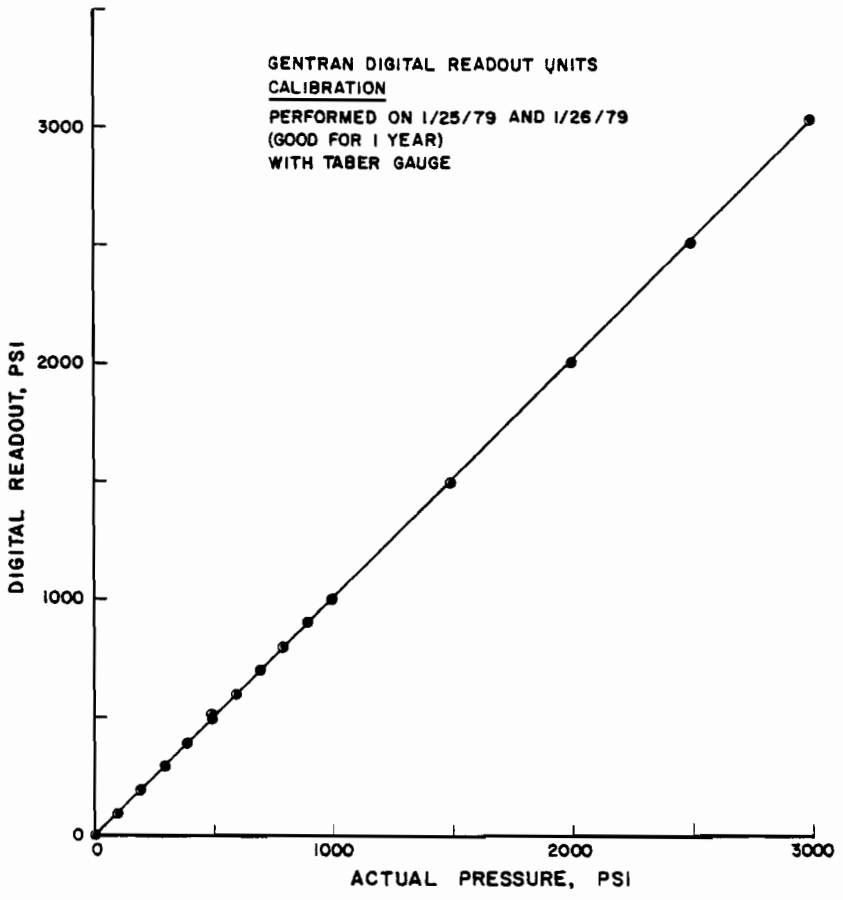

Figure 6. Gentran Digital Readout Unit Calibration

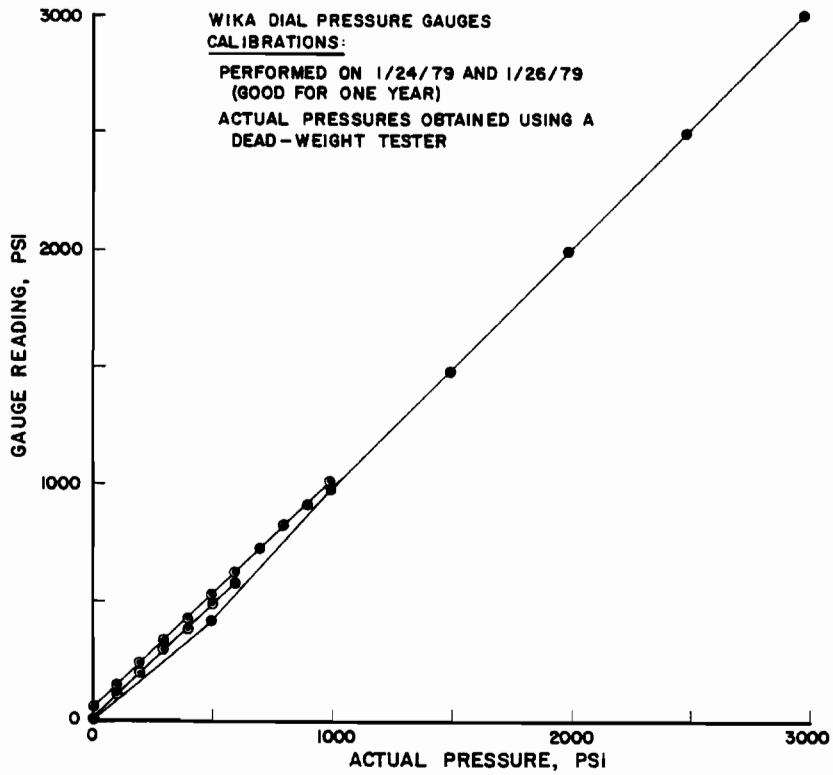

Figure 7. WIKA Dial Pressure Gauge Calibration

APPENDIX C

REACTIVE TORQUE ARM EQUATION

The appendix contains the derivation of the equation used to convert reactive torque arm load cell output from millivolts (mv) to conventional torque units (ft-lb) for Phase I data.

The torque arm transducer (load cell) was initialized at:

$$1 \text{ mv} = 100 \text{ pounds}$$

The length of the torque arm was 2.27 feet (see Figure 3-2). For calibration purposes the arm registers a 64 ft-lb "dead weight" torque, which must be subtracted from the actual torque measurement.

The total resultant turbodrill reactive torque therefore equals:

$$\text{Turbodrill Torque} = \text{Total Torque} - \text{Calibration Arm Torque}$$

$$\text{Torque} = 2.27 \times 100\,(\text{mv}) - 64 \text{ ft-lb}$$

But at no applied torque:

$$0 = 2.27 \times 100 \times (X \text{ mv}) - 64 \text{ ft-lb}$$

where

$$X = 0.28 \text{ mv}$$

Therefore, the reactive torque in foot-pounds can be obtained from the following relationship:

$$\text{Torque} = 227\,(\text{mv} - 0.28)$$

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DRAFT

TEST REPORT

TURBODRILL TESTING PROJECT

PRE-PHASE II & PHASE II

August 1980

For

MORGANTOWN ENERGY TECHNOLOGY CENTER
DEPARTMENT OF ENERGY

Under

METHANE RECOVERY FROM COALBEDS PROJECT
Contract No. DE-AC21-78MC08089

TRW ENERGY SYSTEMS GROUP
Energy Systems Planning Division
8301 Greensboro Drive
McLean, Virginia 22102

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August 1980

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August 1980

EXECUTIVE SUMMARY

A three-phase test project was established to test the Maurer 5-3/8 inch turbodrill as part of the ongoing drilling technology development effort at the DOE/Morgantown Energy Technology Center (METC). The overall goal of the project is to demonstrate applicability of the turbodrill for drilling long, horizontal methane drainage boreholes in coal seams at depths up to 1,000 feet, which appears consistent and attainable with today's directional drilling technology.

Testing activities have been performed under Contract DE-AC21-78MC08089 for the Methane Recovery from Coalbeds Project of DOE/METC and the turbodrills were designed and built by Maurer Engineering Incorporated (MEI) under contracts EY-77-C-21-8093 and EW-78-C-21-8380 with DOE/METC.

The overall goals of the Turbodrill Testing Project were to (1) determine operational characteristics of the Maurer turbodrill and (2) demonstrate applicability of directionally drilling methane drainage boreholes in horizontal coalbeds in advance of active mining operations (or possibly in unmined, steeply dipping coal seams).

In order to achieve these goals, the project was subdivided into phases. Phase I testing was designed to determine baseline performance characteristics of the turbodrill prior to field testing. Phase II testing was to determine both straight hole and directional drilling performance characteristics when operated in conjunction with a drilling rig penetrating previously drilled formations whose characteristics were well known. Full field testing in Phase III was to be conducted after successful completion of Phase II.

Results of the Phase I testing were published in July 1980. This report covers the results of the Phase II testing which reveals serious turbodrill mechanical problems. Phase III testing, therefore, has been postponed indefinitely as a result of these turbodrill performance difficulties discussed in subsequent sections.

Phase II field testing was conducted using a drilling rig at a Gearhart-Owen Industries, Inc., site in Fort Worth, Texas, in accordance with the approved test plan appended to this report. Testing was conducted in two separate test runs. The first test was run in December 1979 during which

the drill motor made approximately 23 feet of hole at penetration rates varying from 100 to 120 feet/hour. Total rotating time on the motor was about one hour in that test. This testing was terminated prematurely due to sudden failure of the lowest radial roller bearing which locked-up the drill motor. Teardown after the test revealed no visible damage to any parts other than one locked-up radial bearing. In that bearing, the individual rollers were skewed, the roller cage deformed, and there was some solid material in the bearing package. However, no plugging-off of lubricating mud flow occured. Buildup of solids was also observed around the uppermost radial bearing; however, that bearing did not show any signs of damage from this one hour test.

After completion of the first test run, the mud circulation system was reconfigured to add more mud cleanup equipment. The second test began in January 1980 using two 5-3/8 inch turbodrills. The first turbodrill ran for approximately 30 minutes before locking up. After the test, teardown revealed that two radial roller bearings had failed. Some granular, drill pipe scale was recovered from the bearing package; however, the thrust bearings were intact. The drill pipe and collars were rattled to remove scale and rust flakes before testing the second drill motor. The second turbodrill ran over two hours during which time it exhibited some performance difficulties (alternate overspeeding and stall) before finally locking up. This turbodrill had exhibited similar operational characteristics during preliminary tachometer development testing. Teardown of the second turbodrill showed failure of the lower thrust roller bearing; however, all radial bearings appeared unaffected. The thrust bearing may have failed due to high dydraulic downthrust not balanced by sufficient weight-on-the-bit. Application of bit weights to balance the hydraulic load resulted in stalling.

The conclusions drawn from Phase II testing are:

- Turbodrill performance in a vertical position conformed to the baseline characteristics (torque versus rotary speed) determined in Phase I testing
- Maurer developed tachometer can generate signals and transmit turbodrill RPM's to the surface

- Turbodrill units exhibited a tendency toward operational instability, i.e., they would run at speeds in excess of 2,000 RPM with little weight-on-bit or stalled consistently at moderate bit weights (6,000-7,000 pounds)

- The flow-through bearing package version of the turbodrill cannot be successfully run on water or water base mud of the quality typically found at drill sites

- The present turbodrill design will probably not perform for the extended periods of time required to drill long methane drainage boreholes on the order of 1,000 to 2,000 feet into shallow coal seams

- The objectives of Phase II of the test project were only partially accomplished. The only significant data obtained were indications of potential drilling rates.

Based on these conclusions, it is recommended that the formal Turbodrill Testing Project be terminated at this time. Performance of the MEI turbodrill to date does not warrant expending additional government effort in further field testing until bearing seals are developed and demonstrated to be effective when drilling with moderate amounts of mud solids.

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1. INTRODUCTION

1.1 BACKGROUND

The DOE is engaged in many efforts to increase resource recovery and supplies of fossil energy. At METC, one of these is directed toward exploring use of downhole drilling motors and directional drilling techniques to improve efficiency and reduce costs of drilling to recovery methane contained in coal. The application is to place long methane drainage boreholes in horizontal coalbeds in advance of active mining operations (or possibly in unmined or steeply dipping coal seams). A major advantage in using downhole drilling motors is significantly increased penetration rates compared to conventional, rotary drilling techniques. Another major advantage of downhole drilling motors is reduction of friction between drill string and wellbore through minimum rotation requirements, especially in drilling directional wells. This can result in less rig trip time and smoother drilling operations because of reduced possibilities of twisting off drill pipe or wearing holes in casing.

1.2 THE TEST PROJECT

The Test Project was established to test the Maurer Engineering (MEI) 5-3/8-inch turbodrill as part of the ongoing drilling technology development effort at DOE/METC, and is an integral part of the ongoing DOE/TRW Methane Recovery from Coalbeds Project. The scope and detailed objectives of the Test Project are discussed in Section 2. The overall goal of the Test Project was to demonstrate applicability of the turbodrill for drilling long, horizontal methane drainage boreholes in coal seams at depths to 1,000 feet, which appears consistent and attainable with today's directional drilling technology. The boreholes will be designed to be drilled vertically at the surface and deflected horizontally at coal seam depth.

The Test Project was divided into distinct steps or elements and structured in the following phases:

<u>Phase I</u>

The primary objective of this phase was to determine baseline performance profiles at zero applied bit-end

pressure drops and with no axial thrust loads (weight-on-bit (WOB) force) applied to the motor. Bench testing in Phase I was performed in a horizontal, aboveground test mode, using the clean drilling mud circulation system at TRW Mission Manufacturing Company in Houston, TX. Preliminary indications of wear on internal parts were to be ascertained from the test. Bit-end pressure drops were not applied in Phase I testing because pressure seals that could tolerate sustained elevated pressure drops of 500 to 1000 psi were unavailable. Axial loading was not considered in Phase I because no equipment was available to conveniently perform that function. The test was performed in a horizontal mode because it was relatively quick and inexpensive, and met the requirements for generating baseline performance data.

Phase II

Phase II testing was performed to evaluate the effects of conditions not applied in Phase I (vertical position, axial/thrust loads, and elevated bit-end pressure drops). Phase II was a controlled field test performed on a drilling rig at Gearhart-Owen Industries' test site located at their wireline crew training facility in Fort Worth, TX. The formations encountered in drilling at this site have been penetrated numerous times for training purposes, and data on straight-hole drilling rates using conventional, rotary drilling equipment were to be made available to evaluate turbodrill performance. A distinct advantage to this site was that downhole geology was known *a priori* to minimize potential hole problems.

Phase III

Phase III drilling technology testing is directed specifically at the coalbed methane resource. Phase III requires drilling a directional well from vertical at the surface to horizontal in a coalbed at depth (or in a steeply dipping coal seam). The site will be selected to reflect methane drainage drilling conditions evident in more rugged field applications.

1.3 PHASE I TESTING

The purpose of Phase I testing was to determine performance and wear characteristics of the MEI 5-3/8-inch turbodrill in an aboveground, bench testing mode. Specific objectives of Phase I testing were:

- Determine performance characteristics; i.e., turbodrill speed, torque, and power as functions of mud flow rate, inlet pressure, and pressure drop across the turbodrill.

- Ascertain wear characteristics experienced in rotary operation under simulated torque conditions in bench tests.
- Determine the leakage rates of drilling fluid at different bit-end pressure drops through the bearing package.
- Acquire data for determining reliability and component service life expectancies.

Both the sealed bearing pack and flow-through versions were tested during pre-Phase I shakedown runs. Difficulties were experienced continually with integrity of the pressure seals at the bit-end of the sealed bearing pack turbodrill. These problems proved insurmountable, and only the flow-through bearing pack turbodrill was used in this phase of the testing project.

The baseline performance data obtained in Phase I testing provided performance characteristics against which the data resulting from subsequent well drilling tests could be assessed. Final Report-Turbodrill Testing Project-Phase I was published in July 1980 and contains test data preliminary to Phase II.

1.4 TURBODRILL DESIGN

The turbodrill consists of a turbine section and a separate bearing package, as shown in Figure 1-1. The driving fluid is drilling mud or water. All blades and vanes are contained in the turbine pack, and all bearings (both thrust and radial) are housed in the bearing pack. The turbine package contains 50 stages of blades and vanes. The bearing package comes in two versions: a sealed bearing pack for drilling with muds containing solids, and a flow-through pack for use primarily with water as the drilling fluid. The sealed bearing pack configuration is designed for directional and straight-hole drilling in conventional oil and gas fields. The flow-through bearing pack version, shown in Figure 1-1, is designed for use with water as the drilling fluid in geothermal applications and in coal seam methane drainage directional drilling. Water passing through the bearing section is intended to cool and lubricate the bearings. In addition, the flow-through bearing package may offer the advantage of longer service intervals compared to the sealed bearing package when drilling in formations where water can be used as the drilling fluid.

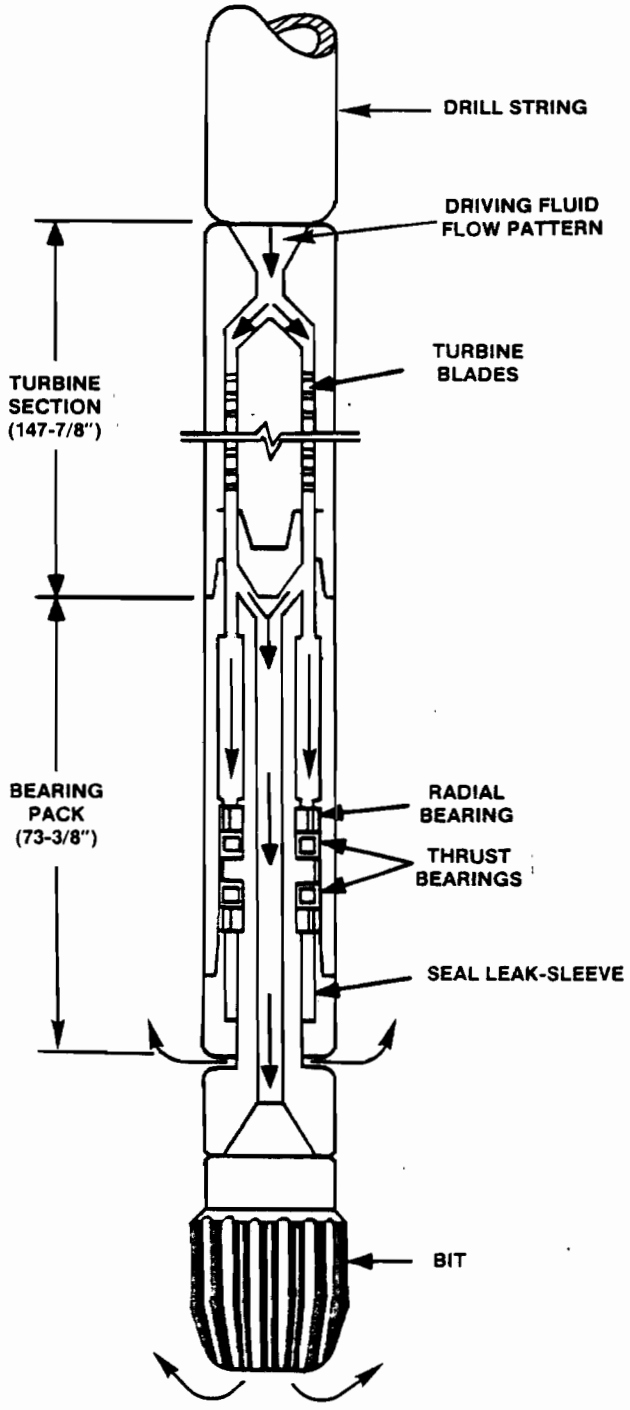


Figure 1-1. Cross Section of Turbodrill Flow-Through Bearing Package

There are two major pressure drops in the turbodrill: one across the stage assembly of blades and vanes in the turbine section (to overcome resistance to rotation, counteract fluid friction, and provide power); and the other in the bearing package across the seal leak-sleeve or pressure seal assembly at the bit-end. The bit pressure drop depends upon the pressure drop across the front-end of the turbodrill. The bit pressure drop is important for proper bottomhole hydraulic cleaning of cuttings from the rock face by counteracting chip hold-down.

