Maurer Engineering Inc.

10301 NW FREEWAY-SUITE 201-HOUSTON, TEXAS 77092
(713) 603 0227

MASTER

IDO/0081-1

BOREHOLE MEASUREMENTS WHILE DRILLING

- SYSTEMS AND ACTIVITIES -

DR. WILLIAM J. MCDONALD

JUNE 1977

WORK PERFORMED UNDER CONTRACT NO. EY-77-X-07-0001
CLIFTON CARWILE PROGRAM MANAGER

PREPARED FOR
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Geothermal Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared to document work sponsored by the United States Government. Neither the United States nor its agent, the United States Energy Research and Development Administration, nor any Federal employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by Maurer Engineering Incorporated or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

BOREHOLE MEASUREMENTS WHILE DRILLING - SYSTEMS AND ACTIVITIES -

DR. WILLIAM J. MCDONALD

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MAURER ENGINEERING INCORPORATED
10301 NW FRWY. , SUITE 202
HOUSTON , TEXAS 77092

JUNE 1977

MEI TR77-14

PREPARED FOR THE
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF GEOTHERMAL ENERGY
UNDER CONTRACT EY-77-X-07-0091
CLIFTON CARWILE PROGRAM MANAGER

SUMMARY AND CONCLUSIONS

Deeper drilling, increased activity offshore and rapidly escalating costs have focused attention on all potential methods of drilling safer and cheaper. Real time data from the bit offers the greatest potential for meeting these needs. As a result, numerous companies are actively competing to develop this oil field service capability and to capture a lucrative world wide market estimated to be \$300-500 million by 1980 and \$500-1,000 million by 1985.

Two basic categories of service are sought. The first, and highest priority, is drilling safety and efficiency; the second is real-time logging, or formation evaluation. Drilling safety and efficiency includes three types of measurements: 1) well control, 2) directional surveying and control and 3) drilling optimization. Oil company management and engineers place strongest (and approximately equal) emphasis on the first two of these, well control and directional information.

This study addresses the types of systems being studied, describes company activity and projects underway, estimates the practical potential for success and considers the commercial market for successful systems. The need for research data on bit hydraulics and drill string dynamics, special deep, hot or sour gas situations and other relatively unusual requirements may become exceptions to the general conclusions that are drawn.

The report documents historical and present activity through presenting the results of extensive literature and

patent researches. Status of current activity of this rapidly evolving technology is primarily based on personal contacts. Chapter IV presents a breakdown of activity by company along with names and addresses for further contact.

Based on this study we conclude:

More than forty companies are directly involved in borehole telemetry projects. More than fifteen projects are in hardware development and/or testing.

Four types of systems are under development: Mud Pressure Pulse; Hard Wire Telemetry; Electromagnetic Systems; and Acoustic Systems.

At the present time, mud pressure pulse has the distinct lead in development. Teleco, Schlumberger and Gearhart-Owen are all likely to offer a real-time data system in late 1977 or 1978. Other systems under development will have to offer special applications, substantially increased capability or lower cost to compete with the mud pulse systems.

Drilling safety is difficult to assign a value, but is extremely important. Greatest economic advantages are realized with MWD systems in the area of drilling faster and more economically, yet safer. These economic advantages are especially important offshore, but also apply to deep onshore exploration.

Directional surveying and control is especially important in offshore platform development wells. Onshore market potential for directional information is small.

Drilling efficiency and optimization, coupled with better well control, will provide the greatest assessable economic benefit. Formation Evaluation is considered of secondary importance but may be inexpensive once the basic telemetry systems are available.

The market potential for MWD systems is expected to exceed \$500 million per year by 1985. Market analysis indicates pricing potential on the order of \$1,000 - 2,000/day for the directional services and perhaps \$2,000-4,000/day for drilling efficiency measurements.

While basic sensor systems are already available, cheaper and more rugged and reliable sensors may be required. Better directional sensors are needed as is further research in types and sensitivity of well control sensors. The area of downhole data processing seems to be neglected at the present.

Downhole motors for both directional and straight hole drilling offer significant potential for improved drilling and will provide expanded market and applicability of MWD systems.

Active development of competitive systems is expected to continue in order to achieve greater reliability, higher data rate, two-way communications and reduced costs.

TABLE OF CONTENTS

	Page
Summary and Conclusions	i
Table of Contents	iv
List of Tables	vi
List of Figures	vii
Introduction	1
Chapter I. Needs for Real-Time Borehole Telemetry	5
Chapter II. Economic Incentives	13
Directional Drilling	13
Directional Safety and Efficiency	20
Logging	22
Summary	23
Chapter III. Basic Systems	25
Mud Pressure Pulses	25
Electromagnetic Methods.....	32
Insulated Conductor Systems.....	34
Acoustic Methods	40
Other Methods	41
Chapter IV. Companies Active in Borehole Measurements	
While Drilling	43
AMOCO Production Company	51
The Analysts	52
Societe Nationale des ELF-Aquitaine	53
Baroid Petroleum Services	55
Basic Sciences, Incorporated	55
BJ-Hughes, Incorporated	56
Chevron Oil Field Research Company.....	57
Continental Oil Company	57
Del Norte Technology Company	57
Develco, Inc.	59
Dornier System GmbH	62
Dresser Industries	62
Dyna-Drill, Division of Smith	
International, Inc.....	63
Eastman-Whipstock	64
ENSCO, Inc.....	64
Exploration Research Company.....	65
EXXON Production Research Company.....	66
Gearhart-Owen Industries, Inc.....	67
General Electric Company	69
Gentrix Engineering Ltd.....	70
Harnessed Energies, Inc.....	71

TABLE OF CONTENTS (Continued)

	Page
Helle Engineering, Inc.....	71
William C. Hooper, Jr.....	72
Institute Francais du Petrole.....	72
Maurer Engineering Inc.....	73
Mobil Research and Development Corp.....	74
Motorola Government Electronics Division....	77
Placid Oil Company.....	77
Raymond Precision Industries Inc.....	78
Raytheon Company.....	79
Sandia Laboratories.....	79
Schlumberger Services Ltd.....	80
Scientific Drilling Controls.....	82
Shell Development Company.....	83
Smith International.....	85
Sperry Research Center.....	86
Sperry-Sun.....	88
Systems, Science and Software (S ³).....	89
Telcom.....	89
Teleco Inc.....	90
Texaco Research.....	91
Texas Dynamatics.....	91
Union Oil Company of California.....	92
Westinghouse Electric Company.....	92
 References.....	 93
Appendix I	
Chronological List of Publications On Downhole Measurements While Drilling.....	 95
Appendix II	
U. S. Patents Relating to Downhole Measurements While Drilling.....	 103
Appendix III	
Non U. S. Patents Relating to Downhole Measurements While Drilling.....	 129

