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ELECTRODRIL SYSTEM FIELD TEST PROGRAM

Phase II, Task B: Deep Drilling System Demonstration, Final Report

MASTER

December 15, 1978

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General Electric Company
Space Division
Houston, Texas

U. S. DEPARTMENT OF ENERGY

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FINAL REPORT

ELECTRODRIL SYSTEM FIELD TEST PROGRAM

PHASE II

TASK B

DEEP DRILLING SYSTEM DEMONSTRATION

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Submitted to

U.S. Department of Energy
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Submitted by

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1.0 SUMMARY

This report documents the results of the Phase II, Task B effort of the Electrodril Deep Drilling System. This effort included the design, fabrication and Systems Verification Testing of the Deep Drilling System. The Systems Verification Test was conducted, during October 1978, in a test well located on the premises of Brown Oil Tools Inc., Houston, Texas

The Systems Verification Test was the culmination of a joint U.S. Department of Energy, Industry and General Electric effort to procure, assemble and demonstrate the key elements of the Electrodril Deep Drilling System preparatory to further demonstrations in a series of operational wells.

In general, the Systems Verification test program was an unqualified success. All of the system elements of the Deep Drilling System were exercised and evaluated and in every instance the system can be declared ready for operational well demonstration.

The motor/bit shaft combination operated very well and post test inspection indicates that seal performance exceeds the design goals. The redesigned oil compensation system demonstrated a usable life in excess of 100 hours between refills.

The rig floor system performed better than expected. The power cable flexural characteristics are much better than anticipated and longitudinal stability is excellent. The area of prime concern relating to cable/connector deployment

over the floor and traveling sheave appears to be groundless. The cable/connector combination, together with the cable slips worked flawlessly. Industry observers have remarked on how easily the cable can be deployed and retrieved.

The prototype production connectors have functioned without failure. The reliability of these devices have been increased tremendously since the initial Phase I tests. During the first test day, six consecutive successful remote matings were recorded and no connector failures were recorded during the entire test program.

The cable reels and drive skid have also worked very well during the test program. The key to this success is careful deployment at the test site and the attention given to correct alignment of the skid axis to the rig vee door.

The power generation subsystem had been extensively tested some months before the onset of the Systems Verification Test program. No major power related problems were therefore expected and none were experienced.

The redesigned and expanded instrumentation subsystem also functioned very well. The downhole unit had been expanded to include an all new formation sensor sub which doubled as the control center for the Electrodril heat sub (deviation sub). Both the formation sensor and the heat sub were developed

independently for application to the Field Test Program. Both of these subs were exercised extensively in the laboratory as their deployment in a cased well limited their full function as part of the Electrodrill drill string. Some electronic component malfunctions were experienced during the early test stages. These problems were isolated quickly and repaired. Subsequent downhole instrumentation deployments were successfully executed and downhole data was displayed both in the Electrodrill instrumentation trailer and on the remote control and display unit.

In general, the test program proceeded very smoothly. The last week of the Task B Program the test well deployment of the Deep Drilling System was demonstrated to the Department of Energy and Industry personnel. These observers agreed, unequivocally, that the Electrodrill Deep Drilling System was ready for field deployment and operational drilling demonstrations.

2.0 INTRODUCTION

The Electrodril Deep Drilling System field test program was initiated in July of 1977. The program was divided into three major tasks to provide the means by which technological progress can be measured and to afford the program major milestones at which time program control decisions can be made.

The first major task (Task A) encompassed the completion of the design engineering and preprocurement documentation effort in preparation for the release of the system design to manufacture.

The second major task (Task B), which began in May of 1978, covered the manufacture, assembly and system verification testing of the Deep Drilling System. The results and the conclusions drawn from the Systems Verification test are presented in this document.

In executing the Task B effort, maximum advantage has been taken of the lessons learned in conducting the Phase I Directional Drilling System Field Test Program. The cable connectors, for example, have been redesigned to make them more rugged and to improve their water blocking capability. In addition, the mating connector design was modified to make it possible to field assemble and replace connectors on the cable. Product improvement has been continued on the downhole motor lower seals and oil compensation system to extend the operational life of the motor to at least 100 hours between refurbishment.

The bit shaft has been redesigned with a new lower seal assembly to assure an operational life between refurbishment of at least 100 hours. Power cable surface handling equipment designs and their operating procedures have also been modified to minimize handling time. Numerous component and subsystems tests have been conducted to assure that these design modifications are technically valid and correctly implemented. A technical description of the system configuration selected is presented in Appendix A.

The intent of the Systems Verification Test was to demonstrate the functional capability of all the Deep Drilling System elements and the total, integrated system and to exercise and evaluate the planned Electrodrill operating procedures to assure their compatibility with existing drill rig procedures. Prior to integration of the Electrodrill system elements at the Brown Oil Tools test facility, all subsystems had been individually tested to assure their readiness for the Systems Verification Test.

3.0 DESIGN CONSIDERATIONS

The basic elements for the Deep Drilling System were demonstrated in a test well during December 1976. The Phase II design effort was directed towards refining system design and incorporating the lessons learned from the Phase I Field Test Program. Specific areas of design work conducted during the Task B effort are described below:

POWER GENERATION SUBSYSTEM

The Electrodril Deep Drilling System power requirements are essentially as follows:

Primary Power: 240 V to 3300V, 3 phase, with variable AC frequency ranging from 12 to 120 Hz. Continuous current rating from 22 to 75 amps.

Secondary Power: 280V, 3 phase, 60 Hz AC
110V, single phase, 60 Hz AC

The satisfaction of these power requirements can be accomplished by two methods:

1. The use of a diesel prime mover coupled to a DC generator to develop basic DC power. The DC power is then applied to DC motor which in turn drives an AC alternator. By varying the speed of the DC motor through changes in excitation voltage, variable frequency AC is generated at specific voltages. Control for the DC motor excitation is developed from

inputs from the downhole current and voltage sensors. A schematic of this power generation approach is shown in Figure 1.

2. The use of a diesel prime mover driving an AC alternator to produce 440V, 60Hz. The 440V AC output is then applied to a static inverter which converts the AC to DC and subsequently "chops" the DC output at varying rates, upon demand, to create variable frequency "pseudo" AC. Control for the DC "chopping" is developed from inputs from the downhole current and voltage sensors. A schematic of this power generation approach is presented in Figure 2.

Both power generation schemes are "demand response" systems and as such their relative ability to respond quickly to the power requirements of the Electrodrill motor is key to the selection decision. Given power demand situations in which the power spectra fluctuate rapidly, as is the case with the Deep Drilling System, the inherent magnetic inertia of the "rotary" system depicted in Figure 1 makes it unsuitable for Electrodrill application. The static inverter system is capable of responding to these power fluctuations. The supporting downhole sensory system and surface controllers must however, be capable of sensing demand and switching power levels at high rates.

A series of studies were made to establish the design characteristics of the static inverter power controller and to determine its transient response capability. Two basic technical approaches were identified as having applicability to the power controller problem: current limiting and voltage limiting.

FIGURE 1
ROTARY POWER GENERATION

FIGURE 2
STATIC INVERTER POWER GENERATION

Neither approach can cover the full power demand spectra of the downhole motor. The best technical compromise is a combination of the two approaches.

As a result of these studies, the decision was made to measure downhole motor voltage and send it to the surface. Current will be measured at the surface downstream of the power converter and output transformer and the rate of change of these two parameters, together with their phase relationship will provide the basis for modulating the static inverter power controller.

The power controller was not planned to be part of the power generation subsystem during the Systems Verification Test at Brown Oil Tools. The plan was to run the system "open" so that voltage and current demand characteristics can be verified before the Field Test demonstrations are begun.

CABLE AND CABLE HANDLING SUBSYSTEM

A general layout of this subsystem at a typical rig site is shown in Figure 3 and consists of a powered cable spool for deploying the electrical cable downhole and the rig floor system which is designed to facilitate cable deployment in and out of the well and to accommodate the rotating/non-rotating environment surrounding the drill string.

Rig Floor Assembly. The technique for deploying the cable at the rig floor differs from that used in the Phase I Directional System in that the Deep Drilling System must provide means for drill pipe rotation to obviate the potential for differential sticking. Pipe rotation will be achieved using

FIGURE 3

TYPICAL ELECTRODRILL SET UP
AT DRILL SITE

the conventional rotary table/kelly combination. Electrical connection to the downhole cable (rotating) and the surface cable (non-rotating) is made through a slip ring assembly located below the rig power swivel (Figure 4). Mud circulation will be made in the conventional manner through a circulating head above the power swivel. A kelly cock will be inserted between the circulating head and slip ring assembly to provide hydraulic safety. The relative desirability of using a power sub (or swivel) to make up the drill string and to rotate the string during the drilling operation was investigated. The consensus of an industry survey made during this time period indicated the preference for the use of the rotary table/kelly combination. Subsequent design reviews have corroborated these findings. Thus, the method of rig floor deployment to be used for the Phase II drilling program will be essentially identical to that successfully demonstrated during the Phase I Deep Drilling Program.

The hole will be drilled ahead 90 feet utilizing two prewired dedicated joints of drill pipe and the prewired kelly. These will then be removed and replaced with a 90 foot stand of prewired pipe. This sequence will be repeated 10 times (a total depth of 1000 feet) at which time the prewired pipe is withdrawn and substituted with standard drill pipe and 1000 feet of cable. This prewired pipe is utilized in place of standard drill pipe for the first 1000 feet to maintain electrical continuity with the deployed downhole lengths of Electrodrill cable during drilling operations. Each succeeding 1000 feet of hole is drilled in a similar manner to a depth of 5000 feet, at which time the prewired pipe is replaced with standard drill

Figure 4
ELECTRODRIL SLIP RING ASSEMBLY

pipe and a 5000 foot length of Electrodril cable is mated downhole with the previously deployed cable. An electrical crossover sub located below the slip ring assembly allows the transition of the electrical cable from inside the drill pipe bore to the outside of the slip ring assembly.

Cable and Connectors. The Electrodril cable requires a total of four conductors as shown in Figure 5. To supply downhole electrical power to the motor, three conductors of No. 6 AWG will be used. A smaller center conductor of No. 18 AWG will be used for instrument power and data transmission. The cable will be composed of multistranded conductors to assure cable flexibility and will be housed in a double layer of torque balanced steel armoring to carry the weight of the cable and provide a return for the instrument power. The cables are connected through specially designed field replaceable connectors (Figure 6) which allows easy assembly of the cable sections while providing high electrical reliability. The cable is supported in the drill pipe by cable hangers which provide cable stability during drilling operations. The hanging weight of the suspended cable is less than 20% of the cable breaking strength.

The importance of keeping both cable and connectors free from water intrusion was shown in Phase I. The cable and connectors used in the Deep Drilling System will be 100% tested to provide assurance that water will not present a problem at the pressures which will be encountered.

Preliminary design trade-offs centered around the selection of a cable design cross-section with basic materials capable of withstanding bottom hole temperatures

Figure 5
Deep Drilling System
Power Cable

Figure 6
FIELD REPLACEABLE CONNECTOR

of 350°F while maintaining high dielectric strength. The requirement for the particular conductor geometry was to obviate inductive coupling between the high voltage motor conductors and the centrally located instrument lead. Material choices for the conductor insulation are currently quite limited due to the downhole environment. EPDM, or EPC polymers were recommended, but after further performance investigation of each it was found that EPC had a very limited downhole life at 300°F or higher. The final insulation selection was therefore EPDM.

Cable Reels. The hydraulic drive cable reels to be used for the Deep Drilling System will accommodate a total of 19,000 feet of cable. The selected cable reel skid arrangement is shown in Figure 7. A total of five reels will be required; three 5,000 foot cable reels, and two duplex 1,000 foot reels. In an effort to minimize "open hole" time, Phase I cable reel up speed has been increased to a maximum of 400 ft/min. This speed is over twice that used for the directional drilling system and is considered adequate for the field test demonstrations. The need for positive cable laydown (spooling) control was also investigated. It was concluded that so long as the cable fleet angle was held to less than 1° there was no need for spooling control. The decision was made to provide cable bedways on the reel drums to minimize the lower tier cable crush loads.

The selection of hydraulic power for the reels was made after trade studies indicated that from a skid weight, safety and economic viewpoint an AC or DC electric system would not be as efficient. The hydraulic system chosen operates

Figure 7
ELECTRODRIL CABLE REEL SYSTEM

nominally at 1500 psi and has automatic fail safe (lockup) features incorporated.

MOTOR SUBSYSTEM

The Phase II Electrodril motor subsystem, excluding the deviation sub and monel collar for the instrumentation, is a total of 51 feet in length, and 7 3/4" in diameter. A cutaway of this assembly, together with pertinent dimensions, is shown in Figure 8. The motor subsystem is electrically protected at the surface. In the event of an overload situation, current sensors will trip the power generation circuit breakers to prevent motor damage. Motor temperature will be sensed downhole and displayed at the surface.

Motor. The Phase II Electrodril motor is centered around a standard industrial REDA type 540 submersible pump motor rated at 150 HP at 1150 V 60 Hz. At this rating the motor has a speed of 3200 rpm. The output of the motor is put through a 16 to 1 gear reduction so that when the motor is operated through its planned range, the effective bit speed range will be from 40 to 400 rpm. Motor speed is varied by changing excitation frequency, which for this system will range from 12 Hz (35 HP) to 120 Hz (285 HP).

A normal start for the Electrodril motor will begin at 12 to 30 Hz depending upon length of cable deployment. This low frequency start is made to minimize the motor inrush current. The motor is then brought up to speed as dictated by the bit type and formation to be drilled.

Figure 8

285 HP ELECTRODRIL MOTOR ASSEMBLY

Gearbox and Protector. The motor gearbox is a double train planetary reduction unit designed and tested to withstand weights on bit of up to 70,000 lbs. and torques in excess of 3,500 lb. ft. A shock absorber unit is provided to isolate the motor from the shock loads produced by the drilling operation. A slip clutch unit, designed to safeguard the motor in the event the bit is suddenly stopped is also included. Internal oil pressure compensation bags are also provided in this assembly to assure that the internal oil pressure is the same as the mud pressure in the mud tube thus maintaining an almost zero pressure drop across the lower motor seals. The oil leakage over the lower motor seal is thus held to a minimum and the seal surface wear characteristics are idealized. Seal leak tests have been conducted. Data from these tests indicates that the Electrodrill design will exhibit less leakage than the manufacturers estimate of 6cc/hr. Pressure compensation bags have been designed with a capacity to accommodate more than a 200 hour downhole deployment.