During typical drilling operations, WOB or downward hydraulic thrust force is transmitted to the bearings via the rotor shaft and axial compression spacer rings mounted on the shaft. There are seven such spacers, three sets of radial roller bearings, and two sets of roller thrust bearings. The bearing pack is designed to maintain a thrust bearing preload to take advantage of the hydraulic downthrust of the turbine in counteracting the upward-acting, bit-reaction force on the bearings, which can result in less dynamic load on the thrust bearings. The nature of these forces was discussed in the Turbodrill Testing Project Phase I Final Report. Final Report-Turbodrill Testing Project-Phase I was published in July 1980 and contains test data preliminary to Phase II. The net effect is that considerably greater weights can be applied to the bit to increase penetration rates while maintaining relatively lower loads on the bearings themselves. The preload also serves to eliminate roller bearing "chatter" when temporarily operating under low- or no-load conditions, for example, at startup. The bearings themselves offer insignificant resistance to rotation and are commercial, off-the-shelf items.

2. TEST PLANNING

2.1 SCOPE OF PHASE II TESTING

In this report, Phase II includes all field testing of the 5-3/8-inch turbodrill including preliminary tests and formal testing at Gearhart-Owen Industries.

The scope of Phase II of the test project is defined by the following:

- Phase II testing and the preliminary field tests represent the first attempts to determine performance characteristics of the MEI 5-3/8-inch turbodrill in drilling application.
- The testing reported herein does not constitute qualification testing or any performance verification effort.

All activities connected with official Phase II testing were governed by the Test Plan appearing in Appendix A.

2.2 OBJECTIVES

Objectives of Phase II testing were:

- Determine drilling rates (drill bit penetration rates) as functions of bit weight (vertical force applied to the bit) and mud flow rates through the turbodrill.
- Demonstrate operational compatibility of the turbodrill in the field with roller-cone bits, conventional diamond bits, and STRATAPAX bits, and evaluate bit performance.
- Ascertain wear characteristics of critical parts in downhole operation under axial thrust and radial load conditions for use in determining component service-life expectancies (time intervals between required tool repairs and/or changeovers).
- Gain field experience in using the 5-3/8-inch turbodrill on a drilling rig to aid operators in optimizing application of turbodrills.

3. TEST FACILITY AND EQUIPMENT

The drilling rig and test facilities were provided by Gearhart-Owen under a TRW subcontract. Maurer Engineering provided drill bits, instrumentation, and the test equipment described in the Phase II Test Plan. A schematic of the type of drilling rig provided by Gearhart-Owen appears in Appendix A, Figure 3-1. A schematic diagram of the mud circulation system on the test site is presented in Figure 3-1. The turbodrill was installed in the downhole assembly as shown in Appendix A, Figure 3-2.

In Figure 3-1, the path of mud flow through the circulation/conditioning/cleaning system can be traced, with pumping power at the test site provided by a Dowell pump truck. Coarse drill cuttings were removed from the mud returning from the well in a 20-40 mesh shale shaker. Settling of larger remaining solid particles took place in the mud pits before the mud was further cleaned by means of the desander/desilter and fine-screen (80-100 mesh) shale shaker mounted atop the mud tank in Figure 3-1. The desilter/desander unit was a Tri-Flo Industries International model with 12 cyclone cones and a maximum rated capacity of 1,200 gallons per minute. A high capacity centrifugal pump was used to charge the desander/desilter unit. The mud processing equipment was arranged so that primary effluent from the desander/desilter flowed to the inlet of the fine-screen shale shaker. From the fine-screen shale shaker, the mud stream was conveyed into the aft compartment of the mud tank and allowed to empty into the mud pit to be recirculated.

The well selected at the Gearhart-Owen site for running downhole tests of the turbodrill had 118 feet of 10-3/4-inch surface conductor cemented in place to protect local surface aquifers and was open hole (9-7/8-inch diameter) from 118 feet to total depth of 650 feet.

The test site mud had a viscosity range of 33 to 60 Marsh funnel seconds and a weight that varied from 8.8 to 9.2 pounds per gallon with an average of 9.0 pounds per gallon. The mud was a water base MAGCOGEL bentonite mud (no barite) with some tannic acid and caustic soda to aid in depositing the required filter cake on the wellbore for hole control.

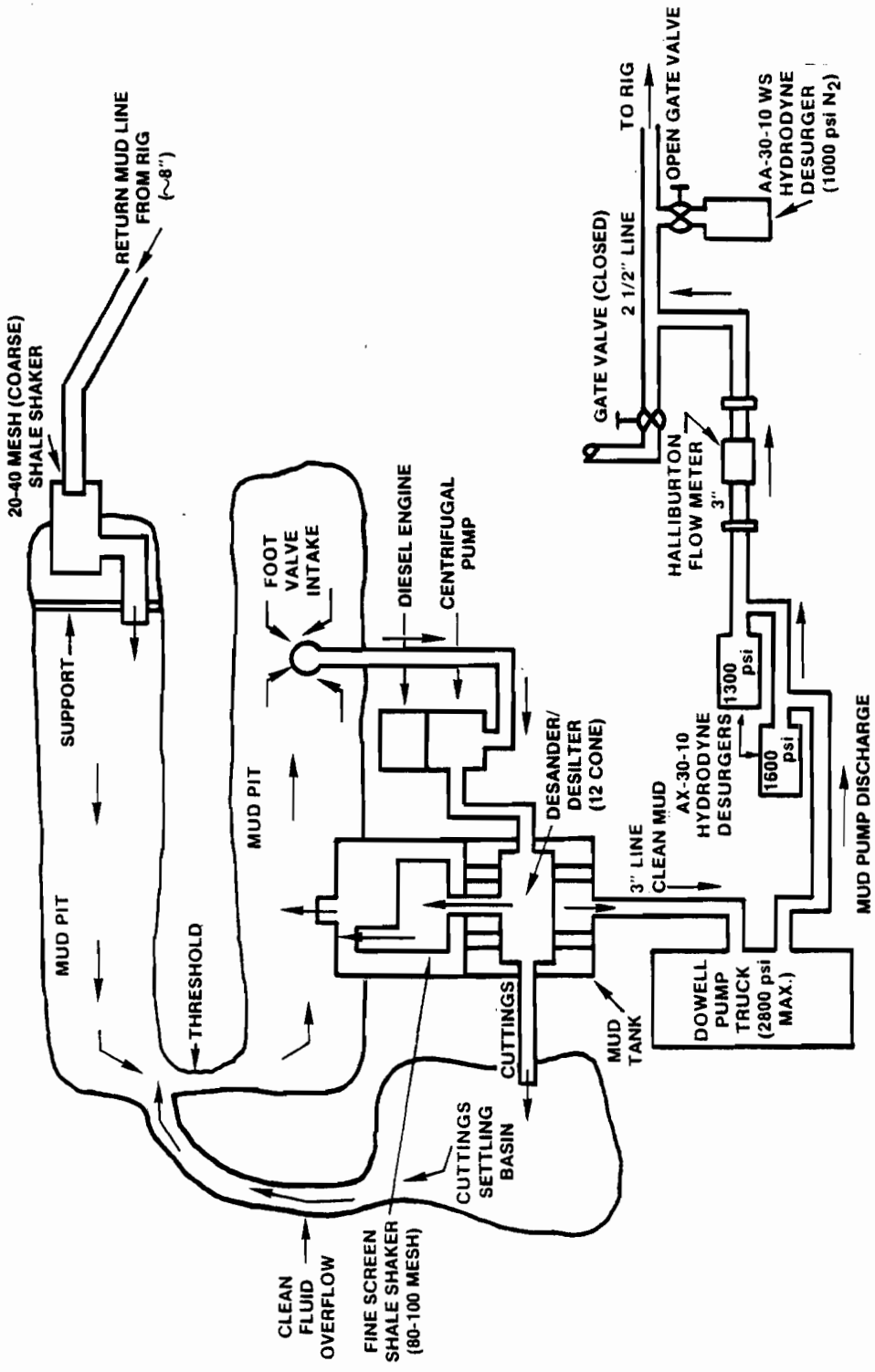


Figure 3-1. Mud Circulation System at Gearhart-Owen Facility

Three Hydrodyne bladder accumulators (desurgers) were installed in the flow line from the Dowell pump truck to the rig (as shown in Figure 3-1) to dampen mud pump surges. The desurgers were charged with nitrogen to 1,600, 1,300, and 1,000 psi, respectively, moving from the pump truck to the rig. They were required to suppress the cyclic flow pulses from the drive pump to preclude the pump flow pulses from overriding the mud pulses returning from the downhole tachometer.

4. PRE-PHASE II TESTING

4.1 BACKGROUND

The recommendation was made in the Phase I Final Report that before proceeding into Phase II testing, a tachometer unit be developed to monitor turbodrill rotary speed downhole. This would help avoid overspeeding of the turbodrill, extend drill bit life, detect stall conditions to keep the bit and motor from becoming stuck in the hole, better match bit weight and rotary speed for stable operation, and maximize rate-of-penetration (ROP) for a truer indication of turbodrill potential drilling performance. Shakedown testing of the tachometer could have been conducted with resumption of formal Phase I testing. However, an opportunity arose to perform these tests in a vertical drilling rig simulator (test tower) at the Terra Tek Drilling Research Laboratory in Salt Lake City, UT, before proceeding into testing on a drilling rig. The management decision was made, therefore, to end Phase I and proceed directly into pre-Phase II activities at Terra Tek. Pre-Phase II testing was not included in the original test activities planned for Phase II; these were shakedown efforts and not guided by the formal Test Plan in Appendix A.

4.2 OBJECTIVES

The objectives of pre-Phase II testing were to (1) check out the design modifications incorporated in the turbodrill as a result of Phase I testing (discussed in the Phase I Final Report); (2) obtain an indication of prototype tachometer performance, and (3) provide turbodrill performance data when drilling through hard granite with a roller bit and in a softer limestone using a Christensen STRATAPAX bit. The reason the STRATAPAX bit was not used in granite was that the material was considered too hard and abrasive for the bit cutting elements. The Phase II objectives did not include evaluating drill bit performance *per se*, since this would require a far more extensive test program than that considered here. Furthermore, bit performance cannot be separated from turbodrill performance when considering only rate-of-penetration results. However, turbodrill performance can be

considered separately because the test procedure is designed to provide the required data to do so. For that reason, data analysis and results on turbodrill performance characteristics in pre-Phase II are presented in this section and compared to those obtained earlier in Phase I. In addition, drill motor vibration data were obtained and spectrum analyses performed on site by Sperry Rand Research Center personnel to determine drive pump fluid pulsation characteristics and to indicate the feasibility of developing a tachometer device to be installed in the motor used in later Phase II testing.

4.3 TESTING AT TERRA TEK

The 5-3/8-inch turbodrill was tested at Terra Tek's Drilling Research Laboratory in Salt Lake City, UT, from April 6, to 11, 1979. The 5-3/8-inch turbodrill, intended primarily for placing methane drainage wells in coal seams, was used to drill both granite and a limestone material. The motor incorporated a Belleville spring thrust bearing race support modification made following the last test of the motor in Phase I. In addition, the turbodrill had the first stage of blades and vanes partially blanked off to produce driving fluid pulsations to aid in the development of a simple downhole tachometer for subsequent field testing (discussed in Section 4.6). No significant increase in average pressure drop across the turbine due to the tachometer unit was registered during an initial, shakedown test performed earlier by MEI at their facility.

A potential problem of downhole speed control became evident during testing of the 5-3/8-inch motor at Terra Tek. Rotary speed was very sensitive to applied bit weight. Since the MEI turbodrill does not contain any gear arrangements or other speed reduction devices, drill bit rotary speed is the same as that of the turbine itself, and no distinction is made between the two in this report. The Terra Tek hydraulic control system for applying bit weight has a high degree of sensitivity that probably exceeds control capability found on conventional drilling rigs. This increases the necessity for a reliable means to determine when the turbodrill breaks away and the speed at which it is turning.

The previously mentioned rock samples were positioned in a test pit below the test tower. The granite sample was "Texas Pink", and the limestone

sample was Carthage marble. Turbodrill driving fluid was circulated by a Continental-EMSCO Company, model FA-1600 triplex pump from a 5,500-gallon water tank. The tests were conducted with the exterior of the motor at atmospheric pressure. However, a special housing was affixed to the top of the rock samples to allow a bit pressure drop of approximately 300 psi while drilling. The tungsten-carbide jet nozzle inserts were not installed in the roller bits to downgrade bit pressure drops to this level in these tests.

The tri-cone roller bit used in granite was a standard oilfield hard-formation type. The bit was a Smith Tool F-9 hard-formation bit (7-7/8-inch diameter with tungsten-carbide inserts ("buttons") and solid journal bearings). The roller bit exhibited only moderate wear during the test. The Christensen 7-7/8-inch diameter STRATAPAX bit with piggyback stabilizer was used to drill in the Carthage marble sample. The Christensen STRATAPAX bit used in the limestone sample sustained some damage in the test--the inner two rows of disks were nearly destroyed. The reason for damage to the STRATAPAX bit could have been a combination of overspeed and/or vibration. The chips produced with both bits were predominantly the size of fine gravel (approximately 3/32-inch in diameter).

4.4 PRE-PHASE II TEST DATA

The test data were obtained on Terra Tek's automated data collection system. This system employed transducers and sensors to measure test variables, a mini-computer to process the data, and automatic equipment to print out data. Rotary speed data were obtained by means of a direct-drive belt/pulley and galvanometer device. The belt was driven by the rotating bit-end of the turbodrill in the test pit. On the average, data were recorded every two to three seconds from the start of a test run. A total of 891 data records were obtained in this manner on the 5-3/8-inch turbodrill at Terra Tek. These data were screened and a representative set of 272 data records was selected for analysis on the basis of being within ± five percent of flow rates that could be compared to previous data reported in the Phase I Final Report. These data are presented in Appendix B of this report.

4.5 DATA ANALYSIS AND RESULTS

The 5-3/8-inch turbodrill was run on water in the vertical test tower for three hours, eight minutes, during which time a total of 891 data sets was obtained. From these, the 272 records in Appendix B were selected for analysis. Results of the analysis are presented in Table 4-1. Data used in calculating these results were further screened to be representative of those in Appendix B and to minimize redundancy, yet exhibit salient features of the turbodrill performance characteristics. The data contain information on the performance of the turbodrill itself, as well as an indication of the performance of particular drill bits used in combination with the turbodrill. The data were analyzed with respect to both aspects (turbodrill and turbodrill with bit) since they are equally important in field operations. The drilling performance data are limited, however, because only two types of bits were used in two types of rock.

Drilling Performance

Examination of the data obtained and observations made during the test indicated that the motor drilled through rock samples at average penetration rates of 30 to 50 feet per hour. Rate-of-penetration data for the 5-3/8-inch turbodrill are presented in Figure 4-1. The data sets used in Figure 4-1 were selected from Table 4-1 on the basis of being representative and within ± five percent on both required flow rates and rotary speeds. Recorded WOB ranged up to 31,000 pounds on the 5-3/8-inch tool. Speed values ranged up to 750 rpm with startup excursions beyond 2,000 rpm; however, some difficulty was experienced in attempting to maintain a constant rotary speed.

The conclusions drawn from the data in Figure 4-1 are that (1) ROP's for both bits and rock types are very sensitive to WOB, as in conventional drilling; and (2) increasing the rotary speed by reducing WOB while increasing the pump rate results in reduced ROP of the STRATAPAX bit in limestone. No conclusion can be drawn from performance of the STRATAPAX bit versus that for the roller-cone bit because of differences in rock type, hardness, and abrasiveness.

Turbodrill Performance

Performance of the 5-3/8-inch MEI turbodrill at Terra Tek appears consistent with previous bench (Phase I) and shakedown testing. Pressure

Table 4-1. Phase II Data Analysis Results

Rock/Bit Type Nominal Flow Rate	Flow Rate gpm	Rotary Speed rpm	Pressure Drop* psi	Output Torque ft-lb	Mechanical Power Out hp	Hydraulic Power In hhp	Overall Efficiency Power Out/ Power In	WOB lb	ROP ft/hr
Limestone/STRATAPAX (100 gpm)	103	357	275	102	6.9	16.5	0.42	673	4.8
	96	504	279	66	6.3	15.6	0.40	-	-
	101	620	240	52	6.1	14.2	0.43	757	4.9
	101	499	319	67	6.4	18.8	0.34	371	2.6
	97	654	316	54	6.4	17.9	0.37	489	2.3
	95	600	248	55	6.3	13.8	0.46	351	2.6
	97	630	307	61	7.3	17.4	0.42	698	3.0
Limestone/STRATAPAX (150 gpm)	150	251	524	247	11.8	45.9	0.26	1784	4.1
	152	1	457	237	0.1	40.5	0.00	1861	1.6
	143	187	454	159	5.7	37.9	0.15	1291	11.5
	150	152	466	167	4.8	40.8	0.12	1371	8.8
	145	226	471	159	6.8	40.0	0.17	3198	16.1
	151	499	579	164	15.6	51.0	0.31	3767	13.0
	152	389	590	187	13.9	52.3	0.27	3932	14.2
	152	683	522	133	17.3	46.3	0.37	852	4.3
Limestone/STRATAPAX (200 gpm)	205	104	854	402	8.0	102.	0.08	2041	7.1
	203	220	951	421	17.6	113.	0.16	1996	7.4
	210	488	1022	370	34.4	125.	0.27	1504	4.0
	200	438	882	370	30.9	103.	0.30	2450	22.2
	197	110	725	258	5.4	83.3	0.06	1712	10.0
	194	155	826	287	8.5	93.5	0.09	5182	19.1
	190	514	662	192	18.8	73.4	0.26	690	0.4
	191	517	868	267	26.3	96.7	0.27	283	14.4
	206	495	966	309	29.1	116.	0.25	510	15.4

*Difference in pressure across turbodrill - between inlet to turbodrill and outlet at water return line connection.