LIST OF TABLES

	Page
TABLE 1 TYPES OF BOREHOLE MEASUREMENTS.....	5
TABLE 2 SAFETY RELATED MEASUREMENTS.....	7
TABLE 3 DIRECTIONAL SURVEYING AND CONTROL MEASUREMENTS.....	8
TABLE 4 DRILLING EFFICIENCY MEASUREMENTS.....	9
TABLE 5 FORMATION EVALUATION MEASUREMENTS.....	11
TABLE 6 ESTIMATED SAVINGS FROM IMPROVED DRILLING.....	21
TABLE 7 BASIC MEASUREMENTS-WHILE-DRILLING SYSTEMS.....	26
TABLE 8 DEPTH CAPABILITY OF MOBIL MUD PULSE SYSTEMS...	31
TABLE 9 COMPANIES ACTIVE IN MWD PROGRAMS.....	44
TABLE 10 ACTIVE HARDWARE-DIRECTED MWD PROJECTS.....	49
TABLE LL EM TRANSMISSION RATES (BITS/SEC.).....	60

LIST OF FIGURES

	Page
Figure 1 - Exxon Borehole Recorder.....	12
Figure 2 - Approximate Development Drilling Costs.....	14
Figure 3 - Estimated Average Offshore Platform Rig Directional Survey Downtime.....	15
Figure 4 - Approximate Total Offshore Platform Well Drilling Time.....	16
Figure 5 - Estimated Number of Directional Platform Wells.....	17
Figure 6 - Directional Survey Market Potential.....	18
Figure 7 - Estimated Offshore Mobile Exploratory Drilling Revenues.....	20
Figure 8 - Mud Pressure Pulse System.....	27
Figure 9 - Teleco System.....	29
Figure 10 - Mobil Borehole Telemetry Tool.....	29
Figure 11 - Mobil Telemetry System Components.....	30
Figure 12 - Shell Hardwire System.....	34
Figure 13 - Shell Tool Joint Connector.....	35
Figure 14 - Exxon Cable System.....	36
Figure 15 - IFP Flexidrill Rig.....	37
Figure 16 - GE/Cullen Telemetry Readout Unit.....	38
Figure 17 - Aquitaine Drilling Lab in Pau, France.....	54
Figure 18 - BJ-Hughes Downhole Pressure Pulse Transmitter.	56
Figure 19 - Del Norte Subsurface Production Valve.....	58
Figure 20 - Develco EM Borehole Unit.....	61
Figure 21 - Gearhart-Owen Mud Pulse Prototype.....	68
Figure 22 - Mobil Mud Pulse Telemetry Tool.....	74
Figure 23 - Mobil Tool Being Assembled.....	75
Figure 24 - Sperry Electronics Package.....	87

INTRODUCTION

Rotary drilling has evolved as an efficient and effective means of exploring the earth for hydrocarbon resources. Even with present high efficiencies, the immense drilling equipment and services market in which over \$6 billion was spent to drill and complete over 40,000 wells in the United States during 1976 means that even small improvements in efficiency can have major economic impact.

Recent increased attention on our energy needs has brought deeper drilling as well as increased activity in higher cost offshore and hostile environments. Basic drilling costs have escalated 150 percent in the last decade.¹ These energy needs and escalating costs have focused attention on all potential methods to drill safer and cheaper. Of the possible methods, real-time data from the bit offers the greatest potential to improve drilling efficiency and effectiveness in both exploration and production wells.

The search for a reliable and diagnostic method of obtaining information for the vicinity of the bit while drilling has been a goal ever since the advent of rotary drilling.² This is evidenced by the numerous patents on this technology which date back more than half a century. (See Appendix II.) Except in very special circumstances, however, previous attempts to develop real-time measurements while drilling (MWD) systems have not met with success. The current needs for a data telemetry system (discussed in the next section) provide the economic and technical incentives which are expected soon to bring about a solution to this problem.

Current technology does not leave us totally ignorant of what is happening at the bit thousands of feet below the rig floor. But current technology is limited to surface evidence of drilling effectiveness. For example, measurements are presently made during drilling which include rotation rate (RPM), penetration rate, hook load, torque and other drilling parameters. Also measured at the surface, are the properties of the drilling fluid (weight, viscosity, gel strength, chlorides content, pH, etc.) as well as pit volumes and drill solids being monitored. Systems are available to take the surface measurements, convert the information from analog to digital form, then process and display the parameters along with information inferred from them. Where experience is sufficient, these measurements are successful in predicting such things as abnormal formation pressure before a well control problem occurs. Lithology can be inferred from certain types of measurements,³ and experiments run varying rotary speed and weight are useful in optimizing drilling. However, the limitation remains that only surface information is available to infer conditions which may be 4 to 5 miles beneath the surface.

Directional surveys of the hole can be made by means of pump down or wireline tools. But this is an after-the-fact measurement which requires significant interruption of the drilling process; there are no systems for navigation of the bit. While 'Teledrift' and 'Teleorienter',⁴ mud pulse systems are presently marketed, these are limited capability and limited application tools which require cessation of drilling and provide information only for those specialized pieces of equipment that they are designed to work with. The Scientific Drilling Controls "EYE" is an accurate, reliable directional tool for use with drilling motors, but this is a wireline device and in addition is fairly expensive. (Several companies offer equipment equivalent to the "EYE").

Coring, drill stem testing, mud-logging, and wireline logging constitute the basic methods of formation evaluation. Coring can be slow and requires a "blind" decision of when to start and stop coring. Tripping is usually required to install the core bit and core barrel and then again to recover the core. The amount of core which can be cut and recovered during a bit run is limited.

Drill stem testing and formation testing are means of obtaining formation fluids without setting pipe. However, these are measurements which require shutting-down the drilling operation then performing these slow and costly tasks.

Mud-logging, the analysis of the drilling fluid for hydrocarbons which enter the mud either from drill cuttings or from adjacent formations, provides insight to the fluids native to the formations being drilled. While the development of sensitive techniques for measuring these hydrocarbons and accounting for background hydrocarbons makes mud logging a useful service, the response time of this system is slow and leaves a drilling engineer without much of the information that he needs to optimize drilling.

Wireline logging is the singly most important means of identifying and evaluating formations penetrated by the bit. This, too, is an after-the-fact measurement, which takes place after drilling a section of hole and removing the drill pipe from the hole. Methods of wireline logging are highly developed and usually give good, detailed results. Under certain conditions the hole cannot be logged, however, or perhaps a detailed suite of logs is not needed. In such circumstances real-time information could save significant logging costs.