Bit Shaft. The bit shafts used in the Phase I Program will not be used in the Deep Drilling test program as their bearings and seals are inadequate to withstand the higher downhole temperatures and pressures. A new bit shaft has been designed to incorporate metal-to-metal seals capable of withstanding pressure differentials in excess of 2,000 psi and bearings rated to accommodate weights on bit of up to 70,000 lbs. and the more severe downhole environment. In addition, the pressure compensation bag in the new assembly has been designed with sufficient oil capacity to assure lubrication is maintained at least for the life of a diamond bit (i.e., 200 hours). The oil is then replenished each time the drill bits are replaced or at intermediate times when the drill string is removed for other reasons.

The seal and bearing design chosen has been utilized extensively in downhole water pump applications. A special internal flush feature assures positive oil to mud leakage to minimize the potential for mud intrusion. In addition, a grease packed labyrinth seal is incorporated into the seal housing to act as a primary mud barrier.

Test data to date on this Electrodrill seal/bearing configuration indicate that actual seal leak rates are much lower than estimated which indicates that the 200 hour oil compensation bag designed into the system has reserve capacity.

Much effort was spent conducting design reviews with Industrial peer groups to establish the manufacturability and maintainability of the device. Design reviews were also conducted with bearing and seal manufacturers to assure that the bearing/seal combination chosen was the best available for the application.

Prior to system verification testing, the redesigned bit shaft will be operated in a mud environment with pressure drops commensurate with those expected during deep drilling. Successful completion of this test will provide confidence that the bearings, seals, and oil pressure compensation system is adequate for the Deep Drilling System.

INSTRUMENTATION SUBSYSTEM

The instrumentation subsystem (Figure 9) remains functionally the same as that demonstrated during the Phase I Program. A basic design ground rule was to

Figure 9
Electrodrill Phase II
Instrumentation Subsystem

utilize as much of the Phase I instrumentation hardware as possible. Modifications to the downhole instrumentation system include:

1. Replacement of the original position monitor with a new three axis solid state device designed by General Electric. The new design is much more sensitive, has much lower hysteresis and higher repeatability than the original electromechanical unit.
2. Replacement of the original instrument pressure housing with a 20,000 psi design.
3. Addition of a formation sensor sub between the Monel collar and the motor. The sensor sub houses a gamma log, outside mud temperature sensor and differential pressure sensor. These three sensors are considered sufficient to demonstrate the capability of formation sensing while drilling.
4. Addition of a temperature and voltage sensor in the motor so that the well being of the motor can be monitored at the surface while drilling is in progress.

Modifications to the surface equipment include addition of a processor/display/recorder system to the data analysis trailer and modifying the driller's console to handle the high motor current.

Downhole Instrument Package. The downhole instrument package has been designed to perform the following functions:

1. Receive from the surface 115V AC 60 Hz electric power and convert and distribute same to support the downhole instrumentation.
2. Monitor up to 15 analog plus 11 digital downhole parameters and process (multiplex) this data.
3. Send to the surface processed data in pre-established digital formats.
4. Receive two to four commands from surface equipment for execution by downhole auxiliary units.

Surface Support Equipment. The surface equipment receives the downhole data, establishes bit and frame synchronization, checks parity, decides on the data acceptability, performs data transformation, routes and displays data.

The surface equipment transmits commands to the downhole equipment utilizing frequency shift keying of the power source to transmit the data. The correct voltage level downhole is also commanded by the surface equipment and maintained by varying the surface voltage level in proportion to the surface power signal level.

The power supply for the surface equipment utilizes 115 VAC - 60 Hz developed from the Electrodril power subsystem. The surface equipment converts this system power to supply the logic and analog power for the surface equipments. The surface equipment power supply also provides the 1000 Hz power for the downhole instruments. Sufficient power is supplied at the surface to assure that $120 \text{ volts} \pm 12\%$ is received by the downhole unit. The surface support equipment includes two data display stations:

1. The display control unit displays the three axis hole direction data and has one other display window for other selectable data.
2. A second microprocessor has been added in the trailer so that raw downhole data can be decoded, converted, and displayed independently from the rig floor display and control unit. This feature, which was not available during Phase I, will permit system diagnostics to be performed and enhance the analysis capabilities to support the evaluation of Electrodril system performance.

4.0 FABRICATION

The functional compatibility of the major elements of the Deep Drilling System was successfully demonstrated during the 1976 Phase I field test demonstration. The equipment inventory, as a result of the Phase I program, was essentially related to the 60 HP Directional Drilling System although there did exist one 285 HP motor and two gear boxes that were available for use in the Phase II program. The remainder of the equipment inventory required to support the Phase II program had to be procured as part of the Task B effort.

The procurement plan for the remainder of the Phase II equipment was concentrated on a "buy" rather than "make" concept. The major exception to this strategy was the make decision for the instrumentation subsystem. The decision to continue with the in house fabrication of instrumentation subsystem elements was based on the assessment that General Electric's forte was in this area; it had the manufacturing continuity and the subsystem was relatively free of problems.

In general, procurements for the Phase II system were made from sources established during the Phase I equipment procurement cycle. One significant exception to the plan was the procurement of the electrical cable. After having established the preferred cable jacketing material (Ethylene, Propylene, Diene Monomer) the original cable manufacturer no bid the procurement specification due to his inability to manufacture an EDPM cable of the size required. Subsequent searches for an alternate manufacturer uncovered an established supplier who had many years of cable manufacture with this material.

Another significant procurement decision for the Phase II program was the selection of a subcontractor to manufacture the field replaceable connectors. During the Phase I program the connectors were manufactured in house. This was done to establish the preferred manufacturing method and to develop quality control criteria so that subsequent production procurements could be intelligently specified. The successful testing of the field replaceable connector concept during the Phase I program facilitated the decision to develop a subcontractor source for these connectors. Full technical and procedural disclosure was made to the selected subcontractor to assure maximum connector technology transfer. In most instances acceptance testing of subcontractor deliverables was accomplished at the subcontractor's facility. GE project engineers were witness to the key elements of each test program. Substandard deliverables were repaired or remade before acceptance was approved.

5.0 TECHNICAL APPROACH TO TEST

The major objective of the Systems Verification Test was to demonstrate the functional compatibility of all the Electrodrill system elements and the readiness of the total system to be deployed in operational wells for further evaluation. It was important, therefore, to develop a test plan so that the System Verification Test could be conducted in an orderly and controlled manner to assure that the test data derived was valid and meaningful. Such a test plan was devised (Appendix B) and adhered to throughout the test period. A summary of the test plan, in schedule form is shown in Table 1.

The fundamental Systems Verification Test concept was to enter the test well initially, with a minimum Electrodrill string, to test this baseline system and then to add other system elements in a logical sequence so that anomalies and failures, when they occurred could be isolated quickly and corrected.

One overriding requirement during the Systems Verification Test was to perform a 100 hour bit shaft test to demonstrate the integrity of the newly designed bit shaft. Clearly it was important to execute this test as early as possible to provide a maximum of time for the correction of any problems isolated during the bit shaft test.

Table 1
SYSTEMS VERIFICATION TEST SCHEDULE

MILESTONES		TEST DAYS AT BOT RIG																									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	CONVENE & DEPLOY EQUIPMENT	Δ	▽																								
2	ASSEMBLE MOTOR & BIT SHAFT	Δ	▽																								
3	RUN 100 HOUR BIT SHAFT TEST		Δ	—	—	—	—	▽																			
4	REMOVE BIT SHAFT & REDEPLOY MOTOR							Δ	▽																		
5	CONDUCT YO YO CABLE TESTS								Δ	▽																	
6	CONDUCT 1000' CABLE TESTS									Δ	▽																
7	CONDUCT CABLE FISHING TESTS										Δ	▽															
8	CONDUCT CABLE & KELLY TESTS											Δ	▽														
9	CONDUCT CABLE/KELLY & DED PIPE TESTS												Δ	▽													
10	CONDUCT TEST WITH 2 x 1000' CABLES													Δ	▽												
11	REMOVE STRING & INSTALL INSTR SUB														Δ	▽											
12	CONDUCT INSTR TESTS ON 1000' CABLE															Δ	▽										
13	REMOVE STRING & INSTALL FORM SENSOR SUB																Δ	▽									
14	CONDUCT TOTAL INSTR TESTS ON 1000' CABLE																	Δ	▽								
15	CONDUCT DEMONSTRATIONS TO INDUSTRY																		Δ	▽							
16																				Δ	▽						
17																											
18																											
19																											
20																											
NOTES																											

The initial test priority then was placed on conducting the 100 hour bit shaft test. This test required the Electrodril motor, the bit shaft appropriately plugged at its lower end to simulate drill bit hydraulics, a minimum of drill pipe, electric cable and pack offs, the power generator and control system. It was not considered important to simulate the rig floor environment in this test as primary concern was focused on the motor/bit shaft compatibility and the capability of the bit shaft to function over the complete speed range of the motor while subjected to a simulated downhole environment.

Upon completion of the 100 hour bit shaft test, the drill string was to be removed from the well and the bit shaft removed from the motor and returned to the assembly facility. The bit shaft was then to be subjected to tear down inspection to evaluate seal and bearing wear characteristics. During this inspection period the motor assembly could be reinserted into the well (without bit shaft) so that cable deployment procedures and connector reliability could be evaluated.

Initially, cable deployment was planned at shallow depths (i.e., less than 1000 ft.) and the cable was deployed onto the motor. This approach was taken so that repetitive connector matings could be made swiftly and thus confidence could be built up in the new connectors. Upon the completion of each connector mating downhole, electrical measurements were to be made to verify that good connector mating had occurred and then the motor was "bumped" and data was taken to assure the electrical characteristics of both motor and cable were satisfactory. These initial cable/connector matings were accomplished in a mud environment, but mud was not circulated.

The next logical step was to land a 1000 ft. cable length in a typical drill string and to connect the prewired kelly to the string so that mud could be circulated at various pressures while the motor was exercised through its power regime. Upon successful completion of this test series, multiple cable lengths and dedicated (prewired) drill pipe were to be deployed in single steps so that all cable and drill pipe combinations could be exercised and evaluated.

Only after establishing the functional reliability of the cable and connectors together with the prewired drill pipe and kelly was the Electrodril instrument sub deployed. This test approach afforded the best possible electrical environment for the instrument sub and minimized the potential for catastrophic failure of the sub due to cable shorts or power excursions.

Testing of the Electrodril instrumentation was to be executed in two parts as the subsystem is divided into two downhole elements. The directional sub, which houses the three axis directional sensors and the downhole signal processing and telemetry, and the formation sensor sub which houses the sensors for evaluating the downhole (drill pipe core and annulus) environment. The directional sub can be deployed downhole without the formation sensor sub as it houses all the downhole data processing and telemetry capability. The formation sensor sub cannot be deployed without the directional sub as it lacks a "stand alone" telemetry capability. The logical sequence for evaluating the Electrodril downhole telemetry and sensors was established as follows: First the directional sub was to be evaluated in the drill string and after successful evaluation, the formation sensor sub was added to evaluate

the full compliment of the Electrodril Deep Drilling System's instrumentation. In both test operations the surface trailer was to be used to collect, process and display the data from the downhole instrumentation.

Upon successful completion of this test program, the drill string was then to be stood back in the derrick and a series of deployment, retrieval and fishing exercises were to be conducted by the drill rig crew so that deployment, retrieval and fishing methods could be evaluated. The latter series of exercises were to be conducted before members of the Electrodril Technical Advisory Board so they, too, could evaluate the system.

6.0 TEST ACCOMPLISHMENTS

6.1 GENERAL

All major system elements were functionally tested prior to shipment to the Brown Oil Tools test site. These functional tests were conducted either at a subcontractor's plant and witnessed by General Electric engineers, or at the General Electric assembly facility in Houston, Texas. The Systems Verification Test was, therefore, to determine the functional compatibility of the total Deep Drilling System and to assure the system was ready for field demonstration.

The Electrodrill Systems Verification Test was conducted in a test well at Brown Oil Tools Inc., Houston, Texas. The system was deployed as a 3400 foot section of a 6000 foot well in 9 5/8" casing. A packer was set at the 3400 foot depth by Brown Oil Tools. General Electric was requested not to remove the packer and the depths for the Systems Verification Test were limited to 3400 feet.

6.2 COMPONENT/SUBSYSTEM TESTS

BIT SHAFT

Prior to the initiation of the 100 hour bit shaft test, the bit shaft was assembled and tested to assure the oil compensation system was operating correctly. The fill procedures for the oil compensation system included evacuation by vacuum pump to approximately 100 torr. This partial vacuum technique verifies that the upper and lower shaft seals are correctly assembled and facilitates quick back-filling of the lubrication cavity with oil.

Upon the successful completion of the evacuation and fill procedure the bit shaft was "run in" on a spin test facility (Figures 10 and 11) to assure the seals are dynamically functioning and that the leak rate is within tolerance. The run in period is typically for 24 hours at the completion of which the bit shaft is set aside and is considered ready for deployment.

MOTOR

The motor is a standard REDA series 540 submersible pump motor upon which is installed a special motor riser to mate with the Electrodril connector system. Integral with the motor riser is the thermister bead for motor core temperature monitoring. The motor riser is installed to the motor by General Electric and subsequent post assembly test consists primarily of electrical high potential testing and resistance checks to ground. The installation of the gear box and oil compensation section is accomplished in a similar manner to that for the bit shaft. The evacuation and fill procedure for the lubrication cavity is also accomplished similar to the bit shaft.

CONNECTORS

Development was started on the field replaceable connectors as a result of the Phase I test program. Materials and processes were evaluated in light of their electrical and mechanical properties, bondability and compatibility.

Prototype designs were made and subjected to tests to determine their reliability under simulated downhole pressures and temperatures. The South Houston field

Figure 10

Figure 11

BIT SHAFT SPIN TEST FACILITY
SHOWING BIT SHAFT BEING RUN-IN

test demonstrated the viability of the design but did not show that the connectors would still mate reliably after repeated matings and unmatings. The test fixture shown in Figure 12 was made to investigate the life characteristics of male/female connector combinations in a simulated tool joint bore. The effects of various dielectric greases as well as the scouring caused by mud was investigated. Rhodium plated conductor rings to minimize the scouring were tested but, because of their additional contact resistance were not used in the final design. As many as 7000 matings were made without appreciable electrical performance decline.

Connectors purchased for the Systems Verification Test had been 100% pressure tested and electrically checked for continuity and leakage to ground prior to shipment. One set of connectors was put on the life test fixture and, after 2500 matings, demonstrated no degradation in electrical contact resistance.

CABLE

Because the final cable diameter greatly affects the proficiency of the cable drum rewind pattern, it was closely monitored and checked during its fabrication. General Electric personnel were witness to the final testing (both electrical and mechanical) at the vendor location. The final product was prestressed prior to shipment to minimize cable stretch during deployment. A sample was also placed in a tensile tester and pulled to destruction to demonstrate that the breaking strength specification was met. The cable vendor subjected samples of the cable to environments which verified their thermal and chemical resistance characteristics.