Table 4-1. Phase II Data Analysis Results (Continued)

Rock/Bit Type Nominal Flow Rate	Flow Rate gpm	Rotary Speed rpm	Pressure Drop psi	Output Torque ft-lb	Mechanical Power Out hp	Hydraulic Power In hhp	Overall Efficiency Power Out/ Power In	WOB lb	ROP ft/hr
Limestone/STRATAPAX (250 gpm)	258	274	1616	670	35.0	243.	0.14	2203	13.6
	253	430	1452	527	43.1	214.	0.20	3615	37.1
	259	448	1547	563	48.0	234.	0.21	3680	37.8
	260	485	1633	587	54.2	248.	0.22	3680	38.3
	262	482	1709	614	56.3	261.	0.22	3883	32.8
	262	480	1714	614	56.1	262.	0.21	3986	33.2
	261	480	1741	621	56.8	265.	0.21	4028	38.8
	262	485	1758	625	57.7	269.	0.21	4048	38.1
	261	474	1762	620	56.0	268.	0.21	4063	37.1
	261	470	1727	622	55.7	263.	0.21	4054	40.1
	261	459	1736	614	53.7	264.	0.20	4160	41.3
	249	234	1358	467	20.8	197.	0.11	1391	6.8
	250	251	1422	491	23.5	207.	0.11	1353	7.6
	257	269	1489	514	26.3	223.	0.12	1309	8.1
	259	270	1569	538	27.7	237.	0.12	1459	8.5
	241	542	1308	421	43.4	184.	0.24	1020	18.7
	245	559	1399	443	47.1	200.	0.24	1146	19.7
	252	551	1471	468	49.1	216.	0.23	1297	20.6
	254	558	1567	495	52.6	232.	0.23	1565	21.5
	261	575	1654	518	56.7	252.	0.23	1801	22.4
Limestone/STRATAPAX (300 gpm)	288	570	2072	663	72.0	348.	0.21	1621	26.6
	295	567	2179	695	75.0	375.	0.20	1659	27.2
	298	590	2252	715	80.3	392.	0.21	1695	27.7

Table 4-1. Phase II Data Analysis Results (Continued)

Rock/Bit Type Nominal Flow Rate	Flow Rate gpm	Rotary Speed rpm	Pressure Drop psi	Output Torque ft-lb	Mechanical Power Out hp	Hydraulic Power In hhp	Overall Efficiency Power Out/ Power In	WOB lb	ROP ft/hr
Limestone/STRATAPAX (300 gpm)	302	581	2341	736	81.4	413.	0.20	1739	28.2
	306	605	2395	760	87.5	428.	0.20	1766	28.5
	305	599	2451	776	88.5	436.	0.20	1842	28.8
	306	573	2458	786	85.8	439.	0.20	1925	29.0
	305	583	2442	788	87.5	435.	0.20	1881	29.2
	303	596	2455	778	88.3	434.	0.20	1966	29.4
	303	461	2447	780	68.5	433.	0.16	1913	29.5
	305	186	2452	784	27.8	436.	0.06	1901	29.7
	305	28	2440	784	4.2	434.	0.01	1863	29.8
	306	8	2466	790	1.2	440.	0.00	1786	29.9
Granite/Roller-Cone (150 gpm)	145	378	486	91	6.5	41.1	0.16	3862	0.4
	148	417	530	108	8.6	45.8	0.19	6462	0.6
	147	383	530	118	8.6	45.5	0.19	6521	0.7
	145	319	525	135	8.2	44.4	0.18	7114	0.9
	149	215	507	132	5.4	44.1	0.12	6498	1.0
	152	232	501	137	6.1	44.4	0.14	6347	1.1
	152	255	522	153	7.4	46.3	0.16	6462	1.2
	152	231	520	149	6.6	46.1	0.14	6840	1.3
	151	248	532	158	7.5	46.9	0.16	7238	1.5
	145	140	469	109	2.9	39.7	0.07	5374	1.6
	154	350	529	132	8.8	47.5	0.19	6424	1.7
	146	443	512	160	13.5	43.6	0.31	6750	13.1
	146	595	512	149	16.9	43.6	0.39	7178	15.1

Table 4-1. Phase II Data Analysis Results (Continued)

Rock/Bit Type Nominal Flow Rate	Flow Rate gpm	Rotary Speed rpm	Pressure Drop psi	Output Torque ft-lb	Mechanical Power Out hp	Hydraulic Power In hhp	Overall Efficiency Power Out/ Power In	WOB lb	ROP ft/hr
Granite/Roller-Cone (150 gpm)	152	483	539	196	18.0	47.8	0.38	8320	13.7
	144	520	487	163	16.1	40.9	0.39	7142	4.4
Granite/Roller-Cone (200 gpm)	191	212	827	280	11.3	92.2	0.12	12,869	1.8
	197	35	787	219	1.5	90.5	0.02	8352	3.0
	197	13	1004	206	0.5	115.	0.00	11,778	3.0
	195	343	856	359	23.4	97.4	0.24	14,750	13.6
	197	519	941	365	36.1	108.	0.33	15,497	14.3
	210	357	1017	466	31.7	125.	0.25	20,131	16.1
	210	310	1024	464	27.4	126.	0.22	19,901	16.9
	194	544	858	314	32.5	97.1	0.33	13,983	5.7
	197	441	871	372	31.2	100.	0.31	16,838	6.1
	206	423	939	406	32.7	113.	0.29	16,196	7.0
	198	419	951	412	32.9	110.	0.30	16,182	7.6
	207	261	927	430	21.4	112.	0.19	16,303	8.1
Granite/Roller-Cone (250 gpm)	239	67	1277	593	7.6	178.	0.04	22,358	6.5
	251	211	1414	618	24.8	207.	0.12	24,579	30.2
	258	741	1540	562	79.3	232.	0.34	24,225	40.7
	257	316	1521	614	36.9	228.	0.16	25,113	37.7
	240	547	1424	568	59.2	199.	0.30	23,374	50.1
	241	438	1419	534	44.5	200.	0.22	21,170	37.0
	241	410	1359	533	41.6	191.	0.22	20,307	38.0
	243	309	1348	548	32.2	191.	0.17	21,226	38.0
	253	509	1457	540	52.3	215.	0.24	21,832	37.8

Table 4-1. Phase II Data Analysis Results (Continued)

Rock/Bit Type Nominal Flow Rate	Flow Rate gpm	Rotary Speed rpm	Pressure Drop psi	Output Torque ft-lb	Mechanical Power Out hp	Hydraulic Power In hhp	Overall Efficiency Power Out/ Power In	WOB lb	ROP ft/hr
Granite/Roller-Cone (250 gpm)	254	338	1466	599	38.5	217.	0.18	22,532	37.9
	258	256	1481	649	31.6	223.	0.14	23,442	38.0
	261	469	1512	597	53.3	230.	0.23	23,315	38.0
	261	274	1523	639	33.3	232.	0.14	23,675	38.2
	261	378	1527	621	44.7	233.	0.19	23,395	38.3
	238	141	1164	497	13.3	162.	0.08	21,403	35.1
	239	191	1200	487	17.7	167.	0.11	22,502	42.4

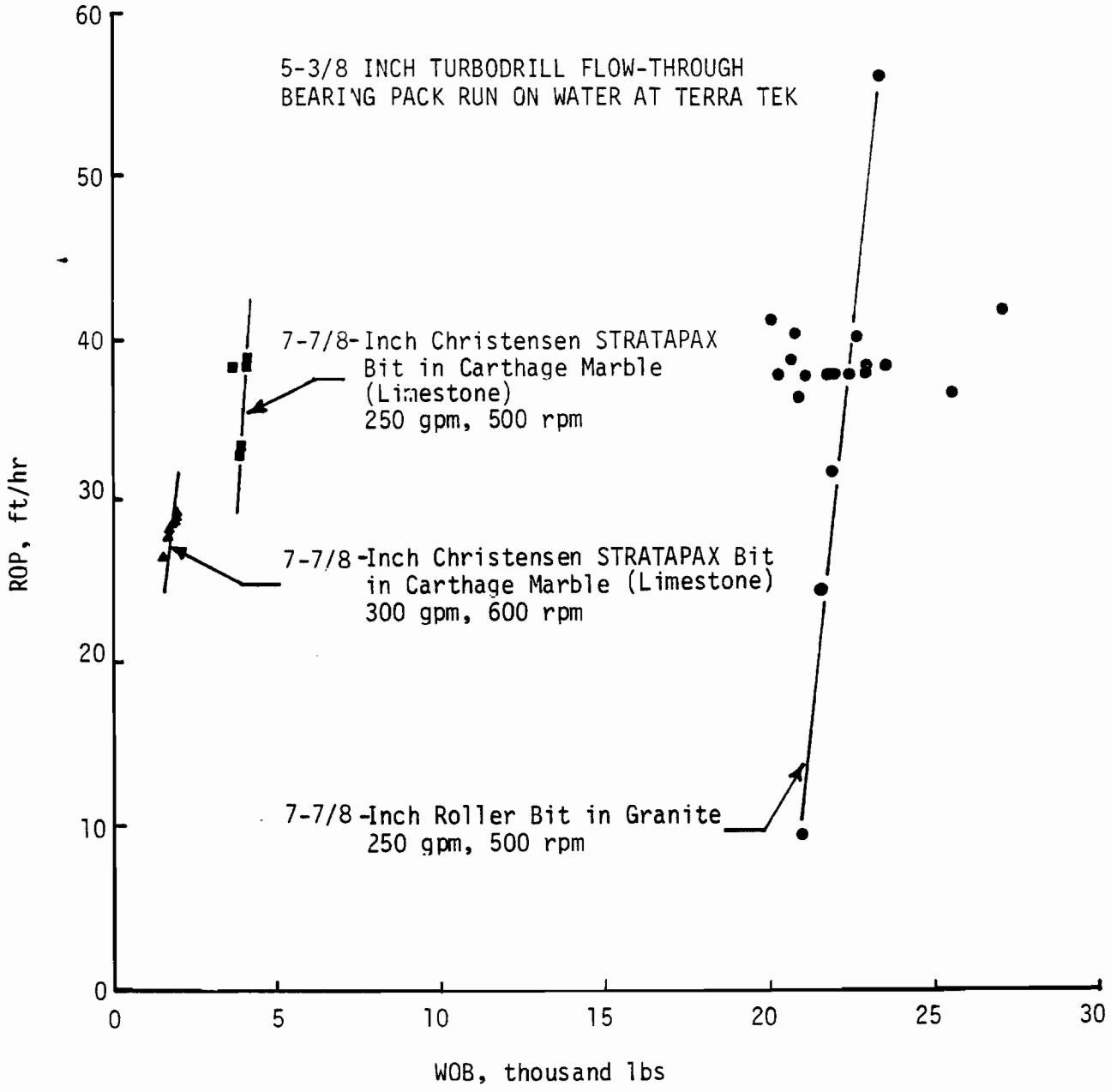


Figure 4-1. Drilling Performance of MEI 5-3/8 Inch Turbodrill at Terra Tek Drilling Research Laboratory

drops across the turbine section ranged up to 2,000 psi as before. Torque responses of the turbodrill are presented in Figure 4-2. Plotting the 272 torque data points in Table B-1 (in Appendix B) revealed a considerable amount of scatter compared to previous test results, the ranges of which are represented by the vertical brackets in Figure 4-2. The significant feature of the pairs of torque curves in Figure 4-2 is that in each case the measured torques were considerably higher at corresponding pump rates compared to previous data obtained in Phase I because of more balanced thrust bearing loads from the application of bit weight. Phase I test results can be found in the Final Report-Turbodrill Testing Project-Phase I published in July 1980. Bit weight application was not simulated in Phase I because the required equipment to apply axial loads to the drill motor was not available.

The data obtained at flow rates of 250 and 300 gpm were selected for further analysis to allow comparison to previous test results from Phase I and shakedown bench tests. A comparison of turbodrill performance at representative operating conditions obtained in the several tests conducted with this motor is presented in Table 4-2. The turbodrill performance characteristics in Figures 4-3 and 4-4 were obtained from the results in Table 4-1. The values of mechanical power output, hydraulic power input, and turbodrill overall efficiency appearing in Table 4-1 were calculated from the raw data in Appendix B, using the following standard equations for rotating hydraulic machinery:

$$\text{Power Out} = \frac{2\pi}{33{,}000} \times (\text{Torque}) \times (\text{Rotary Speed}) \text{ in horsepower, hp}$$

$$\text{Power In} = \frac{1}{1714} \times (\text{Flow Rate}) \times (\text{Total Pressure Drop Across Turbodrill}) \text{ in hydraulic horsepower, hhp}$$

$$\text{Overall Efficiency} = \frac{\text{Power Out}}{\text{Power In}}$$

The torque curves in Figures 4-3 and 4-4 are identical to the corresponding curves in Figure 4-2. The torque values are considerably higher at corresponding speeds and flow rates in this test compared to Phase I due to relief of the thrust bearing pre-load with application of bit weight and, therefore, more balanced loading on the thrust bearings and less resistance to rotation. The total pressure drops across the turbodrill (ΔP_T) shown in Figures 4-3 and 4-4 indicate ΔP_T to be virtually independent of

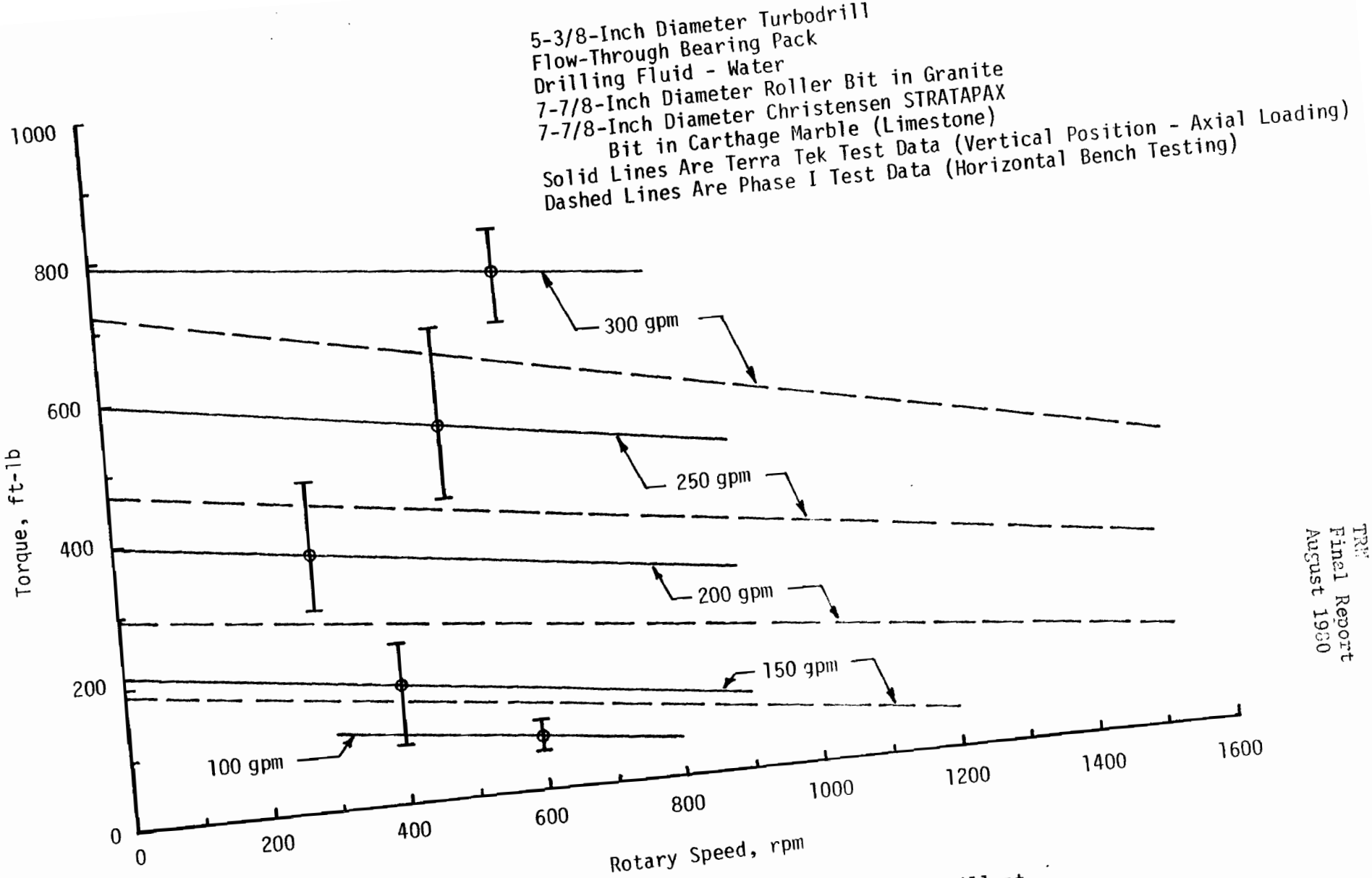
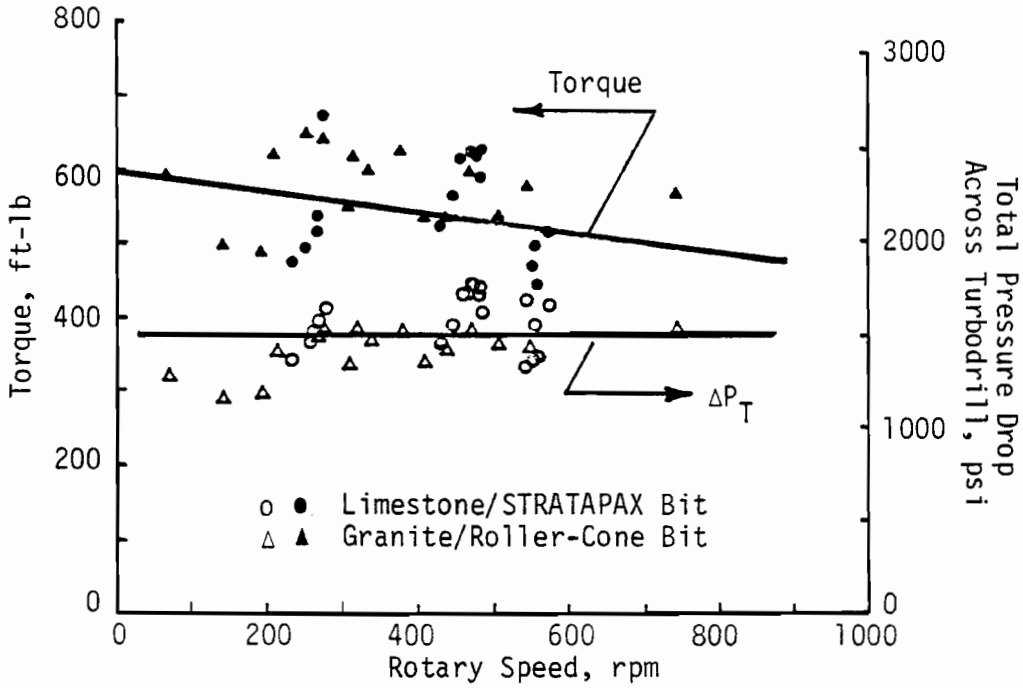