The current, commercially available technology cannot provide all of the information which the geologist, drilling engineer, and manager would like 1) to protect their men and equipment, 2) to drill the most cost-effective well, 3) to assess and make decisions on hydrocarbon resources, and 4) to best manage the company interests. These needs for obtaining the required data from the bit, real-time, are discussed in the following chapter.

NEEDS FOR REAL-TIME BOREHOLE TELEMETRY

To best drill safely and economically one needs data from the bit. However, the technology does not exist to practically and economically obtain such data real-time during the drilling process. As wells have been drilled deeper and in more hostile environments and as offshore exploration has expanded rapidly, the economic incentives to develop the needed technology have become apparent to many.

Two basic categories of data are needed. The first, and most important, is data to drill safer and yet more economically. The second category is that of real-time logging or formation evaluation. As shown in Table 1, the first category which is directed toward improving drilling performance can be sub-divided into three groups: safety, directional surveying and navigation, and drilling efficiency. Oil Company operating personnel assess safety

<u>TABLE 1</u>	
TYPES OF BOREHOLE MEASUREMENTS	
<u>TYPE</u>	<u>PRIORITY</u>
DRILLING SAFETY AND EFFICIENCY	
Well Control	High
Directional Information	High
Efficiency	Moderate to High
FORMATION EVALUATION	Moderate

and directional measurements as the most important of these.⁵ The third type, drilling efficiency or optimization, is of slightly lower priority because there can be mitigating circumstances which prevent us from drilling as fast and as economically as we may know how.

As a practical matter, the types of measurements will overlap. For example, if we could drill with greater certainty of being aware of an impending hazardous well control situation, lighter mud could be used leading to faster penetration (hence greater drilling efficiency). Furthermore, even the two basic categories overlap. For example, the gamma-ray log which is helpful in delineating lithology (particularly shale beds) can be indicative of high pressure zones and is an example of a tool useful in both drilling and in formation evaluation.

Tables 2 through 5 list parameters which are related to the four types of data which will be collected from near the bit during drilling. Well control is expected to be of very high priority. The primary application will be in exploratory wells where geologic conditions are less precisely defined. This is particularly true of offshore exploratory drilling where costs are extremely high and the consequences of a blowout can be very severe.

As shown in Table 2, numerous parameters relate to the well control detection problem. Further research and extensive experience will be required before it is known which of the more promising of these is the most reliable and the most sensitive indicator of an impending blowout. Two-way communication may be developed to allow implementation of downhole safety equipment. In addition to a more knowledgeable drilling operation, well control information from the bit as drilling proceeds will allow improvements in

TABLE 2

SAFETY RELATED MEASUREMENTS

MEASUREMENT	BOREHOLE CONDITION							P-Practical D-Difficult	Priority
	Pressure Balance	Fluid Influx	Gas Influx	Permea- bility	Porosity	Lithology	Formation Damage		
Mud Temperature	X	X						P	High
Mud Temperature Change	X	X						P	High
Annulus Pressure	X	X	X					P	High
Drill Pipe/Annulus ΔP	X	X	X					P	High
Sonic Velocity of Mud	X		X					P	High
Mud Resistivity	X	X	X					P	High
Formation Pressure or Formation/ Annulus ΔP	X	X	X					D	High
Natural Gamma Ray				X	X	X		P	High
S P				X	X	X		P	Moderate
Formation Resistivity Deep Micro Log		X (Invasion)						D D	Moderate Moderate
Sonic Density					X	X		D	Moderate
Gamma Density					X	X		D	Moderate
Surge Pressure (while tripping)							X	P	Moderate

drilling efficiency through better and yet less expensive drilling fluid programs, more complete utilization of drilling time, better selection of casing seats, etc.

The need for directional drilling services primarily applies to development wells drilled from fixed platforms. Except for unusual situations such as the drilling of relief wells, or drilling in densely populated areas, it is uncommon to drill highly deviated wells onshore. The application for directional data onshore may be primarily limited to employing simpler, less expensive devices such as 'Teledrift' to prevent the occurrence of severe "dog-legs."

Directional parameters are listed in Table 3. Azimuth and inclination provide information needed to plot the location of the hole and the direction of drilling. Data on these two parameters allow the control of dog-legs which can lead to drillpipe and casing problems. Directional control is related to tool face and drillstring windup and will be useful in assuring that the planned track of the well is followed.

TABLE 3		
DIRECTIONAL SURVEYING AND CONTROL MEASUREMENTS		
TYPE	P - Practical D - Difficult	PRIORITY
Azimuth	P	High
Inclination	P	High
Tool Face	P	High
Drill String Windup	D	Moderate
Dog-Legs	P	High
Active Directional Control	D	Moderate

Further in the future may be an active system with capability not only to track where the bit is going and to exercise control from the surface but to actively interact at the bottom of the hole to control that direction.

Although the technical need for efficiency measurements is ranked below the need for directional information, improvements in drilling efficiency offer greater potential for economic improvements than does elimination of downtime for directional surveying. As will be discussed later, a 5 percent improvement in overall drilling efficiency will dramatically affect drilling economics and will provide a much broader market than that of directional surveying. Improvements in drilling efficiency will have to be tied to well control since factors allowing faster drilling impact well control. Table 4 lists some of the likely parameters which will be sought. It should be noted that one group of parameters relates to drilling motor performance.

TABLE 4

DRILLING EFFICIENCY MEASUREMENTS

TYPE	P - Practical D - Difficult	PRIORITY
Weight on Bit	P	High
Torque	P	High
Drill String Dynamics	P	Moderate
Drill Pipe Pressure	P	High
Annulus Pressure	P	High
Bit - Tooth Wear	P	Moderate
- Bearing Condition	P	Moderate
Mud - Solids	D	Moderate
- Viscosity	D	Moderate
Drilling Motor - Speed	P	High
Temperature	P	High
Bearing Condition	P	High
Torque	P	Moderate

Downhole motors for straight hole drilling also offer great incentive for reducing drilling costs.⁶ While motors themselves are the subject of intense research and testing, it is unlikely that there will be broad implementation of any motor system without an accompanying telemetry system.

The second main category of information which is sought is that of formation evaluation. Types of logging or formation evaluation measurements are listed in Table 5. Knowledge of formation characteristics could be of great assistance to the geologist and drilling engineer as the well is drilled. It would be an important advantage to be able to measure formation properties ahead of the bit. Also, basic information might be available for holes which could not be logged conventionally. However, it is not expected that formation evaluation measurements while drilling will replace conventional logging and formation evaluation. This is primarily due to the complexity of systems required for detailed logging as well as the high degree of sophistication and sensitivity to which logging systems have been developed. One advantage to obtaining preliminary formation information is that better coring and logging programs can be planned. Coring and logging programs may become more useful and more cost effective in formation evaluation.