Figure 12
CONNECTOR LIFE TEST FIXTURE

It is planned to investigate the use of time domain reflectometry testing techniques to assist in the identification and location of cable/connector faults in the Electrodril string faster and more accurately.

Flexibility tests were not run by the vendor but, during Systems Verification testing it was established that about 4 ft. of cable could be hidden in a 1000 ft. section of 4 1/2" X-hole drill pipe.

CABLE REELS AND DRIVE

Prior to accepting delivery of the cable reels and drive skid from the vendor, testing was conducted to insure that specifications were met. The hydraulic system was operated and reels rotated in both forward and reverse directions over its entire speed range. It was decided that the braking system could best be tested during cable deployment at Brown Oil Tools.

INSTRUMENTATION

For the Phase II program three major changes were incorporated into the basic instrumentation package. A new solid state position monitor was developed to increase reliability and enhance performance accuracy. Since the tests were to be run in a cased straight hole at Brown Oil Tools, no accuracy testing of the new solid state position monitor was possible. The new position monitor was thoroughly tested in a laboratory prior to the Brown Oil Tools testing. Its accuracy and repeatability were demonstrated to be better than 1.0 degrees in drift and 3 degrees in azimuth and tool face. A new sensor package was

developed to function with the downhole directional sub to allow for heat sub control via commands from the surface and for downhole measurement of motor temperature, motor voltage, annulus mud temperature, drill pipe/annulus differential mud pressure, and formation gamma radiation. The third change was the addition of a processor in the data analysis trailer to "back-up" the display control unit and to process downhole and surface measurements for recording on magnetic tape and display on strip chart recorders and on a hard copy printout.

POWER GENERATION

A series of tests, reported on in Appendix D, were conducted to evaluate the transient response characteristics of the motor/inverter combination so that an adequate control system could be designed. The specific objectives of the test program were to determine:

- a. The compatibility of static inverter drive systems to Electrodril applications.
- b. The drill motor losses attributable to oil shear, (windage), at various motor speeds and with different lubricants.
- c. Drill motor starting current requirements at low frequency
- d. Drill motor HP and temperature rise with respect to various power frequencies, loads and cooling flow rates.
- e. Effects of the "Static Inverter Wave forms" upon the downhole telemetry system operation.
- f. The effects of cable IR losses to motor terminal voltage regulation requirements.

6.3 SYSTEMS VERIFICATION TESTS

100 HOUR BIT SHAFT TEST

Prior to the initiation of the 100 hour bit shaft test, the bit shaft was "run in" on the spin test facility as previously described to assure the seals and bearings were in good operating order. Subsequent to this test the bit shaft and motor were assembled together in the rig (Figures 13 and 14). This "in the well" assembly was necessitated because the rig Vee door could not accept an assembly with a length approximately 60 ft. Some concern existed about the ease by which the motor and bit shaft could be assembled in the rig due to the precise makeup requirements of the shock sub and drive splines. The concern, however, was groundless as the bit shaft was mated to the motor quite easily. Subsequent matings and breakings were made during the course of the system verification test which indicates that bit shaft replacement in the rig, should that become necessary, is a relatively easy procedure.

The formal 100 hour bit shaft test was begun October 19 and successfully concluded October 25. Subsequent post test inspection indicates that the overboard leak rate of the shaft seals are well below design limits and thus the oil compensation system appears to be more than adequate to support a 100 hour bit life.

Motor performance during this period was normal. No unusual power surges or voltage fluctuations were noticed and the core temperature of the motor, after initial warmup, stayed within design limits.

A test report documenting the specifics of the 100 hour test is presented in Appendix B.

Figure 13
BIT SHAFT IN SLIPS BEING
PREPARED TO RECEIVE MOTOR

Figure 14
MOTOR BEING MATED TO
BIT SHAFT ASSEMBLY

CABLE AND CONNECTORS

After removal of the bit shaft for post test evaluation, the motor was run in the test well to a depth of approximately 200 ft. The cable skid (Figure 15) and rig sheaves, (Figures 16 and 17) were already in place by virtue of their use in support of the 100 hour bit shaft test.

A sinker bar, weighing approximately 375 pounds, was subsequently prepared for deployment (Figures 18 and 19) and lowered onto the motor using a portion of the 1000 ft. power cable. The cable was then checked for electrical continuity through the downhole connector and motor by measuring these values at the cable connector on the cable skid. Electrical continuity on all four conductors and the electrical resistance to ground for each conductor was also measured. Each of the electrical checks indicated that the sinker bar/connector combination had mated with the motor. The motor was therefore powered up and brought to approximately 200 RPM while in-rush current and applied voltage levels to the output transformer levels were noted. A typical in-rush current maximum would be in the order of 190 amps while applied voltage at 60 Hz would be 1200 volts.

During the first day of connector/sinker bar/cable and motor tests a total of six remote downhole matings were attempted and in all six proper electrical connections were achieved and electrically verified.

CABLE LANDING/PREWIRED KELLY/DEDICATED PIPE

A total of 1024 feet of drill pipe was then added to the top of the motor. An

Figure 15
ELECTRODRIL POWER CABLE SKID
CAPACITY 19000 Ft.

Figure 16
ELECTRODRIL RIG FLOOR SHEAVE

Figure 17
ELECTRODRIL TRAVELING SHEAVE

Figure 18
SINKER BAR IN SPECIAL SLIPS
SUSPENDED IN DRILL PIPE

Figure 19
CABLE ADAPTER BEING
PREPARED FOR SINKER BAR

Electrodrill landing sub was made up to the last joint of drill pipe and the sinker bar/connector/cable was lowered into the hole. When most of the cable was removed from the drum, the cable slips, (Figure 20) were set and the cable was freed from the reel. The wire rope was then attached to the cable end with the landing shoe attached to the male connector and the slips were removed after slack was taken out of the cable/wire rope. The remainder of the cable was lowered into the hole with the cable and wire rope passing over and under the sheaves with no damage. When the landing shoe was secure in the landing sub (Figure 21) the wire rope was removed and the down-hole cable checked electrically. Each of the checks indicated that a successful mate had been achieved. This was verified by "bumping" the motor and monitoring voltage and current. The cable was then retrieved by reversing the deployment procedures previously describe. A total of four redeployments into the same drill string were made with equally successful results. This success gave confidence that cable stretch was essentially negligible and that, once a length was known, the drill string required for landing remained constant. The cable slips worked extremely well in both dry and wet (oily) conditions. No abnormal squeeze appears to have been placed on the cable cross section during the landing or retrieval process.

During this test series a test was conducted to determine the amount of cable that could be "stuffed" into drill pipe. This parameter is important as it affects how accurately the drill pipe tally should be taken and establishes the tolerance allowed on the cable lengths of prewired pipe. The test indicated that approximately four extra feet of cable could be stuffed into 1000 ft. of drill pipe while monitoring good connector mating and correct cable landing.

Figure 20
ELECTRODRIL CABLE SLIPS

Figure 21
UPPER END OF POWER CABLE
SHOWING LANDING SHOE

The prewired kelly was then made up to the drill pipe landing sub and the string was lowered into the hole until the kelly crossover sub was just above the slips (Figure 22). Electrical measurements at the slip ring electrical crossover indicated that correct connector mating had occurred. The surface cable was then connected to the power skid and the motor was turned on. Mud was circulated through the string at pressures up to 850 psi while the motor was slewed from 55 to 257 RPM.

Upon successful completion of the previous test phase, an additional 1000 ft. of cable and two 30 ft. dedicated (prewired) drill pipes were deployed in single steps so that all the cable and drill pipe combinations were exercised and evaluated. The feasibility of making electrical kelly to dedicated pipe connections using the mousehole was also proven. A slip ring assembly was then added to the top of the kelly (Figure 23). Powering the motor through the slip ring was uneventful and demonstrated that string rotation while drilling with the Electrodril system could be readily achieved.

It should be noted that the 90 ft. dedicated stands which are planned for use in the drilling demonstrations were not exercised at the Brown Oil Tools test facility as the derrick was not capable of manipulating them. There is no difference in the electrical or mechanical makeup between the 30 ft. and 90 ft. dedicated stands and, as such, this technical omission is not considered a violation of the validity of the test series.

Figure 22
ELECTRICAL TESTING BEING DONE
AT CABLE CROSSOVER

Figure 23
SLIP RING ASSEMBLY INSTALLED
ABOVE CABLE CROSSOVER

To demonstrate that the landed Electrodril cable could be retrieved in the event that the string was stuck, a specially designed fishing tool was deployed in open drill pipe in which a 1000 ft. cable had been landed. The landing sub for the cable was approximately 200 ft. below the pipe slips. The fishing tool latched on to a fishing neck below the replaceable male connector. A force of 300 pounds greater than the cable hanging weight (i.e., approximately 2300 pounds total) was exerted causing the landing shoe to deform and pass through the tool joints and pipe bores. The landing shoes can be resized and reused without structural deterioration after having been fished.

INSTRUMENTATION SYSTEM

The basic Electrodril instrumentation consists of a downhole directional sub and surface display and control unit. This equipment, together with a data analysis trailer, was tested extensively in both test and operational wells during the Phase I program and was shown to be operationally ready.

For the Phase II Program, however, three major changes were incorporated into this basic instrumentation package. A new solid state position monitor was developed to increase reliability and enhance performance accuracy. A new sensor package was developed to function with the downhole directional sub to allow for heat sub control via commands from the surface and for downhole measurement of motor temperature, motor voltage, annulus mud temperature, drill pipe/annulus differential mud pressure, and formation gamma radiation. The third change was the addition of a processor in the data analysis trailer to "back-up" the display control unit and to process downhole and surface measurements for recording on magnetic tape and display on strip chart recorders and on a hard copy printout.

The Phase II testing of the instrumentation subsystem at Brown Oil Tools was to demonstrate the total instrumentation subsystem with the new instrumentation elements in a simulated drilling environment. Testing was performed in two steps. First, the directional sub was run downhole with the motor to a depth of approximately 1000 feet, mud circulation was established and the instrument successfully operated. This test demonstrated the compatibility of the directional sub with the drill string, motor, and cabling subsystems. Next, the formation sensor sub* and heat sub* were added to the downhole configuration.

The test was performed by lowering the motor, formation sensor package, heat sub and directional sub into the test well, making up electrically and then exercising all portions of the instrumentation system while starting, running (at different frequencies), and stopping the downhole motor. Downhole telemetry was received by the data analysis trailer (Figures 24 and 25) and by the Control and Display Unit (Figure 26) from the directional sub with no loss of data during the entire test. The following measurements were made, processed and displayed during the test:

- * The solid state position monitor, the formation sensor and the heat sub were developed independently for application to the Field Test Program.

Figure 24
ELECTRODRIL DATA ANALYSIS
TRAILER

Figure 25
INTERIOR OF TRAILER SHOWING
DIAGNOSTIC EQUIPMENT

From the directional sub:

Instrument voltage

Instrument temperature

Vibration

Hole position (drift, azimuth, and tool face)

Commands received response

From the downhole sensor package:

Motor voltage

Differential mud pressure

Annulus mud temperature

From surface sensors:

Depth of hole and penetration rate

Mud pressure

Mud flow rate

Motor current

The motor temperature and gamma count measurement channels failed to function during the downhole test due to electronic component malfunctions in the downhole telemetry module. Both channels performed perfectly after the failed electronic components were replaced after the test.

The following drilling parameters were printed out at a preselected rate in the data analysis trailer (Figure 27).

Well data (lease and drilling company information)

Date

Time of day

Well depth

Penetration rate

Well position (drift, azimuth, tool face)

Motor temperature

Instrument temperature

Annulus mud temperature

Motor current

Annulus/drill pipe pressure differential

Surface mud pressure

Surface mud flow rate

Gamma count

Drill string hang weight

Motor RPM

Display formats for this data are shown in Table 2 and 3 and an explanation of the display abbreviations is presented in Table 4.

Figure 26
ELECTRODRIL CONTROL & DISPLAY
UNIT

Figure 27
INTERIOR OF DATA ANALYSIS TRAILER
SHOWING PRINTOUT DEVICES

WELL NO.? - TEST
COUNTY? - HARRIS
STATE? - TEXAS
MAGNETIC DIP ANGLE? - 55.7
TRUE NORTH CORRECTION? - 1
CURRENT DEPTH? - 1015.9
GAMMA MULTIPLIER? - 1
GAMMA CORRECTION RATIO? - 1
MUD PUMP DIAMETER? - 7
MUD PUMP STROKE LENGTH? - 6
NO. MUD PUMP CYLS? - 2