Figure 4-2. Torque Responses of MEI 5-3/8-Inch Turbodrill at Terra Tek Facility in Comparison with Phase I Test Data

Table 4-2. Comparison of Flow-Through Bearing Package Turbodrill Performance to Design Values

		Flow Rate gpm	Rotary Speed rpm	Pressure Drop Across Turbodrill psi	Output Torque ft-lb	Power Output hp	Efficiency Power Out/Power In
Design Values	Roller-Cone Bits	250	200	377	867	33	0.60
	Diamond Bits	250	800	872	501	76	0.60
Shakedown Bench Test No. 5 (Run on Water)		251	192	1030	486	18	0.12
		249	788	1200	377	57	0.32
Phase I Bench Test (Run on 9.35 ppg mud)		250	197	960	461	17	0.12
		252	807	1180	372	57	0.33
Pre-Phase II (Run on Water)(Limestone/STRATA-PAX Bit)		249	234	1358	467	21	0.11
		261	575	1654	518	57	0.23
Pre-Phase II (Run on Water)(Granite/Roller Bit)		251	211	1414	618	25	0.12
		258	741	1540	562	79	0.34



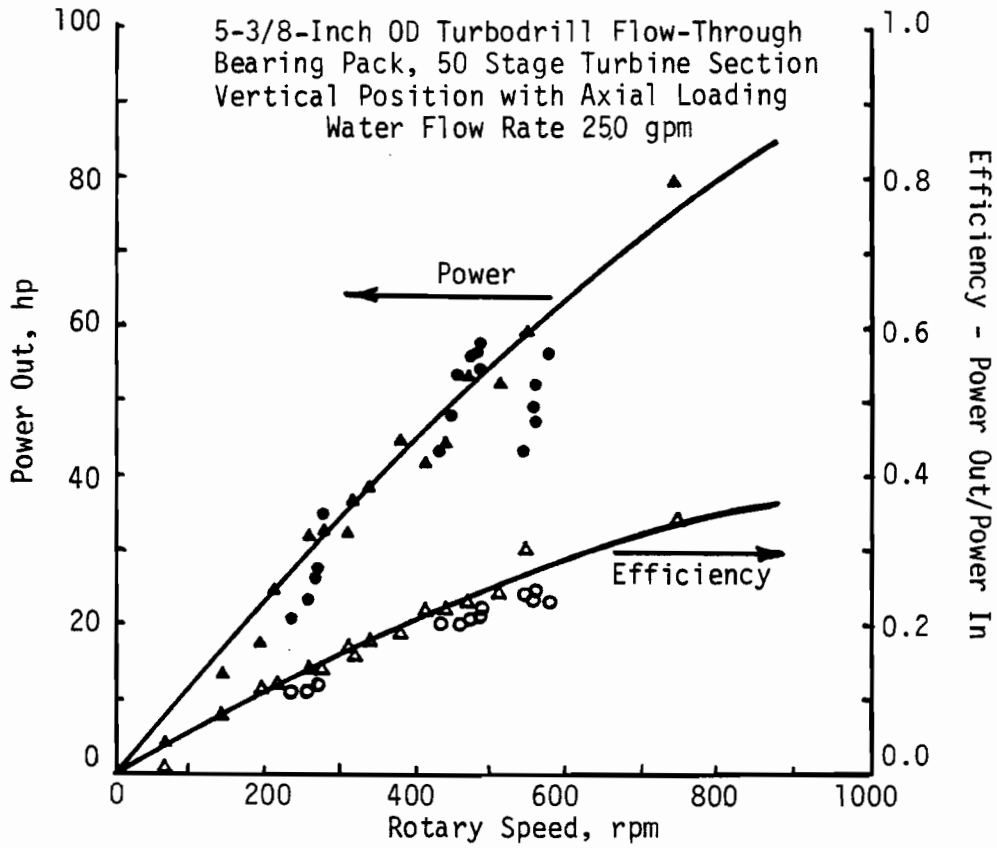
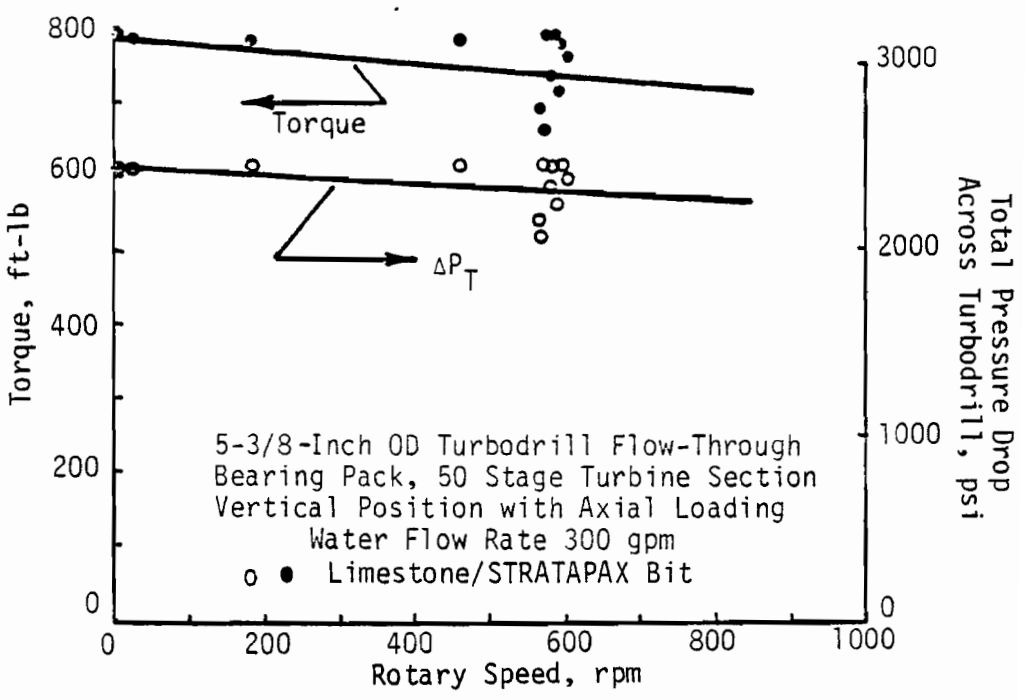


Figure 4-3. Turbodrill Performance Characteristics--Pre-Phase II--250 gpm Water Flow Rate--Drilling in Limestone and Granite



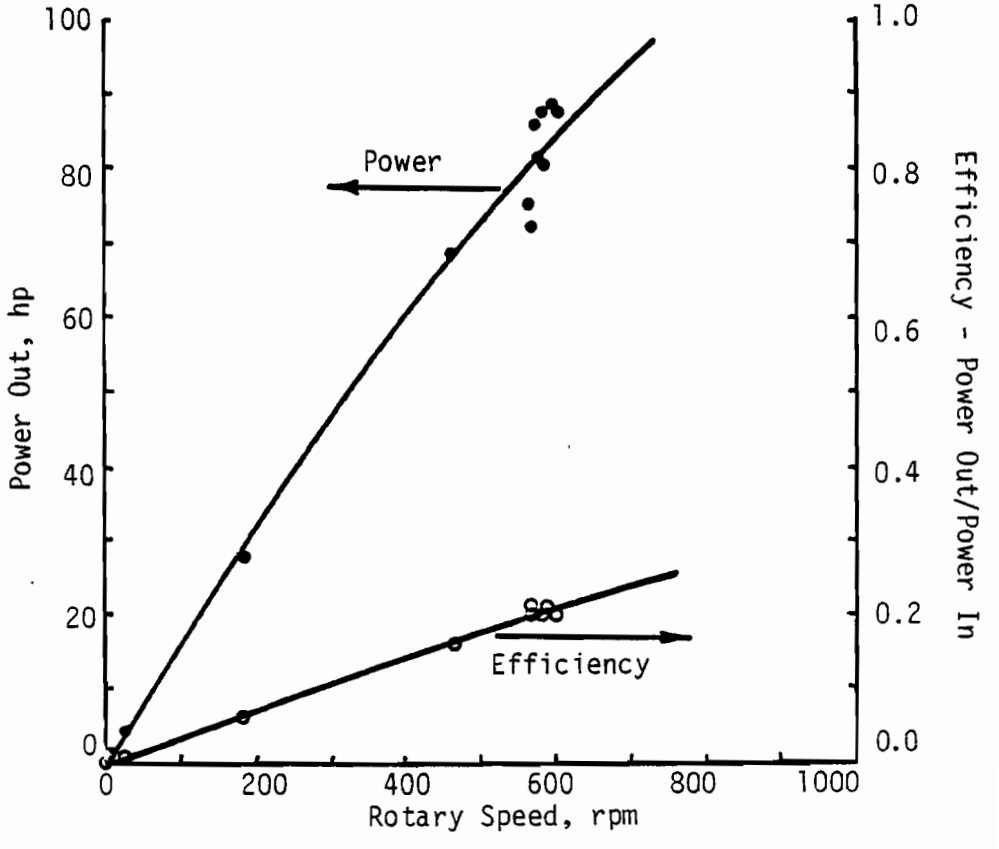


Figure 4-4. Turbodrill Performance Characteristics--Pre-Phase II--300 gpm Water Flow Rate--Drilling in Limestone With STRATAPAX Bit

rotary speed for a given flow rate as in the bench tests reported earlier in the Phase I Final Report.

The power developed by the turbodrill with the application of bit weight at corresponding values of rotary speed is also higher than Phase I values because of higher developed torques. The overall efficiency values, however, remain approximately the same as those obtained in Phase I because of higher total pressure drops across the turbodrill and the consequently higher hydraulic power required to drive the motor.

The conclusion drawn from the analysis results is that bit and rock type seem to make little difference in performance of the turbodrill itself, based on the fact that in Figures 4-3 and 4-4, no trend or bias based on rock and bit type could be found in the data; i.e., the distribution/scatter of data points in those figures did not suggest any dependence of turbodrill performance characteristics on rock or bit type. The only differences appeared earlier in the ROP values in Figure 4-1.

4.6 TACHOMETER PERFORMANCE

A fluid pulse tachometer unit developed by MEI and consisting of six blanked-off blades and vanes in the uppermost turbine stage was run during the pre-Phase II test of the 5-3/8-inch turbodrill at Terra Tek on April 10, 1979. In that test the flow area in the first stage was blanked-off (with epoxy material) from 40 to 80 percent during each revolution (six blades and vanes out of 15) and the turbodrill was run on water. During the test, background vibration data on pump fluid pulse signals and harmonics were obtained along with frequency response data from the tachometer unit itself for analysis by Sperry Rand Research Center personnel. In addition, spectrum analyses were performed on site to determine wave form characteristics to assess the feasibility of developing surface processing and readout equipment for the downhole tachometer. Data obtained during the test indicated that the tachometer concept employed could produce detectable signals. Later analysis showed that suitable surface processing and real-time readout equipment could be developed.

5. PHASE II TESTING

Formal Phase II testing of the MEI 5-3/8-inch turbodrill was initiated on December 6, 1979 at the Gearhart-Owen site. The drill motor made approximately 23 feet of hole (from 657 to 680 feet) at penetration rates between 100 and 120 feet/hour. Total rotating time on the motor was about one hour. A special 7-7/8-inch Reed Rock Bit Company HP-SM-J "high-speed", tri-cone roller bit was used with maximum WOB of about 4,000 pounds. Maximum pump rate was 315 gpm and rig floor line pressure was 2,400 psi. The well had been reamed and preconditioned for two days as part of pre-test activities to remove sloughed clay bridges and debris from the well. Other than this activity, the well had not been entered for over a year prior to this test.

Rate-of-penetration performance data obtained on the drilling rig at Gearhart-Owen consisted of penetration rates versus WOB with pump rate and rotary speed as parameters. Drilling or ROP performance was evaluated based on these four variables. Rock type, bit type, bit size, mud properties, and formation properties are among other parameters that can influence ROP performance of the turbodrill, but their effects were not evaluated in this project.

Testing on December 6 was terminated prematurely due to sudden failure of the lowest radial roller bearing in the bearing package and subsequent locking-up of the motor in the hole. Teardown of the turbodrill revealed no visible damage to any parts other than one locked-up radial bearing. In that bearing the individual rollers were skewed, and the roller cage was twisted and deformed. All other bearings, races, spacers, and sleeves were observed to be in excellent condition. There was also no evidence of burn marks on any parts due to overheating or overspeed of the turbine and the tachometer unit was intact. In addition, there was no evidence of plugging-off of flow through the bearing pack, although buildup of some solids was observed around the uppermost radial bearing. Apparently, this material did not affect operation of that bearing. There was no accumulation of bentonite from the drilling mud in the motor.

Phase II testing of the turbodrill was continued from January 21 to 25, 1980 with two 5-3/8-inch turbodrills on hand. Prior to resumption of testing the mud pits were dredged out to an average depth of eight to 10 feet. The mud, made up of fresh water and bentonite, was cleaned and verified repeatedly to be virtually free (one particle detected on 200-mesh sieve) of any mud solids (particularly sand and other drill cuttings). Marsh funnel viscosity of the mud was 34 sec (pure water is approximately 33 sec). Prior to turbodrill testing, an additional 15 feet of hole were drilled conventionally for well cleanup (total depth was 672 feet at start of test).

On January 23, the first turbodrill was rotated at the surface for six minutes at a pump rate of 150 to 200 gal/min to break it away prior to tripping in the hole. The procedure was repeated five feet off bottom as a check measure prior to drilling. On bottom, the motor drilled intermittently and made a total of five to six feet of hole (at penetration rates from 80 to 90 feet/hour). Conventional rotary drilling rates experienced in the past in the existing 650 foot well at Gearhart-Owen using a 9-7/8-inch Hughes Tool Company milled steel-tooth roller bit, Type OWV-J, were in the neighborhood of 10 to 12 feet per hour at 45 rpm with 20,000 pounds WOB. No direct comparison of drilling rates can be made because of different drill bit sizes. This motor ran a total of approximately 30 minutes when it locked-up. The pump rate to the motor at that point was 230 gal/min with WOB of almost 2,000 pounds. Repeated attempts were made to restart the drill motor; however, after several failed, the decision was made to pull the first motor, transport it to MEI in Houston, and tear it down to determine the cause of failure.

After tripping out of the hole, it was observed that some drill pipe scale was collected in the basket cones. The basket cones are sheet metal cones perforated with small holes to catch loose debris that might get pumped down the drill pipe accidentally. The purpose is to keep this debris out of the drill bit jet nozzles and not cause the bit to "ball-up" downhole. There were three cones in this case placed in separate drill collar joints. A service company was contacted to "rattle" the drill pipe free of scale before proceeding with running the second turbine in the hole. During the rattling operation, large amounts of scale (rust) were removed from the drill pipe and drill collars. Prior to running the motor, the drill string was run into the test well, and mud pumped through it to remove scale particles remaining in the drill pipe and collars.

The second 5-3/8-inch turbodrill was run on January 25. The turbine began rotating with a circulation rate of approximately 105 gpm. The WOB was increased as the circulation rate was increased to 250 gpm. With 3,000 to 4,000 pounds on the bit, the tachometer indicated that turbine speed was approximately 2,000 rpm. With weights of 3,000 to 5,000 pounds, a circulation rate of 273 gpm resulted in a turbine speed of 2,600 rpm. However, as the weight was increased slowly, the turbodrill stalled consistently at a threshold of 6,000 to 7,000 pounds. When the turbine stalled, the circulating mud pressure dropped 200 to 300 psi. Approximately 73 feet of hole were made during this test run. The turbine motor ran for a total of 2-1/4 hours. At that point, it locked up and was also sent to MEI in Houston for teardown and inspection. Both turbodrills run at Gearhart-Owen contained the built-in tachometer unit.

The first 5-3/8-inch turbodrill run at Gearhart-Owen on January 23, 1980, was torn down at MEI's assembly facility in Houston and the findings are as follows:

- The lowest and uppermost radial roller bearings failed, the outer races were cracked open in both cases. The roller cage in the lowest radial bearing was bent and extruded in part between two rollers. Two rollers in that bearing were broken. Other parts of the uppermost radial bearing were intact.

- The equivalent of about one level teaspoon of granular, drill pipe scale, or rust (about the size of fine beach sand) was removed from inside the bearing package housing and internal parts.

- Elements of the tachometer unit were intact. The turbine rotor rotated freely.

- The thrust bearings did exhibit some deformation of the relatively soft copper alloy roller cage material along the leading edges of roller contact.

- All other internal parts appeared normal. There was no evidence of overheating or overspeeding.