A borehole telemetry system must accomplish two basic functions; 1) needed data must be acquired at the bottom of the hole and 2) data must be transmitted to the surface. Downhole recording systems such as that developed by Exxon in the early 1960's and shown in Figure 1 demonstrate that the sensors do not present impossible problems. Therefore, emphasis has been put on developing the telemetry systems discussed later. Sensor development to date has

TABLE 5

FORMATION EVALUATION MEASUREMENTS

TYPE	PRIORITY
Lithology	High
Porosity	High
Permeability	High
Rock Density	Moderate
Mineral Component	Moderate
Natural Radioactivity	High
Bedding Plane Strike & Dip	Moderate
Formation Depth & Thickness	High
Correlation	High
Mechanical Properties	Moderate
Magnetic Properties	Moderate
State of Stress	Moderate
Pore Fluid Properties	
Type	High
Saturation	High
Salinity	High
Density	Moderate
Depth of Invasion	High
Pore Pressure	Moderate
Fluid Flow	Moderate
Dissolved Minerals	Low
Well Geometry	
Gauge (Size & Shape)	High
Fractures	
Location	High
Dip	Moderate
Strike	Moderate

BOTTOM HOLE RECORDER

Figure 1. Exxon Borehole Recorder
(Deily et al, Ref. 7)

emphasized surveying and control of directional wells. This is in part due to the fact that it is not difficult to quantify a very large market for the directional drilling service, and it is difficult to quantify the drilling safety market. While present directional sensors may be adequate, there appears to be room for substantial improvements in the reliability, power consumption and cost of these sensors.

ECONOMIC INCENTIVES

The safety and drilling efficiency category dominates the economics for development of borehole telemetry systems. Since the directional drilling market and the well control and drilling optimization markets are almost mutually exclusive, the economics for the two will be treated separately. Estimates of the market for formation evaluation information are also examined.

Directional Drilling

Present domestic drilling costs exceed \$6 billion⁸ annually with approximately half going to each of the onshore and offshore market. This includes payments to contractors as well as operating and support costs. As illustrated by Figure 2, offshore platform drilling cost are typically twice the cost of an equivalent depth onshore well. (It should be noted that the average onshore well is significantly shallower than the typical offshore well.) Also a typical offshore development well is drilled from a fixed platform and can be highly deviated since 18 to 36 wells are ordinarily drilled from the same platform.

A typical offshore well is on the order of 9,000 to 10,000 feet deep. During the drilling of this well, approximately 60 directional surveys will be made. These surveys will consume an estimated 60 to 80 hours of rig time (see Figure 3). The cost of lost drilling time is considerable since typical platform rig costs including day rate, consumables and management are about \$20,000 per day.

FIG. 2. APPROXIMATE DEVELOPMENT DRILLING COSTS

FIG. 3. ESTIMATED AVERAGE OFFSHORE PLATFORM RIG DIRECTIONAL SURVEY DOWNTIME

Figure 4 shows typical time required to drill development wells from offshore platforms. (Not included is time lost between wells.) The estimated number of directional offshore platform wells projected to 1985 is shown in Figure 5.

FIG. 4. APPROXIMATE TOTAL OFFSHORE PLATFORM WELL DRILLING TIME

FIG. 5 ESTIMATED NUMBER OF DIRECTIONAL PLATFORM WELLS

The projected drilling costs related to directional surveys can be determined using this estimate and assuming a daily rig cost of \$20,000/day including day rate, consumables and management along with an average variable cost of 90 percent. These projected drilling costs are shown in Figure 6.

**FIG. 6 DIRECTIONAL SURVEY MARKET POTENTIAL
(ASSUMES MARKET VALUE = 50% OF DRILLING COSTS SAVED)**

Looking at this on a daily basis, the average platform well takes about 30 days and costs about \$600,000 to drill. Telemetry can save about 2-1/2 days or \$50K (roughly 10%) of this cost. Thus, the directional survey market appears to support a pricing of about \$1,500 per day at full value. A more reasonable estimate and rule of thumb commonly used in a petroleum industry is that the market is valued at 1/2 the potential savings. This would indicate a pricing of about \$800 per day using the 50% factor from above. The probable directional survey market is shown on the lower curve in Figure 6.

These estimates are significantly below the \$4000-5000 per day being charged by Scientific Drilling Controls for the "EYE" and by Sperry-Sun for their equivalent. As a consequence of the high charges, it appears that the companies are only "skimming" the market.

Drilling Safety and Efficiency

Economic incentive for improved overall drilling efficiency is best related to costs of drilling exploratory wells. This is done offshore from mobile rigs such as jack-up, ship-shape floaters and semi-submersibles. Estimates of offshore mobile exploratory rig revenues are shown in Figure 7. This estimate (in constant 1975 dollars) indicates that revenues will exceed \$5 billion by 1980 and likely exceed \$8 billion by 1985. Some authorities expect the market could easily double this.⁹ Thus even a 1% improvement in overall efficiency is important and a 5% improvement in overall efficiency could result in savings of between \$400 and \$800 million per year.

Figure 7. Estimated Offshore Mobile Exploratory Drilling Revenues (after Spears, Ref. 10)

The question is not whether efficiency and drilling rate could be improved by measurement of parameters such as weight on bit, torque, bit condition, well control parameters and other data, but how much efficiency would be improved. Estimates by drilling experts range up to 15% in overall improvement.¹¹ Table 6 shows potential savings for different percentage improvements based on the conservative estimates of revenues shown in Figure 7.

TABLE 6		
ESTIMATED SAVINGS FROM IMPROVED DRILLING		
<u>% IMPROVEMENT</u>	<u>1985 POTENTIAL SAVINGS</u>	<u>PRICE POTENTIAL OFFSHORE TELEMETRY SYSTEM</u>
1%	\$82 million	180 - 360 \$/Day
5%	\$410 million	900 - 1800
10%	\$820 million	1800 - 3600
15%	\$1,230 million	2700 - 5400

At the present time, offshore exploratory rigs cost from \$25,000 to \$125,000/day including variable support costs. The average in 1976 was about \$36,000/day. Based on this daily cost rate, Table 6 includes what is felt to be a realistic estimate of the market and price potential of telemetry systems with broad capability. The lesser amount is based on an assumption that operator and service company share equally in the benefit of such a system and may be more realistic than the upper price potential. No allowance has been included for reduced risk, better equipment life or performance or increased discovery potential. These could be very real benefits and will increase the value of the telemetry systems.