COMPANY: GENERAL ELECTRIC FIELD: BROWN OIL TOOL LEASE: BOT
WELL NO: TEST COUNTY: HARRIS STATE: TEXAS DATE: 11/07/78

TIME HR:MM	DEPTH FEET	PEN F/H	DRFT DEG	AZMTH DEG	TFACE DEG	MTR DGF	INS DGF	ANN DGF	MTR AMP	DPRS PSI	SURF PSI	VOL GPM	GMA CNT	HANGWT POUNDS	SPD RPM
P.15															
18:55	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0508	443	0000	000000	000	
18:55	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0520	472	0000	000000	000	
18:55	01015.9	000	00.1	180.5	000.0-400	059	034	000	0035	0571	520	0000	000000	000	
18:55	01015.9	000	00.1	180.5	000.0-400	059	034	000	0035	0537	504	0000	000000	000	
18:56	01015.9	000	00.0	180.5	000.0-401	059	034	000	0032	0513	328	0000	000000	000	
18:56	01015.9	000	00.1	180.5	000.0-400	059	034	029	0032	0518	472	0000	000000	002	
18:56	01015.9	000	00.2	180.5	000.0-401	059	034	022	0035	0518	472	0000	000000	055	
18:56	01015.9	000	00.1	180.5	000.0-400	059	034	021	0038	0518	496	0000	000000	038	
18:57	01015.9	000	00.3	180.5	000.0-401	059	034	022	0035	0569	456	0000	000000	095	
18:57	01015.9	000	00.2	180.5	000.0-401	059	034	022	0035	0544	464	0000	000000	097	
18:57	01015.9	000	00.2	180.5	000.0-401	059	034	022	0029	0527	448	0000	000000	097	
18:57	01015.9	000	00.2	180.5	000.0-401	059	034	022	0032	0571	536	0000	000000	097	
18:58	01015.9	000	00.0	180.5	000.0-400	059	034	021	0035	0542	472	0000	000000	097	
18:58	01015.9	000	00.0	180.5	000.0-401	059	034	022	0029	0530	416	0000	000000	098	
18:58	01015.9	000	00.1	180.5	000.0-401	059	034	023	0029	0537	504	0000	000000	129	
18:58	01015.9	000	00.2	180.5	000.0-401	059	034	024	0035	0552	512	0000	000000	173	
18:59	01015.9	000	00.2	180.5	000.0-401	059	034	024	0035	0513	528	0000	000000	197	
18:59	01015.9	000	00.0	180.5	000.0-400	059	034	024	0041	0564	560	0000	000000	203	
18:59	01015.9	000	00.1	180.5	000.0-400	059	034	024	0041	0540	528	0000	000000	203	
18:59	01015.9	000	00.2	180.5	000.0-401	059	034	024	0032	0520	456	0000	000000	205	
19:00	01015.9	000	00.1	180.5	000.0-400	059	034	024	0035	0520	512	0000	000000	205	
19:00	01015.9	000	00.0	180.5	000.0-400	059	034	024	0035	0505	480	0000	000000	205	
19:00	01015.9	000	00.2	180.5	000.0-401	059	034	024	0038	0522	448	0000	000000	205	
19:00	01015.9	000	00.0	180.5	000.0-400	059	034	022	0035	0515	488	0000	000000	166	
19:01	01015.9	000	00.1	180.5	000.0-400	059	034	021	0041	0508	472	0000	000000	121	
19:01	01015.9	000	00.1	180.5	000.0-400	059	034	022	0041	0515	392	0000	000000	105	
19:01	01015.9	000	00.0	180.5	000.0-400	059	034	021	0035	0554	456	0000	000000	101	
19:01	01015.9	000	00.2	180.5	000.0-401	059	034	022	0032	0530	488	0000	000000	099	
19:02	01015.9	000	00.1	180.5	000.0-400	059	034	022	0041	0510	416	0000	000000	099	
19:02	01015.9	000	00.2	180.5	000.0-401	059	034	020	0035	0557	480	0000	000000	087	
19:02	01015.9	000	00.3	180.5	000.0-401	059	034	020	0032	0500	528	0000	000000	059	
19:02	01015.9	000	00.2	180.5	000.0-401	059	034	020	0035	0520	512	0000	000000	050	
19:03	01015.9	000	00.1	180.5	000.0-400	059	034	000	0035	0549	528	0000	000000	026	
19:03	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0554	456	0000	000000	003	
19:03	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0518	456	0000	000000	002	
19:03	01015.9	000	00.0	180.5	000.0-400	059	034	000	0035	0515	440	0000	000000	002	
19:04	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0562	472	0000	000000	002	
19:04	01015.9	000	00.2	180.5	000.0-401	059	034	000	0032	0515	424	0000	000000	002	
19:04	01015.9	000	00.1	180.5	000.0-400	059	034	000	0035	0515	424	0000	000000	002	

Table 2

Typical Electrodrill Strip Recorder Traces

Table 3

Electrodrill Instrumentation Data Logger - Explanation of Column Headings

1. "TIME" - local time in hours and minutes
2. "DEPTH" - hole depth in feet
3. "PEN" - penetration rate in feet per hour, averaged over a selected time period. Time period may be changed at will.

DIRECTIONAL PARAMETERS

4. "DRFT" - drift in degrees from vertical
 5. "AZMTH" - azimuth in degrees from North
 6. "TFACE" - tool face in degrees from North or hole top side or hole bottom. Reference is selectable
-

7. "MTR" - motor temperature in degrees F
8. "INS" - instrumentation temperature in degrees F
9. "ANN" - mud temperature in the annulus in degrees F
10. "MTR" - current drawn by motor in amps
11. "DPRS" - Δ pressure. Difference between mud pressure in the drill pipe and in the annulus in psi.
12. "SURF" - mud pressure at the circulating head in psi.
13. "VOL" - mud flow rate in gallons per minute.
14. "GAMMA" - gamma log
15. "HANGWT" - system weight in pounds
16. "SPD" - bit speed in RPM

Table 4

The motor temperature and formation gamma count printouts were erroneous since the corresponding downhole measurement channels failed. Also, the drill string hang weight indication was zero since the hang weight sensor did not arrive by test time.

POWER GENERATION

The power generation subsystem for the Deep Drilling System consists of a rented diesel/electric generator (Figure 28) whose output is 440 V AC at 60 Hz. The generator output is fed into a static inverter, the output of which varies dependent upon the selected excitation frequency. The output of the inverter is put through a multitapped transformer (Figure 29) which boosts the output voltage to that required for driving the downhole motor. The on-off control for this system is located in a stand alone drillers console (Figure 30).

The sensitivity of this subsystem to fluctuating motor demands has been exhaustively evaluated and is reported on in Appendix D. These tests were conducted months before the Systems Verification Test at Brown Oil Tools and it remained only to determine the extent of interference, if any, power switching spikes from the inverter had on the downhole instrumentation.

In general, the power generation subsystem performed very well. No instrumentation data dropouts due to power spikes were recorded. No tests had to be aborted due to failures in the subsystem. Some instability problems were experienced early in the test program at frequencies above 90 Hz. These problems were eliminated however by tuning the control circuits in the inverter.

Figure 28
DIESEL POWER GENERATION UNIT

Figure 29
ELECTRODRIL OUTPUT TRANSFORMER

Figure 30
ELECTRODRIL DRILLERS CONSOLE

7.0 CONCLUSIONS

In general, it can be concluded that the Electrodrill Deep Drilling System Verification Test program was a success. It can thus be further concluded that the system is ready for field deployment and drilling demonstrations so that drilling performance under operating conditions and the economic viability of the system can be evaluated.

All the system elements of the Deep Drilling System were exercised and evaluated during the Systems Verification Test program. The motor/bit shaft combination, in its newly designed configuration, demonstrated that its seal performance exceeded the design goals. In addition, the oil compensation system demonstrated a useable life between maintenance of at least 100 hours.

The rig floor system performed much better than expected as the flexural characteristics of the power cable exceeded expectations. The ability of the cable/connector combination to traverse the upper and lower cable sheaves reduced cable deployment time enormously.

The power generation equipment supported the test program without failure. Although some instability problems were experienced early in the 100 hour bit shaft test at 90 Hz, subsequent tuning of the inverter control circuits eliminated the problem.

The newly designed and expanded instrumentation subsystem gave an impressive display after an early electronic component failure had been rectified. Further design modifications have been included to enhance the reliability of the system.

The ability to fish the power cable from the drill string was demonstrated and thus eliminated a major concern of some potential clients. It should be noted also that this demonstration is the first of its kind for electric drilling motors, the Russians and French both being unable to fish their power cable because of the method used to suspend it in the drill string.

Numerous cable deployments and motor "bumpings" were demonstrated to Industry representatives during the last few days of the Systems Verification Tests. The consensus was that the deployment time had been reduced significantly from the first Phase I demonstration. The rig hands, which had been the crew during the Phase I test series, remarked how much easier the rig floor system was in handling and expressed "new" crews would experience little difficulty in safely picking up the deployment technique.

APPENDIX A

SYSTEM DESCRIPTION

A schematic of the Deep Drilling System is shown in Figure 1. The System is composed of both downhole and surface components. The downhole components consist of an electric drill motor and its mechanical assemblies; cable and connectors; and the instrumentation assembly. The surface components consist of cable skids; power generation equipment; cable handling equipment; power control equipment; and the telemetry, instrumentation, surface processing, display and control unit. These surface components are generally deployed at a rig site in a manner similar to that shown in Figure 2.

The surface and downhole components have been structured in the Deep Drilling System (DDS) to permit their addition in modular fashion to standard rotary drilling rigs depending upon the objectives of the operator of the rig and the configuration of the equipment at the well site. The system's installation and operating procedures have been designed to be compatible with existing rigs and conventional drilling operations.

The DDS is divided into four basic subsystems, each of which is described in the following test.

POWER GENERATION SUBSYSTEM

This subsystem is the power plant for the total Deep Drilling System. The power requirement increases with well depth. It is not considered practical to utilize rig electrical power. In addition to providing

FIGURE 1
DEEP DRILLING SYSTEM
SCHEMATIC

FIGURE 2
SURFACE ELEMENTS
DEEP DRILLING SYSTEM

power for the Electrodril motor, this subsystem provides all auxiliary electrical power (DC and AC) in support of the DDS and includes all the controls, inverters, converters and safeguards to assure correct system performance.

The Electrodril Deep Drilling System power requirements are essentially as follows:

Primary Power: 240V to 3300V, 3Ø, with variable AC frequency ranging from 12 to 120 Hz. Continuous current rating from 22 to 75 amps.

Secondary Power: 208V, 3Ø, 60Hz AC
110V, 1Ø, 60Hz AC

The satisfaction of these power requirements will be accomplished by the use of a diesel prime mover driving an AC alternator to produce 440V, 60Hz. The 440V AC output is then applied to a static inverter which converts the AC to DC and subsequently "chops" the DC output at varying rates, upon demand, to create variable frequency "pseudo" AC. Control for the DC "chopping" is developed from inputs from the downhole current and voltage sensors. A schematic of this power generation approach is presented in Figure 3.

The power generation scheme is a "demand response" system and as such its relative ability to respond quickly to the power requirements of the Electrodril motor is key to its selection. Given power demand situations in which the power spectra fluctuate rapidly, as in the case for the DDS, the inherent inertia of the familiar "rotary"

A5

FIGURE 3
STATIC INVERTER POWER GENERATION

system makes it appear unsuitable for Electrodrill application. The static inverter system is able to respond to power fluctuations, but the supporting downhole sensory system and surface controllers must be capable of sensing demand and switching frequency levels at a high response rate.

CABLE AND HANDLING SUBSYSTEM

This subsystem consists of the cable, cable reels, connectors, slip rings and devices for the deployment of control of same. This subsystem, of necessity, maintains a flexible configuration as it is the details of the drill rig floor and derrick that dictate to a major extent what subsystem elements are deployed. The number of cable reels used, for example, is dictated by how deep the well is at the time of Electrodrill deployment and to what depth the system will be required to drill. A general layout of this subsystem at a typical rig site is shown in Figure 4 and consists of the powered cable spools for deploying the electrical cable downhole and the rig floor system which is designed to facilitate cable deployment in and out of the well and to accommodate the rotating/non-rotating environment surrounding the drill string.

RIG FLOOR ASSEMBLY. The technique for deploying the cable at the rig floor differs from that used in the Phase I Directional System in that the Deep Drilling System is required to provide means for drill pipe rotation to obviate the potential for differential sticking. Pipe rotation will be achieved using the conventional rotary table/kelly combination. Electrical connection to the downhole cable (rotating) and the surface cable (non-rotating) is made through a slip ring assembly located below the rig

FIGURE 4
GENERAL LAYOUT OF
ELECTRODRIL SYSTEM
AT RIG SITE

power swivel (Figure 5). Mud circulation will be made in the conventional manner through a circulating head above the power swivel. A kelly cock will be inserted between the circulating head and slip ring assembly to provide hydraulic safety.

The hole will be drilled ahead 90 feet, utilizing two prewired dedicated joints of drill pipe and the prewired kelly. These will then be removed and replaced with a 90-foot stand of prewired pipe. This sequence will be repeated 10 times (a total depth of 1000 feet) at which time the prewired pipe is withdrawn and substituted with standard drill pipe and 1000 feet of cable. This prewired pipe is utilized in place of standard drill pipe for the first 1000 feet to maintain electrical continuity with the deployed downhole lengths of Electrodrill cable during drilling operations. Each succeeding 1000 feet of hole is drilled in a similar manner to a depth of 5000 feet, at which time the prewired pipe is replaced with standard drill pipe and a 5000 foot length of Electrodrill cable is mated downhole with the previously deployed cable. An electrical crossover sub located below the slip ring assembly allows the transition of the electrical cable from inside the drill pipe bore to the outside of the slip ring assembly.

CABLE AND CONNECTORS. The Electrodrill cable requires a total of four conductors as shown in Figure 6. To supply downhole electrical power to the motor, three conductors of No. 6 AWG will be used. A smaller center conductor of No. 18 AWG will be used for instrument power and data transmission. The cable will be composed of multistranded conductors to assure cable flexibility and will be housed in a double

FIGURE 5
ELECTRODRIL SLIP RING
ASSEMBLY

A10

FIGURE 6
ELECTRODRIL DEEP DRILLING SYSTEM
POWER CABLE

layer of torque balanced steel armoring to carry the weight of the cable and provide a return for the instrument power. The cables are connected through specially designed field replaceable connectors (Figure 7) which allows easy assembly of the cable sections while providing high electrical reliability. The cable is supported in the drill pipe by cable hangers which provide cable stability during drilling operations. The hanging weight of the suspended cable is less than 20% of the cable breaking strength.

CABLE REELS. The cable reels to be used for the DDS will be required to accommodate a total of 19,000 feet of cable. This will be accomplished using cable reel skid as shown in Figure 8. A total of five reels will be required to hold the 19,000 feet of cable; three 5,000 foot cable reels, and two duplex 1,000 foot reels. In an effort to minimize "open hole" time, cable reel speed has been increased to a maximum of 300 ft/min. This speed appeared to be the maximum practical before hydraulic horsepower and cable strength requirements became prohibitive. Cable bedways on all the reel drums have been incorporated to minimize the lower cable tier crush loads.

MOTOR SYSTEM

This subsystem contains the downhole drilling elements such as the bit, bit shaft and motor with gearbox. The correct preparation of this subsystem prior to downhole deployment is key to its operational life. The adjustment of pressure compensation bags and gearbox seal lubrication, for example, have marked effects on the motor's downhole life prior to withdrawal and refurbishment. The Phase II Electrodrill motor subsystem, excluding the deviation sub and monel collar for the instrumentation,

MALE

CABLE ADAPTER

FEMALE

FIGURE 7
ELECTRODRIL FIELD
REPLACEABLE CONNECTOR

A13

FIGURE 8
ELECTRODRIL CABLE
REEL ASSEMBLY

is a total of 51 feet in length. A breakdown of this assembly, together with pertinent dimensions, is shown in Figure 9. The motor subsystem is electrically protected at the surface. In the event of an overload situation, current sensors will trip the power generation circuit breakers to prevent motor damage. Motor temperature will be sensed down-hole and displayed at the surface.

MOTOR

The Phase II Electrodrill motor is centered around a standard industrial REDA type 540 submersible pump motor nominally rated at 150 HP at 60 Hz and 1150 volts. At this rating the motor has a speed of 3200 rpm. The motor has been designed to operate over a frequency range of from 30 to 120 Hz. At the low end, the motor is rated at 35 HP at 12 Hz and 230 volts. At the high end, the motor is rated at 285 HP at 120 Hz and 2300 volts. The output of the motor is put through a 16 to 1 reduction gearbox so that the effective speed range for the drilling bit is 40 to 400 rpm.