Results of tearing down the bearing package of the second 5-3/8-inch turbodrill run at Gearhart-Owen are as follows:

- Lower thrust bearing failed because of excessive loading due most likely to hydraulic downthrust of the turbine.

- All radial roller bearings appeared intact.
- Some very finely ground solid material was found in the bearing package. However, it had to be rubbed between the fingers to detect the presence of solids.
- The Reed roller-cone bit failed due to motor overspeeding. One roller-cone, filled with grease and mud, was frozen in place. Another was also filled with grease and mud but was half-frozen. The third rotated freely but the seal was destroyed.

The conclusion drawn from the above observations and those made earlier after the first Phase II attempt in December 1979 is that clearly the flow-through bearing turbodrill cannot be run with water-based mud or even dirty water. The present design will not allow it to work for the extended periods required to drill long methane drainage boreholes on the order of 1,000 to 2,000 feet into shallow coal seams. However, it should be noted that the lower thrust bearing failure was probably due in part to the formation being drilled so fast that the hydraulic downthrust was greater than the upward thrust due to the WOB, and did not allow the thrust bearing assembly to function according to design.

Wear measurements on the parts designated prior to testing were not obtained by MEI after teardown of the turbodrills following Phase II testing. As a result, no determination of wear rates or assessment of tool repair requirements has been made.

During the first attempt to run the 5-3/8-inch turbodrill on drilling mud in Phase II at Gearhart-Owen on December 6, 1979, the tachometer unit installed in the turbine section (40 to 80 percent blank-off ratio) did not produce discernible signals to indicate turbodrill rotary speeds at the surface from 657 to 680 feet in the hole. At that time, three Hydrodyne bladder accumulators (desurgers) were installed in the flow line from the Dowell pump truck to the drilling rig to damp out mud pump surges. The nitrogen charges on the desurgers (1,600, 1,300 and 1,000 psi, respectively, moving from the pump truck to the rig (see Figure 3-1)) were designed to ensure smooth operation since mud pump discharge pressure averaged 2,800 psi, and mud pressure in the standpipe on the rig floor was 2,400 psi. Mud weight averaged 9.0 pounds per gallon and contained a considerable amount of bentonite and some additional conditioning chemicals to build up gel strength. Failure to detect tachometer signals at the surface could not be explained based on information available at that time.

When Phase II testing resumed with the first of two 5-3/8-inch motors at Gearhart-Owen on January 23, 1980, the tachometer unit did not produce consistent signals to report speed downhole. At one point there was thought to be a signal isolated at about 800 rpm. However, strong harmonics (one at about 1,600 rpm) obscured the primary response. The nitrogen charges on the three desurgers were checked several times to ensure proper performance.

The second 5-3/8-inch motor was run on January 25. With a circulation rate of 250 gal/min and 3,000 to 4,000 pounds WOB, the tachometer indicated that turbine speed was 2,000 rpm. Increasing the mud circulation rate to 273 gpm (with bit weights of 3,000 to 5,000 pounds) resulted in a turbine speed of 2,600 rpm.

6. CONCLUSIONS

The following conclusions were drawn from Phase II testing of the 5-3/8-inch turbodrill:

- Pre-Phase II testing in the Drilling Research Laboratory at Terra Tek demonstrated that the 5-3/8-inch turbodrill is capable of drilling in granite at rates in the range of 30 to 50 feet/hour with a standard roller-cone rock bit and 30 to 40 feet/hour using a STRATAPAX bit in limestone.

- The turbodrill tachometer developed by MEI functioned, and it can be integrated into an instrumentation system to monitor rotary speed from downhole in a well. However, based on performance observed, the accompanying surface readout equipment needs to be developed further.

- The objectives of this phase of the test project were only partially accomplished. The only significant data obtained were indications of potential drilling rates.

- The 5-3/8-inch turbodrill tested at Gearhart-Owen exhibited a tendency toward operational instability; that is, it would either run at speeds in excess of 2,000 rpm with little WOB, or it would stall consistently as moderate bit weights (6,000 to 7,000 pounds) were applied to decrease the rotary speed.

- Evaluations based on observations made during the three teardowns in Phase II testing indicated that the flow-through bearing package turbodrill cannot be run on a water-based mud or even water of the quality typically used for drilling wells in the field. However, it should be noted that the lower thrust bearing failure was probably due in part to the fact that the formation was drilled so fast that the hydraulic downthrust was greater than the upward reaction force due to the WOB, and did not allow the thrust bearing assembly to function according to design.

- The present design will not sustain operation for the extended periods required to drill long methane drainage boreholes on the order of 1,000 to 2,000 feet into shallow coal seams (at depths of burial less than 2,500 feet).

7. RECOMMENDATIONS

The major problem areas in the turbodrill (design, mechanical, and operational) have been sufficiently identified to warrant recommendation that formal turbodrill testing project be terminated at this time. Performance of the turbodrill to date does not warrant additional government effort for field testing units until viable bearing/main pressure seals are developed and demonstrated to be effective in at least a laboratory environment. This work is reportedly being pursued in a separate project.

This recommendation is based on turbodrill performance exhibited in the testing reported in the Phase I Final Report, Phase II field testing results, and the conclusions presented in Section 6. A summary follows:

- In the three recent failures of the turbodrill flow-through bearing package during field testing at Gearhart-Owen, the bearings failed in all three cases.
- The flow-through bearing package turbodrill in its present configuration cannot run for the periods that would be required to drill long, horizontal methane drainage boreholes.

APPENDIX A

PHASE II TEST PLAN

The appendix contains the Test Plan that governed all activities during Phase II testing at Gearhart-Owen Industries in Fort Worth, Texas.

The Plan was reviewed and approved by project participants prior to initiation of Phase II testing.

The Plan contains planning background discussion, project objectives, description of test equipment and facilities, roles and responsibilities of participants, test procedures, and scheduling.

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August 1980

TEST PLAN

for

Field Testing

the

MAURER ENGINEERING 5-3/8 INCH TURBODRILL

at

GEARHART-OWEN INDUSTRIES, INC.

Fort Worth, Texas

D. R. Watkins

TRW Energy Systems Group

McLean, Virginia

October 1979

Approved: _____ Oct 30, 79
M. Gearhart, President — Date
Gearhart-Owen Industries, Inc.

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W. C. Maurer, President — Date
Maurer Engineering Inc.

_____ 10/16/79
R. S. Ottinger, Acting Manager — Date
Methane Recovery from Coalbeds Project
TRW Energy Systems Group

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1.0 INTRODUCTION

This document presents the plan for initial field testing of the 5-3/8 inch diameter turbodrill downhole motor manufactured by Maurer Engineering Inc. (MEI) under Contract No. EY-77-C8093 for the Department of Energy (DOE), Morgantown Energy Technology Center (METC). The plan addresses Phase II of the testing project established to determine operability and performance characteristics of the turbodrill in a field environment. Phase II testing will be conducted at Gearhart-Owen Industries, Inc. (GO) located in Fort Worth, Texas. The plan also states requirements and presents procedures to determine wear characteristics under operating conditions using a drilling rig. Organization of the plan is described by the Table of Contents.

1.1 BACKGROUND

In one of many activities aimed at increasing reserves and production of fossil energy, the DOE is exploring the application of downhole drilling motors and directional drilling techniques in coalbed methane drainage and well drilling operations to improve efficiency and reduce drilling costs. The Maurer Engineering 5-3/8 inch diameter flow-through model turbodrill, shown schematically in Figure 1-1, incorporates several advanced design features:

- High efficiency turbine blade design, providing greater torque with fewer stages and lower driving fluid volume throughput compared to other downhole drill motor designs
- High load capacity roller thrust bearings, permitting greater bit weights (weights applied to the bit) and improved penetration rates

A major advantage of the turbodrill is low drill string and casing wear (due to minimal rotation requirements) which results in increased drilling rates and smoother operation due to decreased chances for "twist-offs" and other potential problems, such as "key-seating" of the drill pipe during directional drilling operations. Another advantage of turbodrills is the potential for significantly greater power transfer to the rock-bit interface for rock cutting compared to conventional rotary drilling equipment. Present-day rotary drilling equipment is limited in horsepower deliverable to the working rock face.

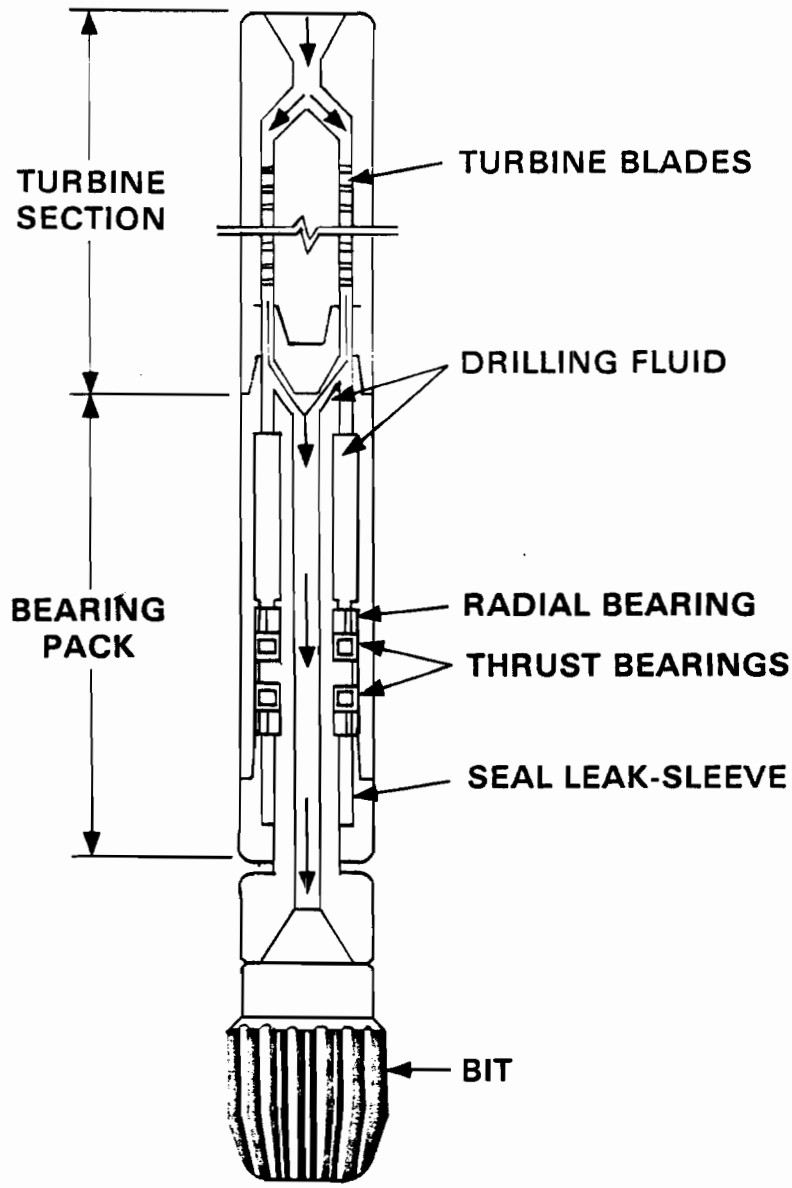

Figure 1-1. Turbodrill - Flow-Through Bearing Package

Baseline performance determination and wear testing to ascertain operating and durability characteristics have been done in Phase I of the testing project. Phase II testing described in this plan will determine both straight-hole and directional drilling performance characteristics under field operating conditions penetrating previously drilled formations whose characteristics are well known through the availability of good offset well data. Phase III of the testing project will demonstrate both straight-hole and directional drilling capability at a field site drilling into formations whose properties are not well known a priori. The objective will be to place a methane drainage borehole in a horizontal coal seam. The specific field site for Phase III has not yet been selected.

The baseline data (determined in Phase I) provide performance characteristics against which to assess the data resulting from subsequent field well drilling tests. Wear and other degradation information were obtained to aid estimation of preliminary tool maintenance requirements and component life expectancy for operational planning. In the past, turbodrills have received limited application due primarily to bearing and seal life limitations.

1.2 OBJECTIVES

The purpose of this Test Plan is to provide coordinated planning, present test requirements, detail test procedures, and furnish supporting information for testing that will determine performance and wear characteristics of the Maurer Engineering 5-3/8 inch turbodrill in a downhole drilling mode.

Objectives of Phase II testing are:

- To determine the drilling rate (drill bit penetration rate) as a function of bit-weight (vertical force applied to the bit), borehole mud pressure and mud flow rate through the turbodrill. The circulating fluid (drilling fluid) used will be conventional drilling mud. (Both rpm and torque and, consequently, power developed by the turbodrill will be functions of mud flow rate.)
- To demonstrate operational compatability of the turbodrill with conventional diamond bits and STRATAPAX bits and to evaluate bit performance

- To ascertain wear characteristics of both thrust and radial bearings in downhole operation under axial and lateral load conditions to be used in determining component service life expectancies (time intervals between required drilling motor changeovers or substitutions)
- To document any additional observations important to establishing tool changeover requirements in field operation
- To gain field experience in using the Maurer Engineering 5-3/8 inch turbodrill on a conventional, oilfield drilling rig to aid operators in optimizing application of turbodrills

1.3 SCOPE

This Test Plan controls all Phase II activities of the MEI 5-3/8 inch turbodrill testing project on an oilfield drilling rig at the Gearhart-Owen Industries, Inc. plant in Fort Worth, Texas.

2.0 TEST REQUIREMENTS

Test procedures and operations shall be designed and implemented to provide data to determine the operational and wear characteristics of the turbodrill in field use. Wear and other degradation of components critical to sustained operation of the turbodrill will be observed, measured, and recorded to the extent required to determine design adequacy and service requirements for field application. As part of this effort, an assessment of turbodrill operating performance and service life expectancy in field use is required.

Test requirements reflecting the above general objectives are specified in this section. Designated responsible personnel, equipment requirements, pre-test requirements, and safety considerations along with other test conditions, procedures, and data requirements are stated. Detailed procedures for satisfying the test requirements are presented in Section 5.

2.1 PERSONNEL

Planning and implementation of the tests require a coordinated effort between METC, MEI, GO, and TRW. These organizations shall function in the capacities listed below. The individuals noted, or a designated alternate, shall be the point of contact for purposes of this test, contractual matters excluded.

Test Controller	H. D. Shoemaker, Assistant Manager Methane Recovery from Coalbeds Project Morgantown Energy Technology Center of DOE
Test Director	R. S. Ottinger, Acting Manager Methane Recovery from Coalbeds Project TRW Energy Systems Group
Test Conductor	A. M. Gearhart, President Gearhart-Owen Industries, Inc.
Test Advisor	W. C. Maurer, President Maurer Engineering Inc.

The test crew provided by MEI shall act primarily in an advisory capacity relating to test operations on the turbodrill itself in accordance with test procedures approved by METC.

TRW will subcontract a directional driller from Eastman Whipstock who is knowledgeable in the use of downhole turbines. His function will be

twofold: act as directional driller at GO and provide operational, hands-on expertise to TRW on site.

2.2 TEST EQUIPMENT AND FACILITIES

The test facilities will be provided, operated, and maintained by Gearhart-Owen. This will include the drilling rig, well site, conventional mud and mud storage tanks, tubular goods and cement, regular single-screen (40-50 mesh) shale shaker, cuttings disposal area (mud pit), and ancillary support facilities. The mud pump and drive will be rented directly by MEI under DOE contract. GO will provide drilling rig operational and supervisory personnel.

The turbodrill shall be furnished, transported, prepared for testing, serviced/maintained, and deactivated by MEI. MEI will provide and operate the assembly tools and equipment (hydraulic assembly stand). MEI will provide drilling fluid solids control service and equipment (fine-screen shale shaker and /or desilter) for turbodrill testing at GO. MEI will also provide and install/ operate instrumentation and related equipment in GO's plant. All required turbodrill spare parts will be provided by MEI under separate contractual arrangement with METC.

Equipment and operating requirements not specifically defined shall be provided by MEI and GO by mutual agreement determined before testing begins. TRW will provide planning for all test operations. MEI will provide technical support as specified in Section 4. TRW shall determine test readiness and verify that all pre-test requirements have been fulfilled prior to test. METC shall have final approval of all plans and procedures.

Test and test support requirements include the following items:

MEI
- Breakout unit and associated equipment
- Trucking to Fort Worth and logistics of all required assembly tools and equipment
- Drill bits (See Section 4)
- Stabilizers (Optional with 6-1/2 inch bits)
- 1-1/2° Bent sub
- Interconnecting hardware (subs)
- Mud pump and drive engine
- Recorders and other associated test equipment
- Instrumentation - generally items installed on MEI equipment or provided to measure/record turbodrill operating parameters
- Turbodrill spare parts (Provided under separate METC contract to MEI)

- Downhole tachometer unit (Developed under separate contract)
- Double-screen (60-80 mesh) shale shaker or desilter to be used with GO provided standard shale shaker (See Section 4)
- Rental of TOTCO drilling rate indicator and recorder

GO
- Drilling rig and well site
- Drill pipe, casing, and cement
- Conventional drill collars
- Monel drill collar(s)
- Mud and cuttings disposal pit
- Mud piping and valving
- Regular (40-50 mesh) shale shaker
- Instrumentation - generally items installed on GO equipment or provided to control/record mud flow

TRW
- Eastman Whipstock directional driller (service provided includes instrument kit, and wire line running gear for obtaining bottomhole survey locations during directional drilling operations)
- Any required mud conditioning chemicals or replacement of mud lost from the GO mud circulation system as a result of this testing activity

2.3 TEST PREREQUISITES

2.3.1 Instrumentation Calibration and Certification

Flow rate and pressure instrumentation and display equipment used in these tests will be calibrated according to accepted, standard industrial procedures by the supplier prior to delivery to the test facility. Certification stickers stating date, responsible party, duration of certification, and standards used shall be affixed to each instrument.

2.3.2 Prerequisite Testing

The requisite formal testing of the turbodrill has already been completed under Phase I of the test project.

2.3.3 Test Setup and Readiness

The turbodrill and all test equipment and support requirements will be verified ready to support testing prior to start of test operations. Test participants shall verify readiness, and TRW shall conduct a test readiness review prior to test. No operation shall be started without specific direction of the Test Director or his designated representative.