According to statements by The Analysts,¹² pricing of the Schlumberger system will be \$4000-8000/day. This appears to be based on two factors: 1) the cost of Schlumberger system and 2) statements that 25-30% improvements may be possible. The present analysis indicates that this is an optimistic estimate. Actual rotating hours are frequently less than 50% of the total time to spud, drill, case and complete a well. A 25-30% overall reduction in costs would be a major accomplishment. While the \$4000-8000 pricing is consistent with present system pricing (Scientific Drilling Controls), it appears from this analysis that this price level will not produce the large market and broad utilization many people are predicting.

Regulatory requirements and blowout risk control are important factors which could greatly expand pricing flexibility.

As far as onshore exploration is concerned, drilling costs are on the order of \$6000-8000/day. Thus, the routine utilization value of a real-time borehole telemetry package would likely be limited to the order of \$500-1000/day. Of course an exception to this value assessment is in deep drilling and in hostile environments. The basic market for borehole telemetry is offshore.

Logging

Real-time formation evaluation data will not likely replace open hole logging and coring. It is likely, however, that some measurements useful in formation evaluation will be used for their value to drilling efficiency and safety. These and other formation/formation fluid indicators will be used to improve geologic and engineering analyses during drilling.

The 1980 anticipated open hole logging market offshore is \$200 million increasing to an estimated \$260 million by 1985. It is not anticipated that this will be affected by borehole telemetry systems. Assuming that at most 10% of the logging market might apply to a real-time logging system, the overall market potential might be \$20 to 30 million, and even this may be too high. It appears that the potential for formation evaluation services is where it becomes a minimal cost add-on to the basic telemetry system which is being run for other purposes. Perhaps the most reasonable approach is to include logging as a part of overall drilling improvement since a major part of its advantage is to reduce downtime for wireline services.

Summary

It appears that the borehole telemetry drilling efficiency market for 1985 is in the range of \$400-800 million per year, while the directional surveying market is \$50-100 million per year. This presumes an overall 5-10% improvement can be demonstrated for the drilling safety and efficiency system. It appears that pricing on the order of \$2-4,000/day for safety and efficiency systems and on the order of \$1-2,000/day for directional systems will be necessary to support the creation and growth of the anticipated market.

BASIC SYSTEMS

Four basic types of systems are showing promise as communication and transmission methods. These are: mud pressure pulses, electromagnetic methods, insulated conductor or hardwire systems, and acoustic methods. Each of these types of systems is under investigation by more than one company, which serves to illustrate that there is no consensus as to which method offers greatest promise overall. In fact, it is quite possible that a successful system may result from a combination of methods. The potential and limitations of these four methods are outlined in Table 7.

Based on research and development experience to date, and applying subjective judgments as to required data rate, system cost, oil field acceptability and other factors, the four systems would be ranked in the order in which they are presented in Table 7. It should be noted, however, that this is a new technology with extremely large market potential and continued evolution of systems is anticipated for many years to improve on cost, reliability, data rate and overall system performance.

The four basic systems are discussed individually below.

Mud Pressure Pulses

In the mud-pressure pulse system, the resistance to the flow of mud through the drill string is modulated or pulsed by means of a valve and control mechanism mounted in a special

TABLE 7
BASIC MEASUREMENTS-WHILE-DRILLING SYSTEMS

<u>System</u>	<u>Depth Capability</u>	<u>Transmission Time (One Word)</u>	<u>Requires Downhole Power Supply</u>	<u>Two-Way System Possible</u>	<u>Relia- bility</u>	<u>Develop- ment Cost</u>	<u>Estimated Capital Cost/Unit (\$1,000)</u>	<u>Evaluation</u>	<u>Comments</u>
Mud Pressure Pulses	>20,000 ft; reduced data rate at deeper depths & higher mud weight & viscosity	6-60 sec.	Yes	?	Good	Moderate	100-300	Excellent	Presently most advanced in development. No problems foreseen in handling majority of applications.
Electro- magnetic Methods	2,000-20,000 ft; is highly system dependent	.1 sec or greater	Yes	Yes	Good	High	100-300	Excellent- Good	Wide variety of systems proposed and being studied. Inherent cap- abilities and limitations not well defined. Has good potential for combination with hard wire system.
Hard-Wire System	>20,000 ft.	Very High	No	Yes	Fair	High	300-500	Fair	Major breakthroughs will be required to overcome objectionable interference with standard rotary drilling practices.
Acoustic Methods	~3,000 ft; greater depth capability for production applications	.1 sec. or greater	Yes	Yes	Good	Low	25-150	Fair	Extensive work to date has not overcome signal to noise limitations in the drilling environment.

drill collar sub near the bit. The pressure pulse travels up the mud column at near the velocity of sound in the mud, about 4,000 to 5,000 ft/sec.¹³ This system is illustrated in Figure 8. The rate of transmission of measurements is relatively slow due to pulse spreading, modulation rate limitations and other limitations characteristic of mud systems.

Figure 8. Mud Pressure Pulse System
(McDonald and Ward, Ref. 2)

In the mud pulse system, the power source for telemetering data is the pressure field developed by the mud pumps on the surface. Modulation of the mud pressure is accomplished downhole and power for modulation of the mud pressure must be available downhole. While mud pressure can be used to cock springs or cams as in the 'Teledrift' system, most advanced systems use either batteries or a mud turbine generator. The mud pressure pulse system should not be confused with acoustic systems which do not depend on having the pumps running to transmit the signal.

The concept of using mud pressure pulses can be traced back to at least 1929 through patent literature. In the 50's and early 60's a mud pressure pulsing system for logging (formation evaluation) while drilling was developed by Arps.¹³ This development demonstrated the feasibility of using mud pulses for measurements while drilling without modification of the basic rotary drilling systems and without special drill pipe. This system was licensed but further development was not pursued.

Basic mud pressure pulse systems are under development by Teleco and Gearhart-Owen. The Teleco system, shown schematically in Figure 9, measures and telemeters three parameters: Hole azimuth, hole inclination and tool orientation.¹⁴ Work on other sensor subsystems and limited downhole data processing is underway. This system requires a downhole power generator and needs approximately one minute to transmit each measurement.

Gearhart-Owen has two mud pulse systems, both reported to be simpler and less expensive than other systems under development. Preliminary tests indicate successful data transmission over depths in excess of 10,000 feet.