GEARBOX AND PROTECTOR

The motor gearbox is a double train planetary reduction unit designed and tested to withstand weights on bit of up to 70,000 lbs. and torques in excess of 3,500 lb. ft. A shock absorber unit is provided to isolate the motor from the shock loads produced by the drilling operation. A slip clutch unit, designed to safeguard the motor in the event the bit is suddenly stopped is also included. Internal oil pressure compensation bags are also provided in this assembly to assure that the internal oil pressure is the same as the mud pressure in the mud tube thus maintaining

FIGURE 9
285 HP ELECTRODRILL MOTOR ASSEMBLY
A15

an almost zero pressure drop across the lower motor seals. The oil leakage over the lower motor seal is thus held to a minimum and the seal surface wear characteristics are idealized.

BIT SHAFT

The bit shafts used in the Phase I Program will not be used in the Deep Drilling test program as their bearings and seals are inadequate to withstand the higher downhole temperatures and pressures. A new bit shaft has been designed to incorporate metal-to-metal seals capable of withstanding pressure differentials in excess of 2,000 psi and bearings rated to accommodate weights on bit of up to 70,000 lbs. and the more severe downhole environment. In addition, the pressure compensation bag in the new assembly has been designed with sufficient oil capacity to assure lubrication is maintained at least for the life of a diamond bit (i.e. 200 hours). The oil is then replenished each time the drill bits are replaced or at intermediate times when the drill string is removed for other reasons.

INSTRUMENTATION SUBSYSTEM

The Instrumentation subsystem includes all elements of data acquisition, processing, transmission and display. Not all of the data acquired and displayed is from downhole instrumentation. Many Electrodrill system parameters are measured at the surface and displayed or recorded. All data received at the data analysis trailer is retrievable. The operational configuration of the data display unit is dictated by the driller's requirements. The instrumentation subsystem block diagram is shown in Figure 10. It remains functionally the same as that demonstrated during

FIGURE 10
ELECTRODRILL PHASE II
INSTRUMENTATION SUBSYSTEM

the Phase I Program. A basic groundrule was to utilize as much of the Phase I instrumentation as possible. Modifications to the downhole instrumentation system includes replacing the original position monitor with a new GE 3-axis solid state position monitor, replacing the instrument pressure housing with one designed to operate to 20,000 PSI, developing and adding a sensor package which contains three formation/drilling parameters and adding a motor temperature sensor. More sensors could have been included in the sensor package but would have necessitated a significant modification to the instrument itself. The three sensors are sufficient to demonstrate the feasibility of formation sensing while drilling.

Modifications to the surface equipment includes addition of a processor/display/recorder system to the data analysis trailer and modifying the driller's console to handle the higher motor current.

DOWNHOLE INSTRUMENT PACKAGE

The downhole instrument package has been designed to perform the following functions:

1. Receive from the surface 115V AC 60 Hz electric power and convert and distribute same to support the downhole instrumentation.
2. Monitor up to 15 analog plus 11 digital downhole parameters and process (multiplex) this data.
3. Send to the surface processed data in pre-established digital formats.
4. Receive up to 4 commands from surface equipment for execution by downhole auxiliary units.

SURFACE SUPPORT EQUIPMENT

The Surface Equipment receives the downhole data, establishes bit and frame synchronization, checks parity, decides on the data acceptability, performs data transformation, routes and displays data.

The surface equipment transmits commands to the downhole equipment utilizing frequency shift keying of the power source to transmit the data. The correct voltage level downhole is also commanded by the surface equipment and maintained by varying the surface voltage level in proportion to the surface power signal level.

The power supply for the surface equipment utilizes 115 VAC - 60 Hz developed from the Electrodrill Power Subsystem. The surface equipment converts this system power to supply the logic and analog power for the surface equipments. The surface equipment power supply also provides the 1000 Hz power for the downhole instruments. Sufficient power is supplied at the surface to assure that 120 volts $\pm$ 12% is received by the downhole unit. The surface support equipment include two data display stations:

1. The display control unit, located on the rig floor in the driller's mud house, displays the three axis hole direction data and has one other display window for other selectable data.
2. The data analysis trailer, where a second microprocessor has been added so that raw downhole data can be decoded, converted, and displayed independently from the rig floor display and control

unit. This feature, which was not available during Phase I, will permit system diagnostics to be performed and enhance the analysis capabilities to support the evaluation of Electro-drill system performance.

APPENDIX B

**TEST PLAN
FOR
ELECTRODRIL SYSTEMS VERIFICATION
OF THE
DEEP DRILLING SYSTEM**

October 1978

GENERAL ELECTRIC

1.0 OBJECTIVE

The purpose of the Systems Verification Test is to demonstrate the functional compatibility of all the Electrodrill system elements and the readiness of the total system to be deployed in operational wells for further evaluation. With the exception of the newly designed bit shaft, the design readiness of the other system elements has previously been demonstrated.

2.0 TEST FACILITY

The Systems Verification test is to be conducted at the Brown Oil Tools, Inc. (BOT) facilities, Houston, Texas. Because of restrictions imposed by the test well configuration, lengths of cable in excess of 1000 feet cannot be hung.

The large derrick will be utilized for the test with the power generation, instrument tailer and cable skid located close to the parking lot facing the rig "V" door. Although a kelly cannot be rotated at BOT, a slip ring assembly and kelly were made part of the Electrodrill test configuration because it is anticipated that they will be used in future operational test well sites.

3.0 VERIFICATION TEST REQUIREMENTS

3.1 GENERAL

The Systems Verification Test should be conducted in an orderly and controlled manner to assure that the test data derived is valid and meaningful.

3.2 RATIONALE

The rationale to be followed in this test program is to enter the test well with a minimum Electrodrill drill string, to test this baseline system and then add other system elements in a logical sequence. Data will be collected so that procedures can be evaluated and "streamlined" to minimize unproductive rig time in future operational deployments.

3.3 BIT SHAFT

A 100 hour test will be performed to demonstrate the integrity of the newly designed bit shaft. The motor/bit shaft compatibility as well as the capability of the bit shaft to function over the complete speed range of the motor while subjected to a downhole environment will be evaluated. Drill bit hydraulics may be simulated by appropriately plugging its lower end.

3.4 CABLE DEPLOYMENT/CONNECTOR RELIABILITY

Because the ability to reliably make electrical connections in a mud environment is key to a successful system, a series of repetitive cable/connector matings should be made to a submerged motor. After each mating the motor should be "bumped" and data collected to evaluate the characteristics of the electrical string.

3.5 CABLE LANDING/PREWIRED KELLY

The motor, with sufficient drill pipe above it, should be deployed so that the 1000 feet cable can be "landed". Data should be collected to allow

determination of cable stretch characteristics as well as drill pipe length tolerance required for cable landing.

After successful landings, the prewired kelly should be joined to the string and the motor turned on. Mud should be circulated at various pressures while the motor is exercised through its power regime.

3.6 DEDICATED PIPE

Dedicated (prewired) joints of drill pipe should be added to the string between the landed cable and kelly after successful completion of Paragraph 3.5.

The ability to make mousehole connections to the dedicated pipe should be evaluated. It is this configuration which is to be used to establish the functional reliability of the basic Electrodrill Deep Drilling System cable, connectors, kelly and prewired pipe.

3.7 DIRECTIONAL SUB

After successful completion of Paragraph 3.6, the directional sub shall be deployed above the motor. Powering up of the system will provide data to evaluate its ability to sense, process and transmit directional parameters.

3.8 FORMATION SENSOR/HEAT SUB

The ability to provide downhole environment data should be evaluated when the formation sensor/heat sub is added to the string between the directional sub and motor. No attempt should be made to power up the heat sub while it is in cased hole at the BOT facility.

3.9 FISHABILITY

It shall be demonstrated that the Electrodril landed cable can be removed through the drill string bore without removing any pipe. The fishing tool should be capable of latching on to the replaceable male connector while an upward applied force deforms the landing shoe and allows the cable to pass through pipe bores and tool joints on its way to the surface. The fishing tool should be capable of being utilized by contract fishing contractors.

3.10 SLIP RING ASSEMBLY

It shall be demonstrated that the Electrodril Deep Drilling System can be powered through the slip ring assembly. This would allow the string to be rotated while drilling.

4.0 SYSTEMS DEMONSTRATION

Upon successful completion of the Systems Verification Test, the methods used for deployment, retrieval and fishing should be evaluated by the drill rig crew as well as knowledgeable representatives of industry. Results of the evaluation should be used to streamline future procedures at operational test sites.

APPENDIX C

ELECTRODRIL
DEEP DRILLING SYSTEM

100 HOUR BIT SHAFT
TEST REPORT

October 1978

GENERAL ELECTRIC

1.0 INTRODUCTION

The bit shaft for the Electrodrill Deep Drilling System underwent a complete redesign to improve oil seal life. The chevron type packing previously used did not have adequate service life in a drilling mud environment. Other design goals and specifications for the bit shaft were as follows:

DESIGN GOALS

- ° 500 hours bearing and seal life
- ° Ease of assembly and disassembly
- ° Use of standard bearings and seals
- ° Keep overall length short as possible

DESIGN SPECIFICATIONS

- ° Axial loads to 70,000 lbs on drill bit, to 42,000 lbs drill bit hanging weight
- ° Radial loads to 10,000 lbs
- ° Temperature, ambient to 500°F
- ° Pressure differential across bit to 1200 psig (internal pressure higher), to 100 psig (external pressure higher)
- ° Torque to 3500 foot pounds
- ° Bit speed 0-600 RPM

Mechanical face seals were selected as the primary oil seals. The lower face seal is pressure balanced designed for pressure differences up to 2500 psig. The upper face seal which is not exposed to a pressure drop is an unbalanced type. The sealing ring and seat for both seals are tungsten carbide.

On the outside (mud side) of both face seals there is a chamber filled with a high temperature grease, with labyrinth seals to slow grease wash out by the drilling mud. The grease in these chambers provide a buffer between the drilling mud and the face seals.

The main thrust bearing is a cylindrical roller bearing with a basic dynamic thrust capacity of 113,000 lbs and a basic static thrust capacity of 231,000 lbs. At 400 RPM and 70,500 lbs on bit the minimum bearing life is 200 hours. The radial bearings are cylindrical roller bearings which have a minimum life of more than 750 hours at 400 RPM and 10,000 lbs radial load. The upper cylindrical roller thrust bearing that takes the hanging loads is more than adequate to meet the design requirements.

The lubrication system for the bit shaft is the same concept as used on the Electrodril motor. Basically it consists of an oil chamber pressurized to the mud pressure within the drill string through a cylindrical shaped elastomer. The usable oil supply is about 1200 cc.

A double cage sprague clutch rated at 4240 ft lbs was included in the bit shaft design. This allows conventional rotary drilling should the need arise. Figures 1 and 2 show fore and aft view of an assembled bit shaft.

2.0 TEST OBJECTIVES

The bit shaft test conducted at Brown Oil Tool was to demonstrate a 100 hour capability of both the motor and bit shaft in a simulated well environment

FIGURE 1

BIT SHAFT VIEWED FROM UPPER END WITH LIFTING RING ATTACHED.

FIGURE 2

BIT SHAFT VIEWED FROM LOWER END

and thus demonstrate the subsystems readiness for field deployment.

3.0 TEST SUMMARY

The 100 hour bit shaft test was successfully completed during the Electrodrill integrated system test. The bit shaft test started on 19 October and was completed on 25 October 1978. Mud pressure during test was generally 650 psig. Bit shaft speeds were varied during the test from 100 to 320 RPM.

The post test inspection of the bit shaft revealed no drilling mud intrusion across the face seals. Lube oil loss during the test was approximately 400 cc. No appreciable seal or bearing wear was noted.

Appendix C1 contains the detailed test report including the initial bit shaft test which started on 18 September and was terminated after 1 1/2 hours when it was noted there was drilling mud in the oil.

1st BIT SHAFT TEST

The 100 hour test was started on 18 September at Brown Oil Tools. The bit shaft and motor assembly was lowered into the well with two joints of 4 1/2" X hole drill pipe. A cable packoff and circulating head was used to facilitate mud circulation and routing of the motor conductors out of the drill pipe. A bull plug with an 0.5 inch diameter orifice was on the bottom of the bit shaft for mud pressure control.

Due to an electrical hookup problem the motor and bit shaft assembly were pulled from the well after 1 1/2 hours of running. It was then noted that drilling mud was in the bit shaft oil. The test was terminated and the bit shaft returned to the shop for disassembly.

Disassembly revealed that at the time of test termination mud was entering into the bit shaft oil chamber both through a ruptured oil bag (see Figure 1) and the upper face seal. The mud was exiting the bit shaft oil chamber across the bottom face seal.

The snap ring holding the stationary point of the bottom face seal had failed and allowed the seal faces to part (see Figure 2). When the bottom seal failed the mud pressure drop normally across the lower pressure balanced seal was now taken across the unbalanced upper seal which is designed for pressures of no more than 250 psi across the seal. The increased pressure on the seal increased the drag on the faces until the set screws holding rotating part of the face seal to the shaft failed. When the rotating part of the seal stopped, the rotating shaft destroyed the O-ring in the rotating part of the

FIGURE 1
RUPTURED OIL BLADDER BAG

FIGURE 2
BOTTOM OF BIT SHAFT SHOWING BROKEN FACE
SEAL RETAINING RING

seal and the seal integrity. The oil bladder rupture was a natural result of the increased pressure across the bladder.

2nd BIT SHAFT TEST

This bit shaft test was an integral part of the Electrodril integrated system test at BOT and was started on 19 October 1978. The test configuration was as shown in Figure 3.

The installation sequence went as follows:

10-19-78

- 1400 hours The bull plug with an 0.5 inch diameter orifice was installed on the bottom of the bit shaft and the bit shaft was installed on the motor assembly while hanging in the rig.
- 1518 hours 1000 ft of drill pipe and cable landing sub was run in well on top of the motor/bit shaft assembly.
- 1617 hours 1000' of electrical cable installed in drill pipe and mated to the top of motor assembly.
- 1641 hours Prewired kelly and electrical crossover sub installed; mechanically and electrically connected to the drill pipe and motor assembly.

Figure 3
BIT SHAFT TEST
CONFIGURATION

10-19-78

1653 hours Circulating head installed on Kelly.

1702 hours Cable from static inverter connected to the electrical crossover sub.

1705 hours Final electrical checks made and motor was turned on for a moment (bumped) to verify.

1706 hours Mud line connected to the circulating head.

1714 hours Electrodrill motor started at 30 Hz.

1717 hours Mud pump started.