2.4 SAFETY

Test personnel shall strictly adhere to published safety practices in accordance with the documents and directives of the organizations listed below:

- OSHA safety regulations/standards
- City of Fort Worth Electrical Code
- Gearhart-Owen Health and Safety Manual
- Safe Practices in Drilling Operations (API Recommended Practices - 2010)

Safety hazards associated with the planned turbodrill operations involve high pressures, rotating heavy equipment, and electric shock. Appropriate controls and safeguards for these hazards are documented above. All test planning and operations shall be done cognizant of these safety requirements. Especially hazardous or unusual situations shall be noted during test operations prior to commencement of testing activities. Instituting corrective measures shall be the responsibility of the Test Conductor*: the driller shall assure compliance with safety precautions and approved controls and safeguards during test operations. The Test Director has standing authority to halt test procedings in the event an unsafe working condition exists.

2.5 TEST OPERATIONS

Test operations shall be performed as described herein. They are designed to satisfy the test requirements described in this section.

The test procedures presented in Section 5 are designed to obtain data in an orderly manner with data logged/recorded as each step/event occurs. All procedures, including those for emergency operations, shall be carried out by the Test Conductor and approved by the Test Director.* Handwritten procedures developed during the course of a test due to unforeseen difficulties are acceptable, but must have Test Director approval prior to implementation.

The driller (responsible individual on the drilling rig) shall be in charge of the operation and maintenance of the drilling rig, associated equipment, and the rig operating crew. The Test Advisor* shall be responsible in all matters relating directly to turbodrill maintenance and operations. Setting of the test conditions specified in Section 5 is the responsibility of the Test Director. However, concurrence of the Test Advisor, Conductor, and Director is required.

*See Section 4 - Roles and Responsibilities

In emergency situations or if unsafe conditions or equipment damage is imminent, and where time is of the essence, the driller shall assume a single point of command, take appropriate actions, and report his actions to the Test Director as soon as practical. In the event that deviation from previously approved procedures occurs, a written report shall be made to the Test Director after the test is terminated. In the event of a procedural error or an unplanned test interruption, Test Advisor, Test Director, and driller agreement must be obtained prior to error correction or test restart.

Monitoring turbodrill speed downhole during Phase II testing is important to the extent that the test may be suspended by the Test Director in the event of malfunction of the tachometer unit.

The drilling rig operator (GO) will be responsible for maintaining proper mud properties during the course of testing. Determination of mud properties will be coordinated on a continuing basis with the Test Advisor (MEI) and Test Director (TRW).

Successful test procedure completion is established when all required data have been acquired and are verified to be in apparent good order.

2.6 DATA REQUIREMENTS

Expected test parameters, other required data, and required instrument response characteristics are covered in the Test Procedures in Section 5.

One copy of the Test Procedures, Section 5 of this Test Plan, shall be designated the "Data Master Copy." Data entries, record of procedural deviations, and other annotations shall be made on this master copy to help avoid recording errors and omissions and to assure accurate, precise, and complete test data use and reporting.

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3.0 TEST STRATEGY

An overview of the test strategy, rationale, and planned testing activities is presented in this section. Detailed procedures and test conditions are described in Section 5.

3.1 TEST DESCRIPTION AND STRATEGY ELEMENTS

The test is described in the form of specific strategy elements designed to achieve the test objectives stated in Section 1.2:

- Verify prior to test operations that instrumentation and recording equipment meet prescribed requirements and that calibrations are valid for the test period. Obtain pre-test and post-test calibrations, where appropriate
- Obtain and log/record data on operating parameters to determine drilling rate (drill bit penetration rate) as a function of bit-weight, circulation rate of the drilling mud, pressure drops and mud properties
- Drill to a total depth of between 2000 and 2400 feet using the turbodrill on a full-scale conventional rotary drilling rig
- Drill with 7-7/8 inch roller-cone rock bits from Reed Tool Company and/or 6-3/4 inch STRATAPAX bits supplied by Sandia Laboratories for these tests
- Use 6-1/2 inch STRATAPAX and conventional diamond bits purchased for the project
- Obtain and record measurements of critical dimensions at the completion of testing to determine wear rates of components important to sustained drill motor operation

3.2 RATIONALE FOR TEST STRATEGY

This subsection describes how each strategy element will be carried out and the reasons behind performing each element.

Prior to test operations, the "as tested" configuration of the turbodrill will be identified with 8" x 10" photographs. The as tested configuration will be further documented with sketches showing dimensions of critical parts. The documented configuration will serve as a basis for subsequent wear measurements. All component part numbers and critical dimensions will be recorded. The condition of bearings and finished surfaces will be noted. Clearances at critical locations will be measured and recorded. Assembly details such as sequence, tightness of fit, applied torques, and lubrication will be described and recorded.

In preparation for testing, calibrated instrumentation is installed/connected, and determined to be in good working order. This will ensure smooth operation of test equipment and systematic acquisition of data.

The turbodrill will be tested on a standard (103 foot high) "East Texas derrick" rotary table drilling rig of the type shown in Figure 3-1. The test configuration is shown in Figure 3-2.

Typical oil field (constant weight) drilling mud will be used in these tests. Samples of mud will be obtained and analyzed for composition and properties (weight or density, viscosity, solids content, and filtrate analysis).

Measurements of the following variables are needed to determine turbodrill performance characteristics as functions of bit-weight and mud flow rate:

- Mud pump discharge pressure
- Weight on the bit
- Mud weight (density)
- Mud flow rate
- Rotary speed
- Penetration rate

Turbodrill penetration rate is primarily a function of bit-weight, borehole mud pressure, and the rate of mud flow through the drill motor. Mud flow rate will be measured and recorded as testing proceeds. Bit-weight is the difference between the weight (force) applied in the vertical direction to the bit by means of heavy, cylindrical drill collars attached to the bottom section of drill pipe above the drill motor itself and the suspended weight on the crown block (see Figure 3-1). Applying more weight to the bit usually increases drilling rate, and a series of up to six such drill collars (26 to 29 feet long each, 5-3/4 inch center diameter with 2-3/8 inch bore, in this instance) may be used in drilling through the Pennsylvanian formations at the Gearhart-Owen site. TOTCO instrumentation on the rig floor will be used to measure and record bit-weight.

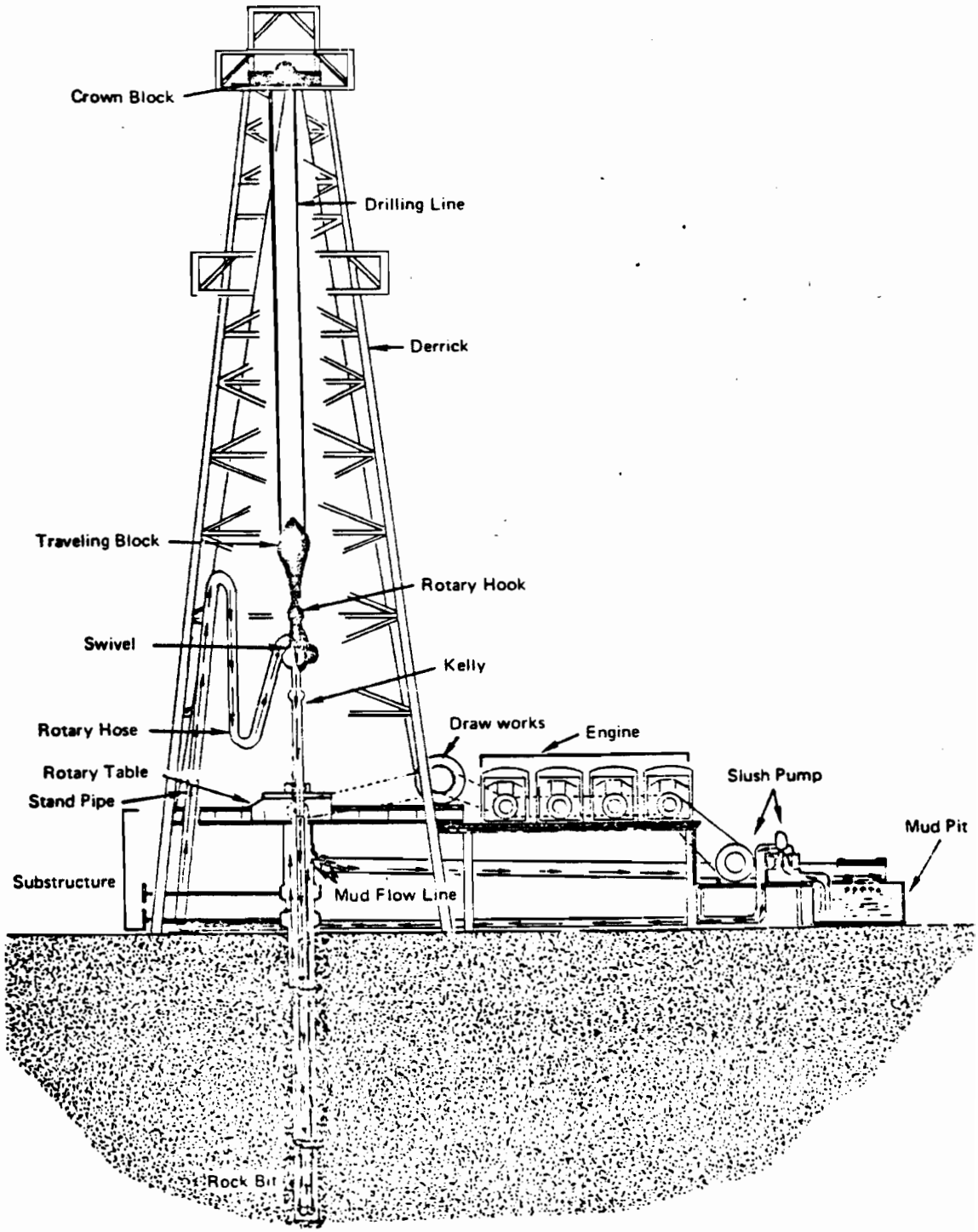
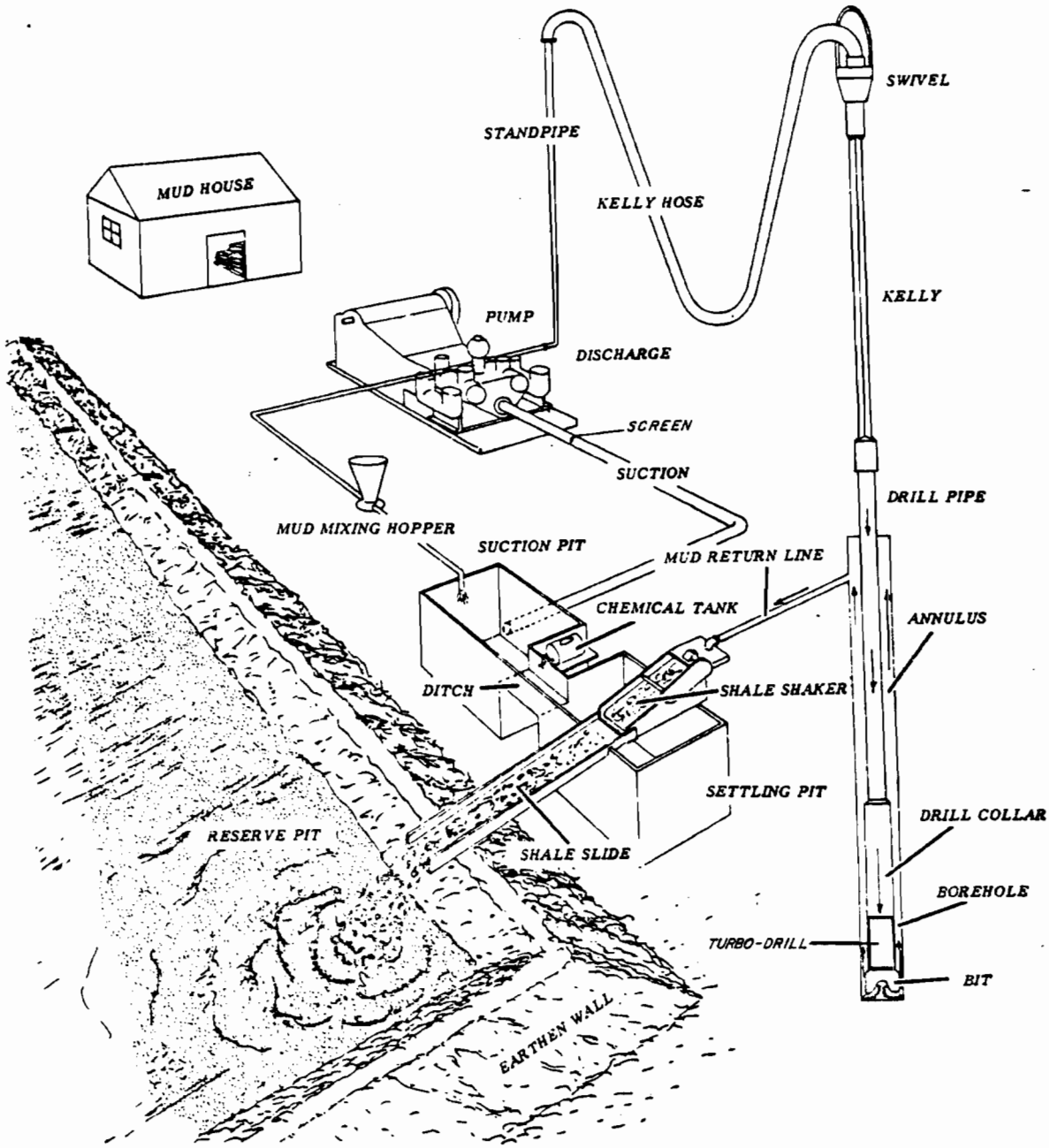


Figure 3-1. Basic Components of a Rotary Drilling Rig



Adapted from:

Petroleum Extension Service
University of Texas at Austin

Figure 3-2. Test Layout Showing Rotary Rig Fluid Circulation Loop and Mud Handling System

Penetration rates also depend on the type of drill bit used. It is planned in these tests to use three different types of bits to ascertain which type may be most compatible with the turbodrill. It is acknowledged that the type of formation and hardness impact heavily the type of drill bit to be used in a particular application. The following bits were purchased for use in Phase II of the turbodrill testing project:

- 6-1/2 inch diameter STRATAPAX bit with piggyback stabilizer
- 6-1/2 diameter conventional diamont bit

The 6-1/2 inch STRATAPAX bit has been purchased from Christensen Diamond Products Company in Salt Lake City, Utah. The conventional diamond bit and piggyback stabilizer were also obtained from Christensen Diamond Products. In addition, two 7-7/8 inch conventional roller-cone bits provided by Reed Tool Company and two or more 6-3/4 inch STRATAPAX type bits supplied by Sandia Laboratories will be used in these tests.

Drilling progress can be seriously impaired by hardness of the formations being penetrated. The bits prescribed for use in this test are designed for medium hardness rock drilling. As a precautionary measure, drilling records and geologic data will be obtained before active test operations commence from GO to ascertain if there are any potentially troublesome areas in the formations to be drilled that require foreknowledge to progress satisfactorily through them. Records will also be obtained from GO on the drill bits used previously and their condition before and after running in the hole to aid in this effort. A determination of the types of bits used with the types of formations penetrated will be made by TRW prior to testing.

Besides providing conventional drilling equipment on-site, the Gearhart-Owen site offers the added advantage of providing good offset well data. Many logs have been run through the formations to be drilled. The lithology is well known. As a result, many potential hole problems can be anticipated. Gearhart-Owen has drilled several 2400 foot wells within a few feet of the test well site. The drilling rig will be equipped with a TOTCO drilling rate recorder, and TOTCO drilling records from those previously drilled wells are available. These records will be used for comparing turbodrill penetration rates to those obtained using conventional equipment. The TOTCO recorder will be used during the turbodrill drilling tests.

The availability of good offset well data will greatly simplify the test procedure and will eliminate the need for alternating conventional rotary drilling with turbodrilling. In most applications, drilling conditions vary between offset wells due to greater spacing resulting in difficulty when attempting to evaluate new tools accurately. This should be no problem with the Gearhart-Owen test site because conventional drilling rates are known in all of the formations to a depth of 2400 feet in close lateral proximity.

The turbodrill will be disassembled, inspected for damage, and wear measurements taken following completion of testing. The information obtained from observations and measurements of wear will allow determination of component life expectancies and establish prescribed service intervals when the drill motor is tested more extensively in more rugged field operations in Phase III of the Test Project.

The drill bits used will be inspected and graded, and the amount of wear (or damage) noted and recorded at the time of turbodrill teardown/inspection. Sustained high drilling rates depend on durability of the drill bit and the ability of the turbodrill to supply power and torque without excessive rotary speed, which is usually detrimental to bit life.

Directional drilling requires, at a minimum, periodic surveys to determine bottomhole location and direction of drilling progress as a matter of standard procedure. There are a number of borehole survey techniques available that vary in degree of sophistication and cost. A periodic, "single-shot" device available at nominal cost, from a directional drilling service company will satisfy the objectives of Phase II testing at Gearhart-Owen. Phase III may have more stringent requirements. Additional requirements for use at GO will involve use of a section of nonmagnetic (Monel) drill collar(s) in the downhole assembly. Wireline equipment is available to lower the survey tool to the bottom to take a shot while drilling string rotation is temporarily suspended. This equipment will be provided by Eastman Whipstock as part of their service.

4.0 ROLES AND RESPONSIBILITIES

Implementation of this test plan will involve several organizations whose roles and responsibilities are identified below:

4.1 TEST PROGRAM DIRECTION AND CONTROL

DOE Programmatic responsibility, allocation of top level funding, and delegation of project implementation authority. Assigned to the Fossil Energy Office.

METC Project implementation and field management. Responsibilities include the preparation of budgets and schedules, coordination with related projects, and monitoring of activities to assure technical adequacy and achievement of project objectives.

4.2 TEST PLANNING, INTEGRATION, AND RESULTS ANALYSIS

METC Overall control and responsibility for test program planning and integration.

TRW Detailed test planning and integration of technical requirements; assigned to TRW Energy Systems Group, Energy Systems Planning Division. This work includes determination of test procedures and analysis of test results.

MEI Test planning and analysis support; test procedure preparation support.