Figure 9. Teleco System (Ref.14)

Schlumberger is actively working on an alternative system using a mud-pressure pulse concept developed by Mobil.¹⁵ The layout of the Mobil "mud siren" or "screamer" as it was called, is shown in Figure 10. The downhole unit is contained in a 7 inch O.D., 17 foot long drill collar. A photograph of

Figure 10. Mobil Borehole Telemetry Tool (Ref. 15)

the rotary valve, turbine and gear train is shown in Figure 11. The rotary valve is used to generate a continuous sonic pressure wave signal in the range of 10-300 Hz in the mud inside the drill string. Data is transmitted digitally by a phase shift method called non-return-to-zero phase shift keying (NRZ-PSK). Data are sent in 10 bit words, plus a parity check, thus allowing 0.1% accuracy. Transmission can be at 3, 1.5 or 0.75 bits/second. Table 8 gives depth capability as a function of mud viscosity and data rate. As noted, the Mobil system is licensed to Schlumberger and is under active field development and testing.

Figure 11. Mobil Telemetry System Components (Ref. 15)

TABLE 8

DEPTH CAPABILITY OF MOBIL MUD PULSE SYSTEM¹⁵

<u>MUD KINEMATIC VISCOSITY, CS</u>	<u>20 PSI PULSE HEIGHT DR = 3 BITS/SEC</u>	<u>80 PSI PULSE HEIGHT DR = 0.75 BITS/SEC</u>
4.6	>20,000	>20,000
10	20,000	>20,000
20	13,000	>20,000
31	11,000	17,000
50	9,000	14,000

There is one special purpose mud pulse system on the market. This is the BJ 'Teledrift' and 'Teleorienter'. It is available for use in directional drilling with the Dyna-Drill downhole motor,⁴ and provides either azimuth or inclination of the drill motor (not both with the same hardware with presently available equipment). This system requires interrupting drilling during transmission of the information.

The inherent advantages of the mud-pressure pulse concept are that neither insulated cables nor special drill pipe are required. Power for the system is derived from the mud stream. The mud pulse systems are basically mechanical and should be reliable. The primary disadvantages are that the system has a relatively slow data rate and the signal must be extracted from a fairly noisy environment. The "mud siren" has a higher data rate, but (at least in current

versions) requires a downhole power generator thus incurring problems in cost and reliability relative to some simpler forms of mud pulsing systems. Sensor systems presently in use require cessation of drilling during acquisition of directional data.

Electromagnetic Methods

Transmission of electromagnetic (EM) signals both through the earth and other drillpipe has been studied as a telemetry method for downhole measurements while drilling. Numerous companies have worked on EM systems. Many of these investigations were on government contract relating to coal mine safety or relating to military applications. For example, Develco developed an EM system under a AEC contract for data transmission for underground nuclear testing. ENSCO has worked on torroidal coupling of EM signals on drill pipe. Westinghouse and Telcom worked on several systems under government contract including work for the USBM on the "mine rescue" project.¹⁶

There are several research projects on EM systems. EM transmission through the earth is being investigated by Raytheon. This system uses the vertically polarized component and a system of repeaters spaced approximately every 1,000 meters in the drill string. Sandia Laboratories is working on several aspects of borehole telemetry relating to EM and acoustic systems. The EM project relates to signal strength and information recovery at the surface for high strength current pulses injected downhole. Sandia is also studying the mapping of induced fractures by electrical methods. Sperry Research is studying fundamental properties of EM and acoustic transmission in a borehole environment.

Neither the Sandia nor Sperry efforts are directed at developing commercial systems at this time. Dornier Systems, a German company, is presently researching EM systems; present status of that work is uncertain.

With the EM method, a relatively high data rate may be possible, and there is no need for special drill pipe. There are several possible disadvantages. Only very low frequency EM signals have low enough attenuation for transmission through the earth to be feasible. Unfortunately these frequencies are near telluric frequencies. Thus background noise makes detection and information recovery with the EM signals very difficult. Attenuation of the EM signals on drill pipe also limits application of this approach. Repeaters would add cost and reliability problems. An EM system would probably have the disadvantages of requiring a downhole power generator. It is not clear that all EM systems are applicable offshore which is a necessary condition for general commercial application.

Insulated Conductor Systems

Wireline systems are presently used for logging and other borehole operations. The adaptation of the electrical conductor or hard wire system to a continuous drilling operation would solve the borehole telemetry problem. However, problems associated with connecting and maintaining such an electrical line under rotary drilling conditions have not met requirements for an easy to use, economical and reliable system.

Hardwire systems are currently being developed by two major oil companies, Shell and Exxon. In the Shell system the electrical conduit and cable is a part of the drill pipe.¹⁷ Special connectors manufactured into the tool joints are used to provide a rapid and easy means of making electrical connections. Figure 12 is a schematic of the Shell system, and Figure 13 shows photographs of the tool joint connector developed for this system. A disadvantage of this system is that it requires a special string of expensive pipe, estimated to be three times the cost of ordinary drill pipe; also, it requires high reliability of many electrical connectors.

Figure 12 Shell Hardwire System (Ref. 17)

Figure 13. Shell Tool Joint Connector

A concept under development by Exxon Production Research Company uses a continuous electrical cable lowered inside the drill string (Figure 14).¹⁸ The excess cable is pulled out as additional joints of drill pipe are added. All of the cable is removed before tripping out of the hole. This system eliminates the need for an electrical connector for each length of drill pipe. However, problems associated with storing the cable in the drill pipe have not yet been overcome.

Figure 14. Exxon Cable System

Two special applications of cable systems are the French Petroleum Institute "Flexidrill" (Figure 14)¹⁹ and the GE/Cullen Electrodrill.²⁰ In the "Flexidrill" system, conductors built into the flexible drilling hose allow monitoring downhole motor performance and other downhole parameters.

Figure 15. IFP Flexidrill Rig

General Electric has joined with Cullen Research on further development of the Cullen Electrodrill. The power cable for the downhole electric motor has one conductor dedicated for telemetry. A downhole package to multiplex and transmit up to sixteen channels of information and surface readout instruments have been developed. The surface readout unit is shown in Figure 16. Recent directional drilling tests using this system were conducted in Houston, Texas.

Figure 16. GE/Cullen Telemetry Readout Unit

A special purpose hardwire system is the "EYE" (Electronic Yaw Equipment), a magnetic survey system for directional drilling, marketed by Scientific Drilling Controls.²¹ The system requires a continuous single conductor wireline inside the drill string during the drilling operation. Continuous signals are transmitted to the surface indicating magnetic direction of the high side of the hole. A compatible tachometer system for use with downhole drilling motors is also available. Sperry-Sun markets a similar system.

Major advantages to a hardwire system are that data rate can be extremely high, two-way communications are simple and electrical power can be supplied over the conductor system. Disadvantages include costs reliability (especially of connectors), wear and failure of cable due to mud abrasion and pipe rotation, potential interference with fishing operations, and requirements for special equipment and supplies such as cable handling reels and non-conductive and non-conductive doping compounds.