1726 hours Mud pressure came up to approximately 500 psig (drill pipe filled).

1728 hours Mud pressure up to approximately 800 psig.

1730 hours Mud pump shut down to fix leak in mud return line (rig problem).

1736 hours Mud pump back up, pressure approximately 650 psig.

START OF 100 HOUR BIT SHAFT TEST

Motor voltage	593 volts	30 Hz
Motor amps	24 amps	

10-19-78

1750 hours Motor voltage frequency upped to 60 Hz

Motor voltage	1150 volts	60 Hz
Motor amps	26 amps	
Mud pressure	650 psig.	

1910 hours Test stopped - inverter tripped out

Problem with Kelly cable. Kelly and electrical crossover sub removed from test configuration. Second 1000' of cable was mated with the 1000' of cable in well. A circulating head and cable pack off was installed on top of the 1000' of drill pipe.

10-21-78

1006 hours Test restarted

Motor voltage	593 volts	30 Hz
Motor amps	24 amps	
Mud pressure	650 psig	

1132 hours Inverter shut down to replace current transducer. Mud pumps stayed on.

10-21-78

1202 hours Test restart

Motor voltage	593 volts	30 Hz
Mud pressure	640 psig	
Motor temperature	190°F-200°F	

10-22-78

Continuous running - all stable for 24 hours.

10-23-78

0735 hours Test stopped to replace defective valve in mud pump.

0910 hours Test restarted at 30 Hz. Motor temperature 206°F.

1300 hours Motor voltage frequency upped to 60 Hz. 1170 volts Motor temperature stabilized at 218°F.

1542 hours Test stopped for mud pump repair

1839 hours Test restart motor voltage frequency at 60 Hz, 1170 volts, mud pressure 650 psig.

10-24-78

All stable with no interruptions during this 24 hours. Motor temperature up to 222°F.

10-25-78

2027 hours Motor voltage frequency upped to 80Hz, 1533 volts, mud pressure 650 psig.

2038 hours Motor voltage frequency varied from 65 Hz to 96 Hz during this period. Motor temperature high was 238°F.

2055 hours End of test.

See Figures 4, 5 and 6 for running time summaries.

<u>DATE</u>	<u>TEST TIME</u>
10-19	1 hour 34 minutes
10-21	12 hour 24 minutes
10-22	24 hours
10-23	19 hours 28 minutes
10-24	24 hours
10-25	20 hours 55 minutes
Total	102 hours 21 minutes

Figure 5

TEST TIME BY DATE SUMMARY

<u>MOTOR VOLTAGE FREQUENCY</u>	<u>TEST TIME</u>
30 Hz	48 hours 03 minutes
60 Hz	53 hours 50 minutes
80 Hz	11 minutes
65-96 Hz	17 minutes
Total	102 hours 21 minutes

Figure 6

TEST TIME AT MOTOR VOLTAGE FREQUENCY

DATE AND TIME	MOTOR VOLTAGE FREQUENCY AND MUD PUMP PRESSURE	TIME	ACCUMULATED TIME
<u>10/19</u>			
1736 hours Test start	30 Hz-650 psig	----	0
1750 hours	60 Hz-650 psig	14 min	14 min
1910 hours Stop	60 Hz-650 psig	1 hr 20 min	1 hr 34 min
<u>10/21</u>			
1106 hrs Start	30 Hz-640 psig	----	1 hr 34 min
1132 hours Stop		26 min	2 hrs
1202 hours Start	30 Hz-640 psig	----	2 hrs
<u>10/22</u>			
<u>10/23</u>			
0735 hrs Stop		43 hr 33 min	45 hr 33 min
0190 hrs Start	30 Hz-650 psig	----	
1300 hours	60 Hz-650 psig	3 hr 50 min	49 hr 23 min
1542 hours Stop		2 hr 42 min	42 hr 5 min
1839 hours Start	60 Hz-650 psig	----	
<u>10/24</u>			
<u>10/25</u>			
2027 hours	80 Hz-650 psig	49 hr 48 min	101 hr 53 min
2038 hours	65-96 Hz-650 psig	11 min	102 hr 4 min
2055 hours Stop		17 min	102 hr 21 min

FIGURE 4
BIT SHAFT TEST TIME SUMMARY

APPENDIX C2

ELECTRODRIL
DEEP DRILLING SYSTEM

100 HOUR BIT SHAFT TEST PLAN

GENERAL ELECTRIC

Thermal Systems Programs

Houston, Texas

INTRODUCTION

During the development of the Electrodril Deep Drilling System equipment requirements, the need was identified for a new bit shaft design to accommodate higher weights on bit, mud pressures, higher downhole temperatures and to exhibit a functional life between routine maintenance of at least 100 hours.

Such a bit shaft has been designed and is currently in the process of assembly. It is planned in the near future to test this new bit shaft assembly with the 285 HP Electrodril motor in a test well at Brown Oil Tools Inc., Houston, Texas. This report documents the test plan for this bit shaft test.

TEST CONFIGURATION

A block diagram of the system elements under test, together with all necessary supporting equipment is shown in Figure 1.

The bit shaft and motor assembly (Figure 2) will be lowered into an 8 1/2" diameter test well at BOT and assembled with two joints of 4 1/2" X hole drill pipe. This downhole assembly will be held in the well at this depth using slips. A cable packoff and circulating head (Figure 3) will be used to facilitate mud circulation and routing of the motor conductors (cable) out of the drill pipe.

The motor conductors (cable) will be routed directly to a variable frequency power converter (static inverter) which is connected to the basic diesel driven,

Figure 2

MOTOR AND BIT ASSEMBLY

Figure 3

CIRCULATING HEAD, WIRELINE PACKOFF

AND CABLE CLAMP WITH CABLE

power generator. All electrical power necessary to support the Electrodrill bit shaft test will be provided by the skid mounted power generator with the exception only of 115V AC lighting power which will come from the BOT rig.

TEST PLAN

The basic objective of the bit shaft test is to accrue 100 hours of running time while circulating mud at realistic pressures to demonstrate the adequacy of the basic bit shaft design to maintain its functional capability. Upon completion of the 100 hour test it is planned to selectively disassemble the bit shaft and motor elements to determine component wear and efficacy of seals.

In addition to this basic test, it is planned to vary the motor speed by varying its excitation frequency. This will be done through the static inverter. The cadence for this motor speed variation is:

Test Hour	Motor Excitation Freq.
000 thru 020	30 Hz
020 thru 100	60 Hz
100 thru 102	90 Hz
102 thru 103	120 Hz

The additional test hours at the higher excitation frequencies was done intentionally so as not to jeopardize the basic 100 hour bit shaft test.

Mud circulation throughout the test will be maintained at 400 gpm and 700 psig. A nominal 10 lb. mud will be used during the test. Mud is circulated in the conventional manner through the drill string. At the bottom of motor/bit shaft assembly a bull plug with an 0.5 in. diameter orifice will be used for pressure control.

DATA ACQUISITION

A number of parameters will be monitored during the planned 100 hour bit shaft test. These parameters will be in addition to the empirical data obtained by virtue of the 100 hours of rotation applied to the Motor/Bit Shaft assembly while in a simulated downhole environment.

The parameters to be continuously monitored will be:

1. Impressed motor voltage
2. Impressed motor current
3. Impressed motor frequency
4. Motor core temperature
5. Input mud temperature
6. Input mud pressure
7. Mud pump flow rate

APPENDIX D

POWER GENERATION TEST REPORT

FINAL REPORT

INTEGRATED TEST FOR
VARIABLE FREQUENCY SCR AC
DRIVES AND SUBMERSIBLE AC
INDUCTION DRILL MOTORS

November 1978

1.1 SUMMARY

This report documents the results of a test program conducted on Emerson Electric AS 4590 static inverter and a REDA 540 series submersible pump motor. The purpose of this test program was to evaluate the transient response characteristics of the motor/inverter combination so that control circuits could be designed for the Electrodril Deep Drilling System.

The specific objectives of the test program was to determine:

- a. The compatibility of "AC Variable Frequency Static Inverter Drive Systems" to Electrodril applications.
- b. The drill motor losses attributable to oil sheer, (windage), at various motor speeds and with different lubricants.
- c. Drill motor starting current requirements at low frequency
- d. Drill motor HP and temperature rise with respect to various power frequencies, loads and cooling flow rates.
- e. Effects of the "Static Inverter Wave forms" upon the downhole telemetry system operation.
- f. The effects of cable IR losses to motor terminal voltage regulation requirements.

1.2 BASIC TEST RESULTS

1.2.1 COMPATIBILITY OF AC STATIC INVERTER DRIVES TO ELECTRODRILL APPLICATIONS

The Emerson AS 4590 drive unit performed satisfactorily for all the 20 HP Reda motor test. The inverter was utilized to operate the 20 HP motor from 15 Hz to 113 Hz under various loads, cable lengths and types of lubricants with no serious perturbations. From the basis of these tests, it is concluded that an AC static inverter drive is satisfactory as the prime drill motor drive unit for actual field drilling applications.

Later Tests using the drive unit with a Reda 150/285 HP motor proved the ability of the drive to run large submersible pump motors. Some instability of the drive unit with the larger motor did occur at higher frequencies ie, (82 - 90 Hz), however discussions with Emerson indicate this could be stabilized through internal adjustments to the drive unit.

1.2.2 LUBE OIL VISCOSITY CONSIDERATIONS

The test series has been completed and in general there were no significant surprises. As expected from TRW REDA's previous analysis, automatic transmission fluid (ATF) provided a 1% increase in the motor's efficiency under full load and about 8% under idle conditions. It must be realized however, that the selection of ATF for an Electrodrill lubricant was based upon the gear box requirement for an anti foaming high temperature non gumming lubricant. Since the motor and gear box are connected together, one lubricant must suffice for both. The purpose of this test was to determine if ATF would provide more or less oil sheer (windage) in the motor at the high RPM's and therefore be more or less efficient.

Starting current requirements based upon these tests indicates there should be no problems starting Electrodrill motors with size #6 cable to 20,000' depths providing the motor step-up transformer has the volts/Hz capability at 5 Hz to allow for cable IR drop. In reality this means the core of the transformer requires extra iron to keep from saturating at the lower frequencies/voltages.

1.2.4 DRILL MOTOR HP OUTPUT AND TEMPERATURE RISE

The purpose of these tests were to measure the HP output of the drill motor at various operating frequencies and to monitor its temperature under loaded conditions. Typically motors operated with variable speed AC drives are operated from very low speeds up through their normal operating frequency. Assuming the motor can be kept cool and electrically sound, advancing frequency and voltage in a linear relationship, (i.e., constant V/Hz) causes an increase in speed, constant torque output and therefore increased horsepower.

Dynamometer testing of the 20 HP motor indicated that the motor will produce 30 HP at 90 Hz, minus windage losses, and 40 HP at 120 Hz minus windage losses. Windage loss does increase significantly above 30 Hz, decreasing the available produced HP. Core temperature at 90 Hz under a full load condition did not exceed 240°F.

1.2.5 EFFECTS OF STATIC INVERTER WAVE FORMS ON DOWNHOLE TELEMETRY

A 20 HP motor was exercised through 2700' of size #10 power cable with the telemetry system functioning. A full range of motor speeds and dynamometer loading produced no data dropouts as observed upon the downhole telemetry. While this test only drew a maximum of 40 amps through the cable vs 75 amps of the large motor, no major problems are anticipated with the telemetry system over longer cable lengths and higher currents.

1.2.6 EFFECTS OF CABLE IR DROP TO MOTOR TERMINAL VOLTAGE REGULATION REQUIREMENTS

Operating the 20 HP motor through 2700' of size #10 cable under various loads provided no significant problems in the ability of the inverter voltage regulator to maintain correct motor terminal voltage. It must be realized however, that three direct sense lines from the motor terminals were provided back to the inverter. 2700' of size #10 cable coupled to the 445V 20 HP 29 Amp Reda, motor simulates about 8000' of size #6 cable coupled to the 150 HP Reda motor.

In actual downhole applications the motor terminal voltage will be sensed by a downhole carrier current telemetry system and relayed to the surface via the motor power leads.

2.0 INTRODUCTION

2.1 GENERAL

A series of tests were outlined in the early summer of 1978 to determine the

feasibility of using variable frequency (Static Inverter SCR) drives for Electrodril downhole drill motor primary power applications.

Until these tests were initiated, primary power was always supplied to the downhole drill motor from a fixed frequency power source, I.E. (60 Hz), or in the case of the Cullen/Continental Emsco tests during the early '70's, from a large rotary variable frequency generating system.

Since the Cullen/Continental Emsco test, the advancement of solid state AC drives have been followed very closely. The reasons for this are as follows:

- a. Electrodril performance is enhanced considerably by providing variable speed capability. Early attempts to accomplish variable speed capability utilized large heavy rotary power generating equipment of which the performance was considered marginal. A smaller, lighter weight solid state system was envisioned, but not available at the power levels required during early Electrodril testing. Technical advances over the years allow manufacturers now to provide light weight small, high horsepower drives.
- b. Cable IR drop below 10,000' in a typical Electrodril system becomes significant. The reason for this is the optimized tradeoff of power cable size vs mud flow requirements through the center of the drill pipe. Any power system utilized to this depth must have the capability of sensing the downhole motor voltage and responding to its demands quickly or else

the motor could stall. Rotary systems with their inherent inductance and hysteresis cannot respond to voltage changes too rapidly. Solid state AC drives usually operate from a phase controlled DC rectifier assembly. The phase controlled rectifier assembly can be slewed in voltage fairly rapidly, making it an excellent for Electrodrill power applications.

2.2 TESTING TIME FRAME AND REQUIREMENTS

The application of solid state AC drives to the Electrodrill system could not have been possible several years ago. As mentioned previously, the reason for this was the unavailability of high horsepower units. The technical uncertainties associated with rotary systems leave some doubts as to the ability of such systems to function at the greater depths.

Therefore, an investigation into applications of AC drives to the Electrodrill system was undertaken. In March 1978 Emerson Electric and TRW REDA were invited to participate. After final negotiations, the equipment was delivered in July 1978. Testing was commenced about the third week of July and continued until the second week of September 1978. Additional tests at Brown Oil Tools continued until November 1978.

2.3 OBJECTIVES

The objectives of these test programs were then as follows:

2.3.1 COMPATIBILITY OF SOLID STATE AC STATIC INVERTER DRIVES TO THE ELECTRODRIL SYSTEM

To determine if solid state drives were technically and economically feasible to apply to Electrodril technology vs rotary power generating systems.

2.3.2 MOTOR EFFECTS

To monitor the motor loaded and unloaded at low and high frequency/voltage inputs to ascertain:

- a. The horsepower developed at each frequency (RPM & TORQUE)
- b. Windage and friction losses with different lubricants.
- c. Heating effect at high RPM's/frequency with various cooling flow rates.