4.3 TEST PERFORMANCE

METC <u>Test Controller</u>

Exercises top-level administrative control and responsibility.

TRW <u>Test Director</u>

Performs as on-site representative for test controller. The test director has overall responsibility for performance of the test program, including approval of test plans and procedures, determining Phase II test readiness, test scheduling, and taking every reasonable precaution to preserve the Government-owned, METC turbodrill. TRW will be cognizant of all communication dealing only with Phase II testing between GO and all other contractors including Maurer Engineering.

GO Test Conductor

Gearhart-Owen Industries, Inc. will provide the test facility, drilling rig and associated support at its Fort Worth, Texas plant. GO will provide the driller and associated operating and supervisory personnel and will implement "hands on" test operations under surveillance of the test director.

MEI Test Advisor

The prime responsibility of the test advisor is to assist the test director in preparation of the Test Plan; to provide technical consultation to the test director; to provide, install, operate and maintain instrumentation; to record performance data, to log running time; and to advise the test conductor (GO) on turbodrill handling and procedures.

This activity includes pre-test preparation, support equipment modifications, preparation of the turbodrill for testing and assistance in turbodrill handling. MEI will also be responsible for obtaining instrumentation with valid calibration for the test period with certification to determine mud flow rates and pressures. MEI will provide all drill bits used in testing operations. The bits to be used include the 6 1/2 inch Christensen STRATAPAX and conventional diamond bits purchased for use in this project, the two 7 7/8 inch tri-cone roller bits furnished by Reed Tool Company, and the two or more 6 3/4 inch STRATAPAX type bits supplied by Sandia Laboratories.

MEI will provide all interconnections (subs) between the drill string and the turbodrill and additional mud flow lines at the surface. MEI will prepare the turbodrill for operation and perform maintenance thereon. MEI will furnish drilling mud solids control service and extra equipment (fine-screen shale shaker or desilter). The desilter, if used, will be obtained from a service company like Baroid, Dresser/Swaco or Tri-Flow and will be standard oilfield type.

4.4 TEST EVALUATION AND REPORTING

TRW Energy Systems Group will coordinate and publish reports with METC approval upon completion of testing at Gearhart-Owen.

5.0 PROCEDURES

Procedures are presented in this section for field testing the Maurer Engineering 5-3/8 inch diameter turbodrill at the Gearhart-Owen Industries plant in Fort Worth, Texas. Specific procedures have been developed to implement the elements of the testing strategy presented in Section 3.1.

5.1 TEST PROCEDURE

The sequence of activities to be performed corresponding to the test strategy elements in Section 3.1 is:

	Activity	Lead Performer
(1)	Prepare test site and conduct pre-test activities	GO, MEI, TRW
(2)	Hold pre-test review to ascertain test readiness	GO, MEI, TRW
(3)	Clean out the existing 650 foot test well for one day with conventional mud circulation technique and prepare for receiving turbodrill	GO
(4)	Break-in turbodrill for 15 minutes off bottom in hole	GO
(5)	Drill with a Reed 7-7/8 inch roller bit for 3 to 5 hours. Pull sooner if any difficulties arise	GO
(6)	Drill with a 6-3/4 inch Sandia STRATAPAX bit for 3 to 5 hours. Pull sooner in case of trouble	GO
(7)	Drill with the 6-1/2 inch Christensen STRATAPAX bit for 3 to 5 hours. Pull sooner if any indication of trouble	GO
(8)	Drill with the Christensen 6-1/2 inch conventional diamond bit for 3 to 5 hours. Pull sooner if any problems develop	GO
(9)	Perform a straighthole endurance test for 1-1/2 days with best performing bit	GO
(10)	Conduct a directional drilling test for 2-1/2 days using the bent sub and best performing bit. Survey bottomhole location periodically	GO
(11)	Transport turbodrill to MEI shop in Houston	MEI
(12)	Disassemble turbodrill, inspect for damage and wear, obtain required wear measurements of critical turbodrill parts, and reassemble with new parts as needed	MEI
(13)	Conduct conventional rotary drilling between turbodrill test on conventional drilling rates.	GO

5.2 TESTING SCHEDULE

Figure 5-1 presents the schedule for performing the sequence of activities in Section 5.1. Required activities prior to testing, as well as subsequent data analysis and reporting of results, are included. It should be noted that the schedule presented proceeds from actual start-up time of Phase II activities. The purpose is only to indicate time periods allotted to perform the individual project activities.

The time schedule presented in Figure 5-1 is consistent with the total rig and pumping time of 10 days available to perform Phase II testing. Rig time at Gearhart-Owen is accrued on the basis of single-shift, 8-hour work days. The time intervals corresponding to the individual test procedures delineated in Section 5.3.2 have been made to allow for sufficient time to make round trips in the hole and still remain within the total time constraint of 10 days.

5.3 IMPLEMENTATION

5.3.1 Instrumentation

As discussed in Section 3.2, the primary performance parameters to be either measured or monitored during testing are volumetric mud flow rate, bit-weight, mud pump discharge pressure, and drilling rate. The key instrumentation required to obtain these quantities is presented in the following list showing the type of instrument and required response ranges corresponding to each variable or parameter:

- Volumetric flow rate of the mud - turbine flow meter (60-500 gpm capacity)
- Bit weight - TOTCO bit-weight indicator and recorder
- Mud pump discharge pressure - dial pressure gauge (0-3000 psi)
- Rotary speed - downhole tachometer unit with digital readout at surface
- Drilling rate - TOTCO drilling rate recorder

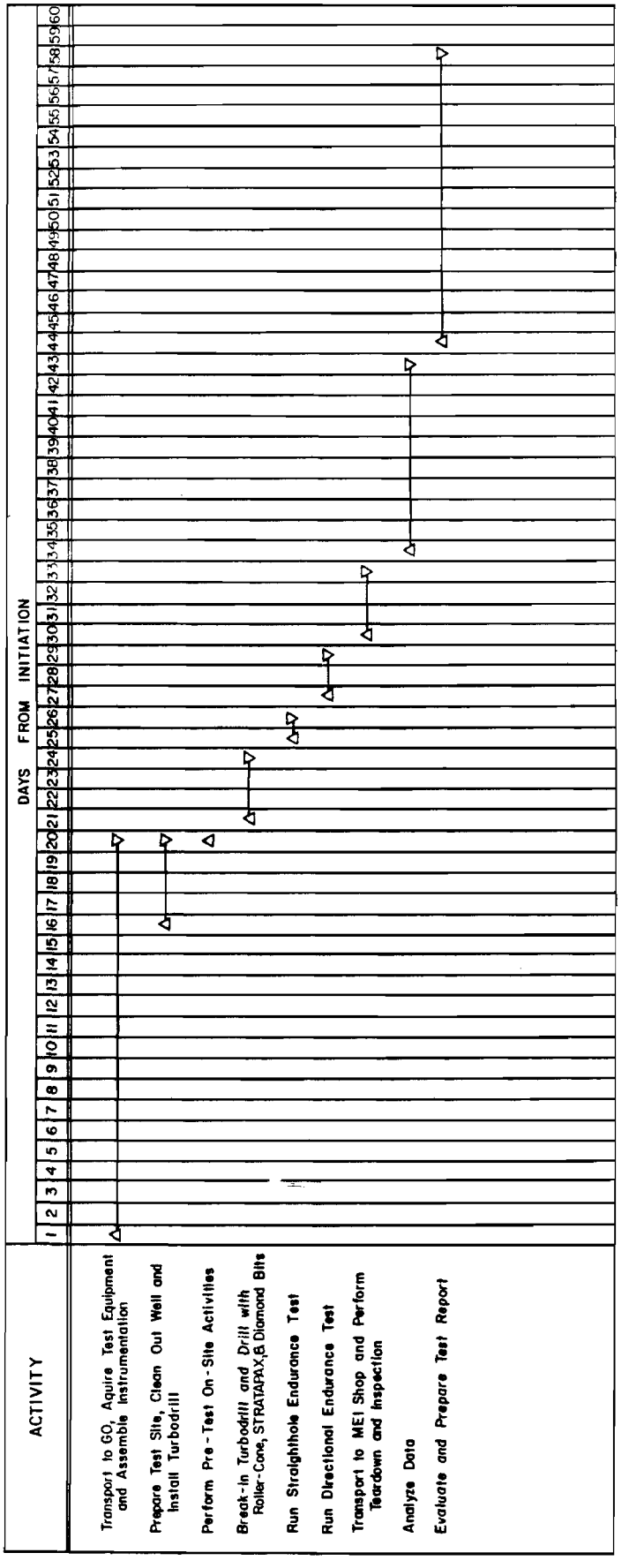


Figure 5-1. Gearhart-Owen Field Testing Schedule

Required accuracies of the above instruments are as follows:

- Turbine flow meter - ± 5 percent full capacity
- Bit-weight indicator - ± 5 percent full scale
- Dial pressure gauge - ± 5 percent full scale
- Tachometer system - ± 10 percent
- Drilling rate recorder - ± 5 percent full scale

The raw data (pressure and flow rate) are recorded by hand on prescribed data sheets (Table 5-1).

The turbine flow meters used in this test require stainless steel construction. Effects of drilling mud on instrument bearings will be considered so as to ensure that instrument response quality does not deteriorate during the tests. A coarse wire-mesh screen will be installed in the mud line (in the pump suction line, see Figure 3-2) to keep any agglomerated particles from lodging in and possibly damaging the instrumentation. The turbine flow meter shall be placed in the straight section of standpipe at least 10 pipe diameters past the elbow to minimize pulsating and/or non-linear responses.

Maximum errors have been estimated for measured variables and quantities whose values depend on the primary, measured variables. Sources of both random and systematic errors have been considered. These include response errors inherent in the instrumentation, calibration errors, and human errors in reading instrumentation and recording output. The following are the estimates of expected maximum errors associated with the test variables and derived quantities:

Mud flow rate	± 6%
Mud pump discharge pressure	± 6%
Hydraulic power input	± 9%
Drilling rate	± 6%

Table 5-1. Sample Data Sheet

Maurer Engineering 5 3/8 Inch Turbodrill

Gearhart-Owen Field Tests

Date / Run No.	Time	Mud Flow Rate gpm	Mud Pump Pressure psig	Drilling Rate min/ft	Turbodrill Rotary Speed rpm	Rotary Table Torque, ft-lb	Bit Weight lbs	Remarks (Appearance of drill cuttings and chemicals added to mud)

5.3.2 Test Procedures

Implementation of each activity in the test procedure is discussed individually in this section. The numeration corresponds to the activities listed in Section 5.1. Responsible organizations are named in the text or appear in parantheses where appropriate.

(1) Prepare Test Site and Conduct Pre-Test Activities

A drill cuttings disposal trough (mud pit) will be provided by GO for cuttings and spent mud. Sufficient working space is to be designated (by MEI and TRW) and provided by GO for test equipment set-up and assembly equipment storage near the drilling rig.

Prior to test, TRW will obtain drilling records and geologic data from GO to ascertain if there are any potentially troublesome areas in the formations to be drilled. TRW will also obtain from GO records of the drill bits used previously and their condition before and after running in the hole to aid in this effort. A correspondence of the types of bits used with the formations penetrated will be made by TRW prior to testing.

As part of the pre-test activities, a complete set of turbodrill specifications and dimensions for evaluation of wear will be recorded by MEI as per Table 5-2. MEI will obtain 8" x 10" photographs of all parts to be measured and inspected for wear later. A complete set of sketches of critical parts will be provided prior to test to document the "as tested" configuration.

It is important in these tests to maintain reasonably constant mud properties since turbodrill performance depends in part on mud properties, particularly viscosity and mud weight (GO).

Table 5-2. Sample Specification Sheet

Maurer Engineering 5-3/8 Inch Turbodrill

Gearhart-Owen Field Testing

Part Name: Date:

Manufacturer:

Model No.:

Part No.:

	Nominal Dimension	Deviation	Remarks
Thrust Bearing Roller Diameter			
Radial Bearing Roller Diameter			
Bearing Pack Rotating Seal Clearance			
Turbine Rotor Blades Nominal Mid-Length Thickness			
Nominal Tip Clearance			
Stator Vanes Nominal Mid-Length Thickness			

Drill Bits:	Cutting Element Height	Thickness	Condition
Christensen STRATAPAX			
(Sandia STRATAPAX)			
Christensen Diamond Bit			

Prior to performing tests, grab samples of drilling mud to be used will be obtained by MEI and analyzed to ascertain weight, viscosity and gel properties, and recorded on a data sheet as per Table 5-3 (MEI).

(2) Hold Pre-Test Review to Ascertain Test Readiness

Conduct a scheduled meeting involving representatives from all test participants to review all pertinent preparations made to date. The objective is to determine that all test prerequisites have been satisfied and are properly documented, especially instrumentation and turbodrill configuration. Rig safety will be discussed and appropriate procedures outlined by the rig operator.

(3) Clean Out Well Using Conventional Mud Circulation Techniques

Clean out existing test well to 650 feet with the rotary rig to establish vertical borehole for straighthole turbodrill testing (GO). Ream to full gauge (7-7/8 inch), if necessary. Observe and record rock chip appearance and mud condition (MEI). Circulate for one day prior to drilling to clear out excessive abrasive solids from mud system.

(4) Break-in Turbodrill

Install turbodrill and break-in for 15 minutes with the tool suspended on drill pipe in the borehole (off bottom or near the surface) without doing any rock cutting and without any axial loads being applied to the drill motor. Check out operation of system. Check all instrument responses.

(5) Drill with Reed Roller-Cone Bit

Mount a Reed 7-7/8 inch tri-cone roller bit and drill for 3 to 5 hours (GO). Pull drill string sooner if there are any indications of trouble. Set the mud pump to deliver a constant flow rate of 250 gpm (GO). After 15 minutes, increase mud flow

Table 5-3. Mud Properties

BASE: Water

PHASES: (i) Water
(ii) Solids
(a) Bentonite/Kaolinite
(b) Barite
(c) Drill Solids
(iii) Additives

WEIGHT:	pounds/gallon
APPARENT VISCOSITY:	cp
PLASTIC VISCOSITY:	cp
YIELD POINT:	pounds/100 square feet
INITIAL GEL:	pounds/100 square feet
10 MINUTE GEL STRENGTH:	pounds/100 square feet
pH:	
API FILTRATE:	cc/30 minutes

rate to 300 gpm (GO). After drilling for another 15 minutes, increase bit-weight by 50 percent and drill for 15 minutes (GO). Then set conditions (bit-weight and mud flow rate) that permit maximum penetration rate and drill for time remaining. Record test variable responses (MEI). Maintain constant mud properties (GO). Observe and record appearance of cuttings; note size and texture, in particular (MEI).

(6) Drill with Sandia STRATAPAX Bit

Drill with a 6-3/4 inch Sandia STRATAPAX bit for 3 to 5 hours. Repeat the sequence of procedures carried out in (5) above (GO). Sequence test and record all data as follows:

Initially, drill at a mud flow rate of 250 gpm and bit-weight used in (5) above (GO). This will establish a common starting point when using different drill bits. After 15 minutes, increase mud flow rate to 300 gpm (GO). After drilling for another 15 minutes, increase bit-weight by 50 percent and drill for 15 minutes (GO). To check for reproducibility, reestablish the initial test conditions in (5) and run for 15 minutes (GO). Use time remaining to drill at conditions permitting maximum rate of penetration. Monitor observations and record all data as per (5) above (MEI).

(7) Drill with Christensen STRATAPAX Bit on Turbodrill

Drill using the 6-1/2 inch Christensen STRATAPAX bit mounted on the turbodrill for 3 to 5 hours (GO). Use the piggyback stabilizer. Follow instructions in (6) above.

(8) Drill with a Conventional Diamond Bit

Drill for 3 to 5 hours using the 6-1/2 inch conventional diamond bit from Christensen Diamond Products (GO), using the piggyback stabilizer. Repeat the sequence of operations employed and follow instruction in (6) above. Record all data in like manner.

(9) Perform a Straighthole Endurance Test

Run a 1-1/2 day straighthole endurance drilling test. Use the best performing drill bit. Use the bit-weight and mud flow rate to maximize penetration rate as in previous tests, as specified by the test director. However, begin this test with the initial bit-weight and mud flow rate used when the particular drill bit was first run. This is done for 15 minutes to check reproducibility in drill bit and turbodrill performance as specified in (6) above.

(10) Conduct a Directional Drilling Test

Install the turbodrill in the drill string with a 1-1/2° bent sub. Perform a 2-1/2 day directional drilling test under the same test conditions and using the same procedures for obtaining initial data to check reproducibility and subsequent data as used in the straighthole endurance test in item (9) above. Obtain periodic bottomhole location surveys every 100 to 200 feet in the directional hole or as stated by the test director.

(11) Transport Turbodrill to MEI Shop in Houston

Remove the turbodrill from the drilling string, package it, and transport by truck to MEI's assembly and inspection facility in Houston (MEI).

After testing is done, make note of wear and damage to drill bits, measure and record cutting element critical dimensions according to Table 5-2 for determination of wear rates on bits. Note rounding of cutting edges and any chipping, cracking, or pitting (MEI).

(12) Inspect and Service Turbodrill (MEI)

This is the only drill motor teardown and inspection/wear measurement to be performed in Phase II. Especially careful examination will be made of all rotating and mating parts in the turbine and bearing packs. Damage and wear characteristics will be noted: disassemble the turbine pack and bearing pack and visually inspect parts for signs of wear and degradation. Obtain and record micrometer measurements of all critical dimensions of

vital components, such as thrust and radial bearing rollers, turbine blade and stator vane width, and thickness (at mid-chord and mid-length), and nomimal tip clearance. Record all visual signs of erosion, pitting, scoring, and other degradation of metal parts on data sheets as per Table 5-2. Take 8" x 10" photographs of all parts showing signs of wear during each inspection. Service and replace worn or damaged parts in the bearing package, as needed, and reassemble the drill motor.

(13) Conduct Conventional Rotary Drilling between Turbodrill Tests (GO)

Obtain data on conventional rotary drilling rates between turbodrill tests whenever possible during the test program. These data will supplement and verify the offset well data that GO already has from previous drilling. In each instance the drill bits and drilling parameters used will correspond to those used immediately before in the last turbodrill run.