Acoustic Methods

Another potential method for borehole telemetry is by transmission of acoustic or seismic signals through the drill pipe or the earth. As discussed earlier, the acoustic system should not be confused with mud pressure pulse systems. Acoustic systems do not depend on having the mud pumps running for signal transmission. The very low intensity of the signal which can be generated downhole, along with the acoustic noise generated by the drilling system, makes signal detection difficult. Reflective and refractive interference resulting from changing diameters and thread make-up at the tool joints compounds the signal attenuation problem.

Sperry-Sun has developed and field tested an acoustic telemetry system to supplement their wireline directional survey services. William Hooper abandoned an acoustic MWD system after several years of work. Sperry Research uses an acoustic system with their geothermal pump. Basic Sciences has developed an acoustical method of telemetering bottom hole pressure data to the surface in producing wells from depths of at least 5,000 feet. An acoustic system for actuating downhole devices has been developed by Motorola. This system, which transmits a coded acoustic signal on the production tubing, was tested by Exxon at the Friendswood, Texas, test facility. Del Norte Technology markets an acoustic sub surface control valve. Sandia Laboratories and Sperry Research also have research programs on applications of acoustic methods for borehole telemetry.

The primary advantages to acoustic systems seem to be simplicity and cost. An important disadvantage is that high signal attenuation and acoustic noise generated in drilling limit range. Repeaters incur reliability and cost problems. Downhole power consumption could be a problem.

Other Methods

Other methods and special applications which have been studied include tracers (radioactive and chemical), drill pipe vibration and torque, and downhole recorders.

The use of tracers released into the flowing mud stream as a means of information transfer has been studied periodically in the past, and numerous patents have been issued on the use of tracers. The tracers can be radioactive materials, chemicals, special gases, organic compounds, or other materials. The tracer method has the disadvantage that signals are delayed by the time for mud to circulate from the bit to the surface, an identical constraint to that affecting mud logging. In deep wells this delay may be as much as 2 to 4 hours. Also, the tracer may become so diffused as to make its use as a quantitative indicator very difficult. Other limitations include low data rate and two-way communications are not possible.

The drill pipe is an existing "communications link" with the bit. From it we know average rotation speed, average torque to rotate the pipe and bit, and average weight of the drilling assembly as it hangs in the buoyant drilling mud. The drill string directly measures how fast drilling is proceeding.

Vibrations of the drill pipe have been used as an indicator of drill-bit condition and drilling performance. Aquitaine has licensed to Dresser and others a vibrations log called the SNAP Log. These measurements can be useful, but attempts to use these and other surface indications of drilling performance to infer formation pore pressure, bit tooth and bearing condition, etc., have not met with broad acceptance.

Downhole recorders have been used to measure and record drilling and formation parameters at the bit during drilling. These have been limited to research studies, primarily for use in optimizing drilling performance. In most of these systems the recorder is run with the bit and recovered on a trip. There is no real-time communication of data, although information recorded and studied "after-the-fact" can be very useful in analyses of drilling performance. Exxon developed and used a downhole recorder system in the late 60's.⁷

COMPANIES ACTIVE IN BOREHOLE MEASUREMENTS WHILE DRILLING

Companies which are presently active in borehole telemetry projects are listed in Table 9 along with brief comments about their activities. The list contains over 40 companies whose interests range from actively following present programs, to financial investment in projects, to actually conducting hardware development and testing programs. Some of the companies listed have worked on telemetry for oilwell production systems only. They are included in this list because, theoretically, their technology should be adaptable to the drilling situation.

This chapter discusses the activities of each of the companies listed in Table 9 individually. Where information is available, the system and the work on it is described, an assessment is made of their current activity level and an evaluation is made of the outlook for their work. Names and addresses are presented for each company so that direct contact is possible.

This information was obtained from literature and personal contacts with knowledgeable industry personnel and is believed to be accurate and complete. However, some active companies may have been omitted inadvertently, either through oversight or because of the proprietary and confidential nature of their work.

Table 10 lists companies which are developing and testing hardware for measurements while drilling. This table presents the type of system they are working on, the status of their activity, a judgment as to the potential for a technically successful project, the potential for commercialization for their system, and remarks about the project.

TABLE 9

COMPANIES ACTIVE IN MWD PROGRAMS

<u>Company</u>	<u>Location</u>	<u>Type System</u>	<u>Activity</u>
AMOCO Production Research	Tulsa, Oklahoma		Financial and testing support to Gearhart-Owen, Gentrix, GE/Cullen and possibly others.
Analysts	Houston, Texas	Mud Pulse	Schlumberger affiliate working on surface equipment and data processing for Schlumberger system.
Aquitaine (SNEA)	Pau, France	Mud Pulse	Joint Interest with Raymond Precision in Teleco.
		Drill Pipe	Developed "SNAP" log for measuring drillpipe vibrations on surface as indicative of certain downhole parameters.
Baroid	Houston, Texas		Has surface data processing units and actively follows developments in MWD.
Basic Sciences	Tulsa, Oklahoma	Acoustic	Developed & markets system to telemeter production pressure data.
Byron-Jackson	Houston, Texas	Mud Pulse	Developed "Teledrift" and "Teleorienter" system.
Chevron Research	LaHabre, California		Financial support of Teleco and GE/Cullen projects.
Conoco	Houston, Texas		Financial support of Teleco Project.
Del Norte Technology	Eules, Texas	Acoustic	Developed and tested downhole production safety valve.

TABLE 9 (Continued)

Develco	Mountain View, Ca.	EM	Government funded research for nuclear test applications.
Dornier System	Hamburg, Germany		Survey and evaluation of systems for German DGMK.
Dresser Industries	Houston, Texas		Financial support of GE Electrodrill Program.
		Drill Pipe	Licensed by Aquitaine for SNAP log, some development work.
Dyna-Drill	Houston, Texas	Mud Pulse	Markets "Teledrift" and "Teleorienter" system
Eastman Whipstock	Houston, Texas	Wire	Commercial application of steering tool similar to Scientific Drilling Controls "EYE".
ENSCO	Springfield, Va.	EM	Government contracts on steering near-horizontal holes in coal beds.
Exploration Research	Houston, Texas	Acoustic	Prototype testing in progress
Exxon Production Research	Houston, Texas	Wire	Work on wireline system with drill pipe storage of cable. Participant in Teleco joint Industry/Government project.
Gearhart-Owen	Ft. Worth, Texas	Mud Pulse	Developing two types of systems.
		Wire	Has worked with Exxon on sensors and testing of their wire system.
General Electric	Houston, Texas	Wire	Has telemetry system as part of Electrodrill motor and cable assembly. Joint government/industry test program underway.