2.3.3 STARTING

To determine starting current requirements of the Reda motors at low frequencies so inverter starting circuitry and output transformer requirements could be specified.

2.3.4 TELEMETRY EFFECTS

To determine if motor operation at different frequencies and loads will affect the downhole telemetry monitoring system.

2.3.5 VOLTAGE REGULATION REQUIREMENTS

To verify that the voltage monitoring and regulation circuitry of the Emerson AS 4590 can respond to cable IR loss and maintain the motor terminal voltage.

3.0 TECHNICAL APPROACH

3.1 GENERAL

A test tank was fabricated to hold the 20 HP motor upright in a flow of water while testing it for oil sheer or windage. See Figure 3.1.1. In addition, another test stand was fabricated to couple the assembled motor, gear box and protector assembly to a dynamometer. See Figure 3.1.2. Figure 3.1.3 is the basic schematic for the testing series. Minor changes in the test stand configuration or schematic to fit any particular test will be as described in each test.

3.2 INSTRUMENTATION

3.2.1 SPECIAL INSTRUMENTATION

Special instrumentation was required for the motor current and motor voltage monitoring. The special instrumentation was necessary due to the non-standard frequency outputs of the static inverter and the DC components of the 6 step wave form provided by it.

To read the RMS output of the static inverter/transformer to the motor, HP 3400A True RMS voltmeters were utilized. These voltmeters provide a true RMS reading of the voltage wave form supplied to them regardless of its complexity.

A Columbia AC/DC clamp-on ammeter was used for motor current measurements to insure accuracy at different frequencies and with the DC components of the six step inverter wave form.

TEST STAND BLOCK DIAGRAM

Test #1, 2, 3, 4

Figure 3.1.1

D10

D11

HORIZONTAL TEST STAND

TEST #5, 6, 7, 8

Figure 3.1.2

D12

Figure 3.1.3
TEST STAND ELECTRICAL SCHEMATIC

3.2.2 STANDARD INSTRUMENTATION

All other instrumentation utilized for testing was standard off shelf manufactured items available through typical test equipment supply channels.

3.2.3 INSTRUMENTATION SYMBOLS AND CONNECTION

Refer to Figure 3.1.3. In the referred schematic each instrumentation bubble is designated with a symbol and an arrow to the point connected within the test figure. An explanation of the symbols, where the instrument is attached or what it is measuring and where it may be found in the data sheet is presented on Page D42.

3.3 TESTS PERFORMED

3.1.1 GENERAL

The following tests were performed to satisfy the objectives as spelled out in Section 2.0 and as summarized in Section 1.0

A. Motor oil sheer (windage) Test - Reda #2 Mineral Oil

Remarks

Test #1 - Up Frequency

20 HP motor connected directly to inverter/

Test #2 - down Frequency

transformer - no gear box, protector assembly
test stand #1

B. Motor oil sheer (windage) test - Dexron ATF

Remarks

Test #3 up Frequency

Same as Item A. above

Test #4 down Frequency

C. Gear box and protector losses

Test #5 - 20 HP motor gear box and protector connected directly to inverter. No load on dynamometer.

D. Dynamometer Test A

Test #6 - 20 HP motor - gear box and protector connected directly to inverter and dynamometer

E. Dynamometer Test B

Test #7 - 20 HP motor - gear box and protector assembly connected through 2700' of size #10 cable to inverter and to dynamometer

F. Motor locked rotor and low frequency starting current test

Test #8 - TBA

3.4 TEST DESCRIPTIONS AND RESULTS

3.4.1 OIL SHEER AND WINDAGE TEST #1, 2, 3, 4

Tests 1, 2, 3 and 4 were accomplished utilizing the test stand shown in Figure 3.1.1. The 20 HP motor was exercised through a series of frequency ranges with REDA #2 mineral oil and Dexron ATF as lubricants under no load conditions. Data sheets for tests 1, 2, 3 and 4 show static readings for each of these tests at different operating points. For analysis purposes the down frequency of each test (2 and 4) were utilized, the lubricant in each case being at maximum operating temperature.

As can be seen in test 2 down frequency, the motor requires 6600 watts to idle at 113 Hz and 1500 watts to idle at 60 Hz. This basic test verifies within reason that the oil sheer and frictional losses within the motor increase as the square of the RPM or frequency ratio. Therefore operating the motor at 30 Hz produced 1/4 the losses from windage and friction than operating it at 60 Hz and 120 Hz operation will produce four times or over the losses experienced at 60 Hz.

One might conclude then that assuming the motor can be kept cool, operation at double the frequency, i.e. (120 Hz) does not produce double the horsepower or 40 HP due to the increase in frictional and windage losses. In reality the smaller REDA motors are only about 70% or so efficient but are conservatively rated. It may be assumed that at 60 Hz operation and 29 amps the 20 HP motor will produce at least 21 HP and at 120 Hz would produce about 42 HP.

The extra loss will cause the motor actually to produce only 36.78 HP or about a 14% loss in optimum output.

If these calculations were transferred to the 150 HP 540 REDA motor series, it would be logical to assume a 260 HP output of the large motor i.e. (150 HP) when operating it at 120 Hz.

Differences in the amount of idle wattages between REDA #2 mineral oil and ATF may seem large at first (8%) under idle conditions. When the difference in idle wattages are compared to the loaded run wattages however, only a 1% difference between REDA mineral oil and Dexron ATF can be seen. This difference drops to less than 1/2% at temperatures above 300°F due to the different viscosity index curves of the different lubricants. It can be assumed the REDA motors will run satisfactorily with Dexron ATF as a lubricant with about a 1% efficiency increase.

3.4.2 GEAR BOX AND PROTECTOR ASSEMBLY LOSSES TEST #5

In order to ascertain the predicted motor and gear box/protector assemblies

horsepower output into the dynamometer, the motor and gear box assembly was operated horizontally at no load for test #5, see Figure 3.1.2. By subtracting the idle motor wattage requirements from that with the gear box and protector assembly, the actual loss in the gear box and protector can be predicted.

The following differences were recorded between the motor idle and motor idle with the gear box/protector.

Frequency	Watts Δ	HP Consumed
@ 30 Hz	1500	2.1
@ 60 Hz	5600	7.5
@ 90 Hz	17300	23.1 (22-23) ⁽¹⁾
@ 113 Hz	21900	29.35 (28-29) ⁽¹⁾

(1) Changes with temperature significantly

While not exactly linear to the assumption that the losses due to windage and friction will be as to the square of the increased ratio, the above values do bear some relation to this theory.

It may be assumed that at high RPM's, (7200 from the motor) at 120 Hz, the gear box/protector loss will be about 30 HP. Therefore the horsepower required to drive the gear box must be subtracted from the total system to arrive at actual

shaft HP output for any motor frequency combination. If the 21 HP motor operating at 90 Hz is equivalent to about 32 HP, a 22 HP gear box loss would leave about 10 HP available. At 90 Hz, the shaft RPM is 323 producing 200 pounds at 29 amps motor current. This is about a 12 HP output and within reason to the expected results. At 60 Hz the gear box loss would be 7.5 HP - 21 = 13.5 HP output. In test #6 the actual motor assembly output was 217 RPM x 320' lbs $\div$ 5250 = 13.2 HP

The significance of the above information can be utilized in determining the total system performance, efficiency and thermal distribution.

3.4.3 DYNAMOMETER TEST A #6

The first test using the dynamometer, test #6, was accomplished to ascertain the developed motor horsepower at various frequencies minus the gear box and protector section losses. At a 29 amp motor current drain:

90 Hz produced a HP output of 13.5 Hp

60 Hz produced a HP output of 13.22 HP

30 Hz produced a HP output of 7.8 HP.

See data sheet 5.1.C Test #6

It is quite obvious that in the case of a 20 HP motor driving the gear box/ protector assembly, no significant HP output is available by increasing frequency. The reason for this is that the increased horsepower produced by the motor is consumed by the additional losses in the gear box and protector.

Since the gear box and protector losses are constant however, their losses are less significant when using the larger field deployed Electrodrill motors of 60 (120) and 150 (300) HP ratings.

3.4.4 DYNAMOMETER TEST B #7

The purpose of the dynamometer test #7 was to introduce cable IR drop into the system to ascertain if the inverter sense and voltage control circuitry could maintain proper motor terminal voltage under step load.

If proper motor voltage cannot be maintained during intermittent loading of the motor, torque output will drop with a resultant stalling of the motor. See test data sheet 5.1 C Test #7.

All data taken on this sheet indicated the ability of the static inverter to maintain proper motor terminal voltage under various loads. The cable length chosen was 2775 feet of size #10 power cable. Transposition of this data to effective other motor and cable combination/lengths may be found in Section 5.4.

3.4.5 LOCKED ROTOR AND STARTING TORQUE TEST #8

The dynamometer loading was slowly adjusted upward until the motor refused to start. This occurred at about 125 foot pounds. Then the loading was backed off until reliable starting could be obtained at 105 foot pounds. See data sheet for test #8.

If the 20 HP Motor can produce 105 foot pounds of starting torque, it may be assumed the 150 HP motor will produce over 700 foot pounds when started with comparable voltage, frequency and current parameters. Considering the motor and bit will be lifted off bottom in Electrodril applications, no starting problems are anticipated.

TEST STAND PHOTOGRAPHS

OIL SHEER TEST STAND
TEST #1,2,3,4

HORIZONTAL DYNAMOMETER
TEST STAND TEST #5,6,7,8

REAR VIEW OF DYNAMOMETER CONNECTED
TO 20 HP MOTOR

REAR VIEW OF INVERTER SHOWING
STEP UP TRANSFORMER

4.0 TEST DATA

4.1 GENERAL

The following test data sheets are the raw data as taken in test #1 through #8. In addition to the test data sheets, strip chart recordings were taken of various parameters in real time. Since the test data strip chart recordings are so bulky, they cannot be reproduced for this report. The REDA 20 HP 540 series motor used for the test was REDA part No. #63268-7 rated at 445 V 3 phase AC 60 Hz and 29 amps.

4.2 MOTOR TEMPERATURE MEASUREMENTS

NOTE: All motor temperature measurements shown in the attached data sheets were taken with a thermocouple mounted either in the very top of the motor or gear box assembly in the motor lubricant.

In an effort to determine true motor core temperature additional tests were made utilizing a wheatstone bridge to measure the motor's stator resistance. Comparing the cold stator resistance to the hot running resistance gives the motor's true core temperature. When the true motor temperatures were calculated, they showed that when the lubricant was at 187 - 190°F, the core of the motor was at 240°F, or about 26 percent higher. It can therefore be assumed the actual motor temperatures were about 26 percent higher than those shown in the attached data sheets. In no case did the test temperatures exceed the Electrodril maximum allowable motor temperature of 300°F.

OIL SHEER TEST
REDA #2 OIL

Date/Time 8/1/78
Motor Type/HP 540 REDA 20 HP
Motor 011 REDA #2
Motor Serial No. _____

DATA SHEET 5.1A TEST #1 - Up in Freq

Freq. Hz	Vo Volts RMS	Vm Volts RMS	Io Amps RMS	Vdc Volts DC	Idc Amps DC	Watts Input	Torque Ft Lbs	Load	Mtr Temp Time
113		750	8.0	328	37.5	7700 7200		No Load Note: Watts drop as motor heats	See 5.1D
90		632	7.1	270	29.5	5000 4750		No Load	
60		420	6.4	184.5	18.5	2500		No Load	
30		210	5.0	94	9.0	1100		No Load	
15		105	3.2	49	7	400		No Load	
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

OIL SHEER TEST
 REDA #2 OIL

5.1 D MOTOR TEMPERATURE LOG

Date/Time 8/1/78

Motor Type H.P. REDA 540-20HP

Motor Oil REDA #2

Motor Serial No. _____

Cooling Medium, water, Rate none

Fo	Vm	Load	Temp 2 Min	4 Min	6 Min	10 Min	15 Min +	Comments	
30	210	0	106F 84.6	Mtr Tank				Start Temp 84.6	
60	420	0			130 86.8	Mtr Tank est.			
90	632	0				153 90	Tank		
113	750	0					174 96	Tank	
15	105	0		93 83				Mtr & Tank allowed to cool before 15 Hz test	

OIL SHEER TEST
REDA #2 OIL

Date/Time 8/1/78
Motor Type/HP 540 REDA 20 HP
Motor 011 REDA #2
Motor Serial No. _____

DATA SHEET 5.1A TEST # 2 Dwn Freq

Freq. Hz	Vo Volts RMS	Vm Volts RMS	Io Amps RMS	Vdc Volts DC	Idc Amps DC	Watts Input	Torque Ft Lbs	Load	Mtr Temp Time
113	890 890 890	750	7.5	238	36	6600		No Load 40 HP Overload	See 5.1D
90	667.5 667.5 667.5	630	6.4	270	24.5	2900		No Load 30 HP Overload	
60	445 445 445	430	5.3	182	11	1500		No Load 20 HP Overload	
30	222.5 222.5 222.5	215	3.8	92	2	400		No Load 10 HP Overload	
	111.25 111.25 111.25							No Load 5 HP Overload	
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

OIL SHEER TEST
 REDA #2 OIL

5.1 D MOTOR TEMPERATURE LOG

Date/Time 8/1/78

Motor Type H.P. 540 REDA 20 HP

Motor Oil REDA #2

Motor Serial No. _____

TEST _____

Cooling Medium, water, Rate 0

Fo	Vm	Load	Temp 2 Min	4 Min	6 Min	10 Min	15 Min	Comments	
113	750	0					184F	Mtr hot from test	#1 Up Freq
							107F	2nd Figure Tank Temp	
90	630	0					179		
							117	Tank	
60	420	0					166		
							123	Tank	
30	215	0					152		
							127	Tank	

Date/Time
 Motor Type/HP
 Motor Oil
 Motor Serial No.

8/1/78

540 REDA 20HP
 DEXRON ATF

DATA SHEET 5.1B TEST # 3 UP FREQ

Freq. Hz	V _o Volts RMS	V _m Volts RMS	I _o Amps RMS	V _{dc} Volts DC	I _{dc} Amps DC	Watts Input	Torque Ft Lbs	Load	Mtr Temp Time
113		780	8.0	328	27.5	7200 6300		No Load. Note: Watts drop as Mtr heats	See 5.1D
90		630	7.1	270	29?	4800		No load	
60		420	6.0	184	17	2300		No load	
30		212	4.4	93	6.5	800		No load	
15		106	2.8	48	3.8	300		No load	
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

5.1 D MOTOR TEMPERATURE LOG

OIL SHEER TEST ATF

Date/Time 8/1/78Motor Type H.P. REDA 540 20HP

Motor 011

Motor Serial No. _____

TEST 5.1B #3 Up FreqCooling Medium, water, Rate 0

Fo	Vm	Load	Temp 2 Min	4 Min	6 Min	10 Min	15 Min +	Comments	
15	106	0		94.7	Mtr				
				89	tank				
30	212	0			104	mtr			
					89	Tank			
60	420	0				122			
						90	Tank		
90	630	0					144		
							91.8	Tank	
113	780	0					177		
							101	Tank	

OIL SHEER TEST ATF

Date/Time 8/1/78

Motor Type/HP

540 REDA 20HP

Motor 011

DEXRON ATF

Motor Serial No.