6.0 TEST EVALUATION AND DELIVERABLES

6.1 DATA ANALYSIS AND REPORTING

Evaluation and reporting of the test results is the responsibility of TRW. Significant results shall be conveyed to METC and MEI verbally, by technical memoranda, and by written reports.

The report contents are as follows:

- Data analysis and test results pertaining to turbodrill operation on a conventional oilfield drilling rig
- Observations pertaining to field application of a turbodrill. Information to aid operators in optimizing use of turbodrills in the field
- Assessment of wear rates of critical components and determination of expected service life expectancies of these parts
- Recommendations concerning future turbodrill testing. Updating of Phase III test planning with regard to field testing of the turbodrill in placing a directional borehole in a horizontal coal seam
- Assessment of the test results from a programmatic viewpoint. Correlation with the results of other projects. Recommendations for possible changes in project planning or adjustments in emphasis in other projects

6.2 TEST PROJECT DELIVERABLES

Required deliverables are listed below:

- A draft final test report shall be submitted to METC and MEI for comment within thirty days after termination of testing
- Three copies of the final test report shall be submitted to METC and two copies to MEI within thirty days after receipt of comments

Phase II of the project will be considered complete when all of the test activities listed in Subsection 5.1 and the reporting requirements above have been completed.

UGR File #462
TRW
Final Report
August 1980

APPENDIX B

PRE-PHASE II TEST DATA

This appendix contains the raw data obtained in pre-Phase II testing of the 5-3/8 inch turbodrill at Terra Tek in Salt Lake City, Utah on April 10-11, 1979.

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 1	102	145	378	525	39	91	3862	0.4	Start up Hole #1
	103	147	426	556	39	87	5716	0.4	Roller-cone bit in granite
	104	143	382	560	34	96	6103	0.4	
	105	145	369	565	39	105	6156	0.4	
	106	147	390	566	38	100	6117	0.4	Water flow rate is 150 gpm
	108	148	372	574	31	108	6451	0.5	
	110	148	393	570	38	112	6504	0.5	
	111	147	410	570	35	112	6459	0.5	
	112	148	417	570	40	108	6462	0.6	
	113	149	401	569	48	112	6456	0.6	
	114	149	402	569	34	114	6704	0.6	
	115	149	371	567	40	116	6881	0.6	
	116	149	390	575	43	116	6486	0.6	
	117	148	387	569	36	115	6483	0.7	
	118	147	404	573	50	119	6462	0.7	
	119	148	378	571	31	118	6498	0.7	
	120	147	383	572	42	118	6521	0.7	
	122	143	379	568	37	124	6710	0.8	
	123	146	342	572	41	125	6810	0.8	
	124	145	405	571	38	124	6454	0.8	
	125	143	374	569	41	119	6498	0.8	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 1	127	146	348	570	47	127	6474	0.9	
	128	143	358	569	40	128	6698	0.9	
	129	147	357	570	38	128	6840	0.9	
	130	145	319	566	41	135	7114	0.9	
	131	147	233	556	40	142	7226	1.0	
	132	144	229	552	42	136	7028	1.0	
	133	145	243	547	43	130	6498	1.0	
	134	149	257	553	39	135	6566	1.0	
	135	149	215	547	40	132	6498	1.0	
	136	148	252	546	39	137	6504	1.0	
	137	150	227	545	39	129	6445	1.1	
	138	152	232	544	43	137	6347	1.1	
	139	150	222	542	44	131	6342	1.1	
	140	143	180	541	45	132	6306	1.1	
	141	145	226	541	43	124	6094	1.1	
	142	148	248	549	40	127	6112	1.2	
	143	150	224	555	43	129	6097	1.2	
	144	149	228	562	39	148	6132	1.2	
	145	149	260	565	40	143	6462	1.2	
	146	152	255	566	44	153	6462	1.2	
	147	150	256	565	40	151	6689	1.2	
	148	147	238	572	38	158	6854	1.2	
	149	146	297	567	38	146	6683	1.3	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 1	150	150	275	574	38	156	7235	1.3	
	151	145	267	568	44	163	7220	1.3	
	152	149	251	564	43	156	6866	1.3	
	153	144	245	559	40	155	7244	1.3	
	154	152	231	557	37	149	6840	1.3	
	155	150	271	561	41	144	6854	1.3	
	156	148	255	567	42	160	7238	1.4	
	157	146	243	565	38	152	7217	1.4	
	158	146	272	569	43	152	7096	1.4	
	159	147	242	568	42	165	6866	1.4	
	160	147	267	573	37	153	7232	1.4	
	161	146	235	567	42	156	7238	1.4	
	162	151	248	572	40	158	7238	1.5	
	163	146	235	570	43	157	7220	1.5	
	164	152	264	569	37	155	6878	1.5	
	165	152	221	566	39	150	7247	1.5	
	169	143	644	538	36	71	8692	1.5	
	171	142	300	541	39	126	6501	1.6	
	178	145	140	503	34	109	5374	1.6	
	180	154	280	555	39	128	6669	1.6	
	181	154	350	570	41	132	6424	1.7	
	182	155	316	574	41	131	7217	1.7	
	183	157	280	587	43	146	7347	1.7	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date	Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79	1	184	156	350	602	47	134	7618	1.7	
		185	153	266	607	45	159	7981	1.7	
4/10/79	2	194	191	212	872	45	280	12,869	1.8	Changed Flow rate to 200 gpm
		195	193	299	905	48	284	12,550	1.9	
		196	200	239	935	44	298	14,325	1.9	
		197	201	185	941	50	311	14,352	1.9	
		236	197	35	832	45	219	8352	3.0	
		244	198	25	1046	44	157	9195	3.0	
		245	197	13	1049	45	206	11,778	3.0	
4/10/79	3	14	146	443	550	38	160	6750	13.1	Hole #2 Roller-cone bit in granite
		16	146	595	555	43	149	7178	15.1	
		19	144	340	545	40	180	9119	17.3	
		22	146	401	538	37	175	3491	17.0	Water flow rate is 150 gpm
		26	149	477	553	36	189	8305	16.6	
		28	151	449	571	46	189	8264	15.4	
		29	144	361	578	37	195	8358	14.9	
		30	151	425	573	42	197	8741	14.5	
		31	148	423	582	46	197	8815	14.1	
		32	152	483	586	47	196	8320	13.7	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 3	33	154	397	591	43	205	8420	13.4	
	34	155	465	597	43	198	8706	13.1	
4/10/79 4	49	196	312	858	52	332	13,992	13.1	Changed flow rate to 200 gpm
	51	191	452	891	51	324	14,022	13.4	
	52	190	366	897	53	347	14,753	13.5	
	53	195	343	906	50	359	14,750	13.6	
	54	197	533	956	52	335	14,685	13.8	
	55	198	318	968	54	378	15,656	13.9	
	56	201	370	974	58	378	15,494	14.1	
	57	197	519	997	56	365	15,497	14.3	
	58	196	519	1011	61	363	16,098	14.4	
	59	204	432	1022	55	425	18,196	14.9	
	61	207	505	1060	61	429	19,308	15.6	
	62	210	357	1075	58	466	20,131	16.1	
	63	207	377	1076	50	458	20,391	16.5	
	64	210	310	1078	54	464	19,901	16.9	
4/10/79 5	80	239	67	1336	59	593	22,358	6.5	Changed flow rate to 250 gpm
	82	238	563	1384	56	499	21,116	14.3	
	84	238	581	1385	57	514	21,172	20.1	
	86	241	510	1392	55	530	21,509	24.7	
	87	246	562	1457	64	504	21,683	26.7	
	88	250	534	1477	64	548	23,060	28.6	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 5	89	251	211	1479	65	618	24,579	30.2	
	91	260	526	1607	79	621	25,574	36.9	
	92	259	498	1623	78	665	27,161	41.9	
	117	256	341	1692	57	627	26,521	12.5	
	118	258	328	1494	52	720	23,308	27.4	
	119	257	664	1553	52	550	22,700	36.7	
	121	258	741	1581	41	562	24,225	40.7	
	123	257	316	1552	31	614	25,113	37.7	
	132	246	441	1284	-	477	19,278	2.0	Return line pressures fell off abruptly - obstruction in line probably
	133	245	361	1330	-	503	20,397	6.8	
	134	255	526	1390	-	548	21,939	30.9	
	144	238	441	1235	-	489	20,397	42.5	
	145	242	506	1260	-	481	20,099	41.2	
	146	242	481	1290	-	499	20,765	40.2	
	147	238	572	1311	-	492	21,385	40.1	
	148	240	360	1306	-	545	22,677	40.0	
	149	249	507	1370	-	532	22,671	40.1	
	150	248	561	1396	-	537	23,069	40.2	
	151	250	468	1409	-	569	23,444	40.3	
	152	248	354	1425	-	571	24,063	40.6	
	153	251	460	1406	-	563	23,043	40.5	
	154	252	394	1418	-	577	21,913	40.4	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 5	155	254	374	1431	-	582	21,122	40.1	
	156	260	279	1440	-	597	21,895	39.8	
	163	242	562	1266	-	491	19,798	41.4	
	164	243	486	1289	-	510	20,662	38.8	
	165	248	502	1302	-	521	20,332	37.9	
	166	247	433	1322	-	536	21,898	37.7	
	167	246	322	1335	-	551	21,919	37.6	
	168	254	373	1385	-	574	22,379	37.0	
4/10/79 6	39	144	520	520	33	163	7142	4.4	Hole #3 Roller-cone bit in granite
	41	147	384	536	38	191	8357	4.5	
	42	143	408	543	36	202	8697	4.6	
	43	150	419	547	32	199	8688	4.7	
	44	155	377	557	37	208	8318	4.7	Water flow rate is 150 gpm
	45	156	415	576	46	215	9060	4.8	
	46	155	400	590	34	222	9432	4.9	
	47	157	409	603	40	228	9607	5.0	
4/10/79 7	53	194	544	859	51	314	13,983	5.7	Changed flow rate to 200 gpm
	55	197	441	915	44	372	16,838	6.1	
	56	202	470	942	50	377	16,988	6.3	
	57	195	352	966	50	399	17,269	6.5	
	58	199	370	989	52	417	16,282	6.7	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 7	60	206	423	984	45	406	16,196	7.0	
	61	199	260	994	48	428	16,657	7.1	
	62	200	251	992	54	434	16,143	7.3	
	64	205	422	992	46	407	15,821	7.5	
	65	198	419	1004	53	412	16,182	7.6	
	66	199	334	995	51	424	16,288	7.7	
	68	198	267	1007	49	437	17,018	7.9	
	69	206	266	985	47	439	16,578	8.0	
	70	207	261	975	48	430	16,303	8.1	
	72	199	210	975	48	439	16,994	8.2	
4/10/79 8	87	240	545	1334	49	497	19,778	9.5	Changed flow rate to 250 gpm
	88	240	509	1369	59	528	20,913	9.6	
	89	241	545	1398	61	538	21,781	9.7	
	96	242	635	1513	55	546	22,106	34.5	
	97	240	547	1493	69	568	23,374	50.1	
	98	239	523	1474	63	572	23,312	56.2	
	100	242	445	1418	56	577	23,064	45.5	
	101	239	189	1414	57	600	23,667	49.1	
	108	242	749	1414	52	489	18,696	41.0	
	119	239	524	1532	61	511	20,868	36.4	
	120	241	438	1488	69	534	21,170	37.0	
	121	244	133	1425	65	602	21,811	37.3	
	122	243	454	1421	60	526	20,206	37.6	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 8	123	244	381	1422	61	537	20,304	37.7	
	124	242	482	1411	56	517	20,224	37.9	
	125	243	418	1417	62	529	20,330	38.0	
	126	241	410	1417	58	533	20,307	38.0	
	127	241	438	1416	56	525	20,392	38.0	
	128	243	309	1405	57	548	21,226	38.0	
	129	246	434	1424	58	531	20,313	38.0	
	130	252	476	1455	44	540	20,963	37.9	
	131	250	516	1490	52	527	21,167	37.8	
	132	253	509	1512	55	540	21,832	37.8	
	133	253	540	1521	57	550	21,941	37.8	
	134	251	419	1535	39	575	22,934	37.8	
	135	256	455	1527	75	569	22,730	37.9	
	136	253	499	1535	59	569	22,588	37.9	
	137	255	340	1522	61	607	23,055	37.9	
	138	254	338	1522	56	599	22,532	37.9	
	139	255	512	1536	52	570	21,926	37.9	
	140	255	405	1546	66	594	22,656	37.9	
	141	259	509	1567	51	571	22,482	37.9	
	142	255	506	1582	58	576	22,919	38.0	
	143	258	256	1545	64	649	23,442	38.0	
	144	261	469	1577	65	597	23,315	38.0	
	145	259	549	1603	73	591	23,291	38.1	

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Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/10/79 8	146	261	316	1585	62	616	24,219	38.2	
	147	259	364	1603	51	623	24,077	38.2	
	148	261	274	1572	49	639	23,675	38.2	
	149	262	476	1584	50	614	22,949	38.2	
	150	261	378	1586	59	621	23,395	38.3	
	151	261	579	1599	61	592	23,008	38.3	
	152	259	489	1608	55	607	23,554	38.3	
	179	239	413	1279	53	466	21,864	38.5	
	180	240	376	1288	57	465	22,127	38.4	
	181	240	299	1266	56	472	21,897	38.1	
	182	238	370	1268	47	457	21,374	37.6	
	187	238	141	1221	57	497	21,403	35.1	
	188	239	237	1225	55	455	21,125	34.4	
	190	238	655	1263	49	417	19,406	33.3	
	192	240	663	1168	54	371	13,584	-	
	194	239	571	1256	60	397	19,627	51.4	
	197	240	337	1254	57	459	22,284	44.8	Stop for the day to change rock sample and bit
	198	239	191	1252	52	487	22,502	42.4	
4/11/79 9	14	103	357	300	25	102	673	4.8	Hole #4 STRATAPAX bit in Carthage marble Water flow rate is 100 gpm

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/11/79 10	24	258	274	1682	66	670	2203	13.6	Changed flow rate to 250 gpm
4/11/79 11	40	150	251	556	32	247	1784	4.1	Changed flow rate to 150 gpm
4/11/79 12	44	205	104	898	44	402	2041	7.1	Changed flow rate to 200 gpm
	46	203	220	991	40	421	1996	7.4	
	49	210	488	1062	40	370	1504	4.0	
4/11/79 13	58	152	0.5	494	37	237	1861	1.6	Changed flow rate to 150 gpm
4/11/79 14	85	200	438	929	47	370	2450	22.2	Changed flow rate to 200 gpm
4/11/79 15	114	253	430	1493	41	527	3615	37.1	Changed flow rate to 250 gpm
	115	259	448	1603	56	563	3680	37.8	
	116	260	485	1695	62	587	3680	38.3	
	118	262	482	1749	40	614	3883	32.8	
	119	262	480	1765	51	614	3986	33.2	
	120	261	480	1782	41	621	4028	38.8	
	121	262	485	1795	37	625	4048	38.1	
	122	261	474	1798	36	620	4063	37.1	
	123	261	470	1792	65	622	4054	40.1	
	124	261	459	1808	72	614	4160	41.3	
4/11/79 16	19	143	187	506	52	159	1291	11.5	Hole #5 STRATAPAX bit in Carthage marble Water flow rate is 150 gpm

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/11/79 17	23	96	504	320	41	66	-	-	Changed flow rate to 100 gpm
	26	101	620	255	15	52	757	4.9	
4/11/79 18	34	150	152	497	31	167	1371	8.8	Changed flow rate to 150 gpm
4/11/79 19	39	197	110	765	40	258	1712	10.0	Changed flow rate to 200 gpm
4/11/79 20	53	145	226	509	38	159	3198	16.1	Changed flow rate to 150 gpm
	56	151	499	603	24	164	3767	13.0	
	57	152	389	616	26	187	3932	14.2	
4/11/79 21	63	194	155	856	30	287	5182	19.1	Changed flow rate to 200 gpm
4/11/79 22	70	101	499	321	2	67	371	2.6	Changed flow rate to 100 gpm
	71	97	654	318	2	54	489	2.3	
	72	95	600	249	1	55	351	2.6	
	73	97	630	308	1	61	698	3.0	
4/11/79 23	75	152	683	525	3	133	852	4.3	Changed flow rate to 150 gpm
4/11/79 24	90	249	234	1395	37	467	1391	6.8	Changed flow rate to 250 gpm
	91	250	251	1469	47	491	1353	7.6	
	92	257	269	1534	45	514	1309	8.1	
	93	259	270	1614	45	538	1459	8.5	

TABLE B-1. Test Data Obtained at Terra Tek - Maurer Engineering 5-3/8 Inch Turbodrill

Date / Run No.	Data Record No.	Water Flow Rate gpm	Rotary Speed rpm	Inlet Pressure psi	Return Line Pressure psi	Output Torque ft-lb	Weight On Bit lbs	Rate Of Penetration ft/hr	Remarks
4/11/79 25	102	190	514	698	36	192	690	0.4	Changed flow rate to 200 gpm
	115	191	517	905	37	267	283	14.4	
	116	206	495	1008	42	309	510	15.4	
4/11/79 26	119	241	542	1354	46	421	1020	18.7	Changed flow rate to 250 gpm
	120	245	559	1448	49	443	1146	19.7	
	121	252	551	1523	52	468	1297	20.6	
	122	254	558	1614	47	495	1565	21.5	
	123	261	575	1703	49	518	1801	22.4	
4/11/79 28	128	288	570	2124	52	663	1621	22.6	Changed flow rate to 300 gpm
	129	295	567	2229	50	695	1659	27.2	
	130	298	590	2300	48	715	1695	27.7	
	131	302	581	2390	49	736	1739	28.2	
	132	306	605	2425	30	760	1766	28.5	
	133	305	599	2489	38	776	1842	28.8	
	134	306	573	2490	32	786	1925	29.0	
	135	305	583	2495	53	788	1881	29.2	
	136	303	596	2505	50	778	1966	29.4	
	137	303	461	2504	57	780	1913	29.5	
	138	305	186	2494	42	784	1901	29.7	
	139	305	28	2497	57	784	1863	29.8	
	140	306	8	2510	44	790	1786	29.9	