DATA SHEET 5.1B TEST # 4 Dwn Freq

Freq. Hz	Vo Volts RMS	Vin Volts RMS	Io Amps RMS	Vdc Volts DC	Idc Amps DC	Watts Input	Torque Ft. Lbs	Load	Mtr Temp Time
113		770	7.3	327	34	6100		No Load	See 5.1D
90		630	6.2	268	24	3700		No Load	
60		420	5.2	182	10.5	1400		No Load	
30		212.8	3.8	92	0	300		No Load	
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

OIL SHEER TEST ATF

5.1 D MOTOR TEMPERATURE LOG

Date/Time 8/1/78Motor Type H.P. 540 REDA 20HPMotor Oil DEXRON ATF

Motor Serial No. _____

TEST 5.1B #4 dwn FreqCooling Medium, Water, Rate 0

Fo/Hz	Vm	Load	Temp 2 Min	4 Min	6 Min	10 Min	15 Min +	Comments	
113	770	0				Mtr Temp	181	Mtr Hot from Test	#3 up Freq
							110	Tank Temp	
90	630	0					177		
							118	Tank	
60	420	0					164		
							124	Tank	
30	212.8	0					154		
							126	Tank	

IDLE TEST WITH GEAR BOX

Date/Time
 Motor Type/HP REDA 540-20HP
 Motor Oil DEXRON ATF
 Motor Serial No.

DATA SHEET 5.1B TEST # 5 Up Freq

Freq. Hz	Vo Volts RMS	Vi Volts RMS	Io Amps RMS	Vdc Volts DC	Idc Amps DC	Watts Input	Torque Ft Lbs	Load	Mtr Temp Time
100	741	680	24.5	299	120	26,500		No load	187°
90	667.5	620	26	271	94	21000		No Load	136
60	445	424	15.2	186	52	8500		No load	105°F
30	222.5	220	8.5	96	19	2500		No load	92°F
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

IDLE TEST WITH GEAR BOX

Date/Time
Motor Type/HP
Motor 011
Motor Serial No.

REDA 540 20HP

DEXRON ATF

DATA SHEET 5.1B TEST # 5 Dwn Freq

Freq. Hz	Vo Volts RMS	Vin Volts RMS	Io Amps RMS	Vdc Volts DC	Idc Amps DC	Watts Input	Torque Ft Lbs	Load	Mtr Temp Time
113	741	680	24.5	299		28 KW		No Load	187°F
90	667.5	620	26	271	94	21,000			185°F
60	445	424	12.5	184	40+	7KW		No load	170°F
30	222.5	220	6.5	93	10	1.8KW		No load	161°F
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

DYNAMOMETER TEST

1 CABLE LENGTH 0-MTR DIRECT TO INVERTER

1. G RESISTANCE - 0

INDUCTOR SIZE N/A

Date/Time

8/22/78

Motor Type/HP

REDA 540-60HP - 20HP

Motor Oil

DEXRON ATF

Motor Serial No.

DATA SHEET 5.1 C TEST #6

Hz	V _o Volts RMS	V _m Volts RMS	I _o Amps RMS	V _{dc} Volts DC	I _{dc} - Amps DC	Slip RPM	Torque	Load	KW Input	Mtr Temp
89	740	740	32.5	328	120	323	220'lbs	No Load 120 HP O/L		163°F
60	500+	500+	28.4	226	96	216-217	320'lbs	No Load 60 HP O/L	33 KW to 31 KW	125°F
30	219	219	34	96	120	105-108	380'lbs	No Load 10 HP O/L	9-10KW	102°F
								No Load Stalled		

Check system performance with step load changes and various R1 cable lengths. Visicorder should be at least 2" peak to peak sensitivity and enough horizontal speed for good resolution of wave shapes.

R1 CABLE LENGTH 2775'
LEG RESISTANCE 3
CONDUCTOR SIZE #10

8/22/78

REDA 540-60HP - 20 H

DEXRON ATF

[illegible]

D34

DYNOMOMETER TEST WITH CABLE

R1 CABLE LENGTH 2775
 LLG RESISTANCE - 3
 CONDUCTOR SIZE #10

Date/Time

8/22/78

Motor Type/HP

REDA 540-20HP

Motor Oil

DEXRON ATF

Motor Serial No.

DATA SHEET 5.1 C TEST #7

req. Hz	Vo Volts RMS	Vm Volts RMS	Io Amps RMS	Vdc Volts DC	I _{dc} - Amps DC	Slip RPM	Torque	Load	KW Input	Mtr Temp
90	764	650	24+	329	115 P	329	0	No Load	27	See 5.1D
90	810	650	35	353	160 P	323	200+	30 HP	41	
90	824	640	38	363	165 P	320	240+	0/L	48	
60	500	440	14.5	216	63 52	220	0	No Load	10	
60	580	440	30	259	125	213	320	20 HP	27	
60	604	444	34	272	140	210	370	0/L	32	
30	260	224	8.5	113.4	26 26	111	0	No Load	3.5	
30	364	230	28.5	163	120 100	106	380	10 HP	16.5	
30	390	230	34	177	140	105	460	0/L	21	
15	136	118	4.4	60	14	N/K	0	No Load	1.8	
15	244	124	24	113	100 98	N/K	380	5 HP	9.5	
15	260	124	26+	118	120 P	N/K	420+	0/L	11.5	
								No Load		
								Stalled		

Check system performance with step load changes and various R1 cable lengths. Visicorder should be at least 2" peak to peak sensitivity and enough horizontal speed for good resolution of wave shapes.

DYNOMOMETER TEST WITH CABLE

5.1 D MOTOR TEMPERATURE LOG

TEST 5.1C #7

Mtr Cooling Medium, water, Rate 8 gal/min

Date/Time 8/22/78

Motor Type H.P. REDA 540-20HP

Motor Oil DEXRON ATF

Motor Serial No. _____

Fo	Vm	Load	Temp 2 Min	4 Min	6 Min	10 Min	15 Min +	Comments
30 30 30	224 230 230	0 380'lbs 460'lbs		92F	99.6F	106 F		30Hz Test Run First
60 60 60	440 440 444	0 320'lbs 370'lbs					126 136 142	60 Hz 2nd
15 15 15	124	0 370'lbs 420					132 122 121	15 Hz 3rd
								Shut Down Cooled off
90 90 90	650 650 640	0 200+ 240+			141+ 170 178			90 Last

STARTING TORQUE TEST

DATA SHEET 5.1B TEST # 8

Date/Time
Motor Type/HP
Motor 011
Motor Serial No.:

REDA 540 20 HP
ATF

Freq. Hz	V _o Volts RMS	V _{in} Volts RMS	I _o Amps RMS	V _{dc} Volts DC	I _{dc} Amps DC	Slip RPM	Torque Ft Lbs	Load	Mtr Temp Time
5	180 ⁽¹⁾	68 ⁽¹⁾	28 +	85 ⁽¹⁾			N/A	No Load	See 5.1D
5	190 ⁽¹⁾	68 ⁽¹⁾	28.5+	89 ⁽¹⁾			105	Max	
5	190 ⁽¹⁾	68	29 +	89 ⁽¹⁾			125	Stalled	
(1) Voltage starts at 0 - increases to this value then drops off as motor starts to run.									
10	To give Normal Excita- tion							No Load 3.33 HP Overload	
5	To give Start Torque Req							No Load 1.7 HP 1.7 HP Stalled	

Note: Measure motor temperature rise at full load every 2 minutes to extrapolate temperature rise curve - if necessary use separate data sheet 5.1D - show cooling medium and rate.

5.0 CONCLUSIONS

5.1 APPLICABILITY OF SOLID STATE AC DRIVES TO SUBMERSIBLE MOTOR APPLICATIONS

As mentioned in the summary, there seems to be no doubt that solid state AC variable frequency drives are applicable to driving submersible AC induction motors such as that used for Electrodrill. The test series and subsequent Brown Oil Tools 100 hour bit shaft test proved conclusively the ability of the solid state drive to operate the downhole motor satisfactorily. Not only did the test prove basic operation of the motor but they also verified the relationship of the constant torque, variable speed/HP relationship offered by providing variable frequency/voltage. Therefore, operating the Electrodrill motor at 30 Hz provides 1/2 speed and 1/2 HP from that at 60 Hz, and 90 Hz operation provides 1 1/2 times the speed and horsepower as that of operating at 60 Hz. Of course the limiting factor is the cooling capability of the motor when operated above its rated frequency and horsepower. For Electrodrill applications, the tests indicate that it seems possible to operate to 90 Hz without heating problems. At speeds above 90 Hz heating problems could be encountered if mud flow and mud temperature are not sufficient for the heat removal.

Certainly one problem associated with operating an electrical induction motor drilling at extreme depths is cable IR drop. If the power system cannot sense and respond to the motor terminal voltage requirements quickly, the motor will stall drawing excessive locked rotor current. Static inverter AC drives usually operate with phase controlled DC rectifier assemblies. With proper sense and control circuitry, these phase control rectifier assemblies can

slew the inverter output voltage to compensate for the cable IR drop as motor loading or current increases. All testing indicated an excellent ability to accomplish motor terminal voltage control with the Emerson AS 4590 drive.

It is felt with large bulky rotary equipment that high response voltage control would be difficult due to the inductance and hysteresis of the generator field.

5.2 MOTOR AND GEAR BOX LUBRICANTS

During the Cullen/Continental Emsco Electrodrill test of the 1969/1970 time period, it is reported that gumming or shellacing the gear box occurred under heavy loads of high RPM. In an effort to reduce the gumming, Exxon Dexron "Automatic Transmission Fluid" was selected as a gear box lubricant instead of Reda mineral oil.

Since the motor and gear box are an integral component, filling the gear box with ATF also means filling the motor with ATF.

There has been concern over the years as to the lubricating qualities of the ATF and how it would affect motor efficiency. The test series just performed showed no excessive wear on the motor from operating it at high RPM's with ATF as a lubricant. In addition, efficiency of the motor was increased from 1 to 1/2%, depending on temperature, by utilizing automatic transmission fluid.

5.3 STARTING CURRENT CONSIDERATIONS

The Electrodrill power transmission system is of necessity fairly inefficient. Mud flow requirements down the center of the drill pipe dictate that the power cable be reasonably smaller than that which would be required for efficient

power transmission. Considering that the motor inrush current can be 5 times the running current when starting at 60 Hz, it can be seen that starting even the 60 HP motor at 60 Hz would be depth limited.

Tests with the variable frequency AC static inverter drive, indicate that starting current is reduced to rated running current or less by starting the motor at 5 Hz. These tests collaborate data provided by Baylor engineering over ten years ago estimating the starting current at 5 Hz to be the Electrodril motor's rated loaded running current at 60 Hz.

It then can be assumed that starting of Electrodril motors at depths of over 20,000 feet can be accomplished easily when using variable frequency AC drives. The only requirement associated with using such a low starting frequency is that the inverter must operate through an output motor step-up transformer. In order to allow for cable IR drop at starting, i.e., (5Hz), the inverter output transformer must be able to handle a high V/Hz ratio at 5 Hz. Engineering wise this means providing the transformer with a much larger core than would normally be necessary in a 60 Hz operation. In essence this is no particular problem other than the transformer has to be specially wound which makes it somewhat larger than a normal 60 Hz transformer of equal rating.

5.4 EFFECTIVE SIMULATION OF VARIOUS MOTOR AND CABLE COMBINATIONS BASED ON THE 20 HP MOTOR TEST

The 20 HP 445 VAC 3 phase 60 Hz REDA submersible pump induction motor was tested with the static inverter connected through 2775 feet of size #10 power cable in test #7. The 20 HP motor is rated for 29 amps under fully loaded conditions. Size #10 cable exhibits about three ohms per leg per 2775 feet.

The voltage drop then equals:

$$29 \times 3 \times 1.732 = 150 \text{ V drop between any two power legs.}$$

150 V is 33.70 percent of the 445 60 Hz required motor voltage.

Therefore exercising the small motor with 2775 feet of size #10 cable is the same voltage drop wise as exercising the 60 HP motor through 6755 feet of size #10 cable based upon the following calculations.

60 HP REDA motor is rated 32 amps at 1200 volts 60 Hz AC

$$33.7 \text{ percent of } 1200 \text{ V} = 404 \div 1.732 = 233$$

$$233/32 = 7.2964 \div 1.1 = 6,755 \text{ feet}$$

In addition, the 150 HP REDA motor is rated at 75 amps 1150 VAC 60 Hz.

$$33.7 \text{ percent of } 1150 \text{ V} = 387.55 \div 1.732 = 223/75A. = 2.9334 \div .41$$

$$\text{---}'s \text{ (size \#6 cable resistance per 1000')} = 7,276 \text{ feet}$$

Neglecting any loss in the step-up transformer one can assume the 20 HP motor test simulates operating the 150 HP motor then to a depth of 7,276 feet utilizing size #6 power cable with a resistance of .41 ohms per 1000 feet.

DATA SYMBOLOGY

V_{dc} Inverter DC Buss voltage - Digital voltmeter connected to inverter DC Buss (all data sheets)

I_{dc} Inverter DC Buss current - Clamp on ammeter in DC Buss circuit (Some data sheets).

F Inverter output frequency - frequency counter attached to inverter master oscillator (all data sheets).

V_o Inverter/transformer RMS output to cable or motor.

V_m Motor terminal voltage - RMS voltmeter attached to motor terminals. (all data sheets).

Note: V_o and V_m will be the same where R_l (cable) is not included.

I_o Current output to motor - Columbia AC/DC clamp on ammeter (all data sheets)

T_o Motor temperature - thermocouple mounted in the lubricant at the top of the motor (all data sheets).

T_c Torque load - Dynamometer reading in foot lbs of torque (as applicable data sheets)

S_l Motor slip or RPM - Reading on RPM meter of dynamometer. May be compared to frequency of voltage applied to motor vs synchronus RPM operation (as applicable data sheets).

C_f Coolant flow in GPM - Type coolant and approximate flow rate (as applicable data sheets).

R_l Cable resistance in ohms per leg - (as applicable data sheets)