TABLE 9 (Continued)

Gentrix Engineering Ltd.	Calgary, Alberta, Canada	Mud Pulse	Field testing reportedly underway.
Harnessed Energies	Maynard, Massachusetts		Directional Sensor for Westinghouse.
Helle Engineering Inc.	San Diego, California	Acoustic	Developed system to monitor and transmit corrosion in production systems at depths to 10,000'
Hooper, Wm. C.	Houston, Texas	Acoustic	Investor support of individ- uals efforts.
Institute Francais du Petrole	Rueil Malmaison, France	Wire	Telemetry system as part of Flexidrill system.
Maurer Engineering Inc.	Houston, Texas		Survey and evaluation studies for government and industrial clients.
Mobil Research & Development Corporation	Dallas, Texas	Mud Pulse	Developed system which is presently licensed to Schlumberger.
Motorola	Scottsdale, Ariz.	Acoustic	Developed acoustic system for use in explosive fracturing Tested as means of activating downhole safety valve.
Placid Oil Co.	Dallas, Texas		Financial support of Teleco project.
Raymond Precision Industries, Inc.	Middletown, Conn.	Mud Pulse	51% owner of Teleco
Raytheon Company	Sudbury, Mass.	EM	Developing through-earth EM system with repeaters.

TABLE 9 (Continued)

Sandia Laboratories	Albuquerque, NM	EM	Basic studies of pulsed current transmission.
Schlumberger Services Ltd.	Houston, Texas	Mud Pulse	Licensed to develop and market Mobil mud "screamer" system.
Scientific Drilling Controls	Newport Beach, Ca.	Wire	Commercially available system for directional measurements.
Shell Development Co.	Houston, Texas	Wire	Field testing system using a special drill pipe with tool joint connector. Substantial work on downhole sensors. Financial support of Teleco project.
Smith International	Newport Beach, Ca.		Owns Dyna-Drill. Reportedly negotiating for purchase of marketing rights to MWD system.
Sperry Research Center	Sudbury, Mass.	Acoustic	Developing system for use with downhole geothermal pump.
		EM	Research on EM system.
Sperry-Sun	Houston, Texas	Wire	Commercially available system for directional measurements.
		Acoustic	Field testing MWD system.
Systems, Science & Software (S3)	La Jolla, Ca.		Government funded work on downhole electronics.
Telcom	McLean, Va.	EM	Developed system for mine rescue work.

TABLE 9 (Continued)

Teleco Incorporated	Middletown, Conn.	Mud Pulse	Owned by SNEA and Raymond Precision Industries. Active field test program underway. Present effort is jointly funded by government, oil companies and Teleco.
Texaco Research	Houston, Texas		Previously active in bottom hole instrumentation.
Texas Dynamics	Dallas, Texas		Consulting work on downhole systems.
Union Research	Brea, Ca.		Financial support of GE/Cullen project.
Westinghouse Electric Corp.	Baltimore, Md.	EM	Developed and demonstrated rescue communications system. Some internal work at present.

TABLE 10

ACTIVE HARDWARE-DIRECTED
MEASUREMENTS-WHILE-DRILLING PROJECTS

COMPANY	TYPE	STATUS	TECHNICAL POTENTIAL*	COMMERCIAL POTENTIAL*	REMARKS
Byron-Jackson	Mud Pressure Pulse (MPP)	Presently markets Teledrift	E	E	Low cost, limited capability system; no major changes foreseen.
Exploration Research	Acoustic	Prototype Testing	G	G	Some field testing completed. Major company cooperative project pending.
Exxon Research	Wire	Prototype Testing	G	F	Would license system if successful; strong emphasis on sensors.
French Petroleum Institute	Wire	Field Testing	E	E	Special purpose system as part of Flexidrill system.
Gearhart-Owen	MPP	Field Testing	E	E	One of leaders. Working with Exxon Research and others.
	Wire	Prototype Testing	G	F	
General Electric	Wire	Field Testing	E	E	Special purpose system as part of electric drilling motor project.
Gentrix	MPP	Field Testing	E	E	Status uncertain.
Raytheon	EM	Prototype Design	G	F	ELF(1-10Hz) studies.
Sandia	EM	Prototype Design	F	F	Basic Studies.

E - Excellent
G - Good
F - Fair

TABLE 10 (Continued)

COMPANY	TYPE	STATUS	TECHNICAL POTENTIAL	COMMERCIAL POTENTIAL	REMARKS
Schlumberger	MPP	Field Testing	E	E	Higher data rate capability; likely higher cost than G/O or Teleco.
Shell	Wire	Field Testing	E	F	Would like to license system.
Sperry Research	Acoustic	Prototype Design	F	F	Govt. funded research project.
Sperry Sun	Acoustic	Field Testing	G	F	Encountering severe attenuation problems beyond 500m.
Teleco	MPP	Field Testing	E	E	Likely nearest to commercialization.
Westinghouse	EM	Prototype Design	E	F	100 Hz range system.

AMOCO Production Company
Dr. Al Jageler
P. O. Box 591
Tulsa, Oklahoma 74102
(918) 627-3400

AMOCO does not have an active program to develop their own hardware for a data telemetry system. However, they do maintain an active interest in work conducted by others. Financial support is being provided to the Gearhart-Owen program by the Drilling Optimization Group. In addition, AMOCO is supporting work by Gentrax and is contributing to the joint U.S. Government (ERDA)/industry program on the GE/Cullen Electrodrill. AMOCO has tested telemetry systems and has expressed a willingness to test any system that shows promise of being successful.

The Analysts
Dr. William Koch
4140 D Directors Row
Houston, Texas 77018
(713) 686-5516

The Analysts is an affiliated company of Schlumberger which offers geologic logging and drilling data services. They are particularly strong in computer processing and interpretation of drilling data at the well site. The Analysts have an agreement with Schlumberger to market any MWD system which Schlumberger may develop¹². In return, according to M. E. McCutcheon, President of The Analysts, Schlumberger has taken a 27% interest in The Analysts with the right of refusal to buy the remainder of the Company.

Under the Analysts agreement, they would buy the MWD tools from Schlumberger and pay a royalty based on marketing income. Apparently they are planning to market the MWD tool with their computerized drilling data services. The Analysts have predicted that the pricing of such services as a complete package including MWD will be on the order of \$4-8,000 per day.

The Analysts have stated that full commercial marketing of the MWD system is at least two or more years away.

Societe Nationale des ELF-Aquitaine (SNEA)
Dr. Claude Quichaud
26 Avenue des Lilas
64000 Pau, France

Aquitaine originated the work on the system that has become the Teleco mud pulse system. They are at present a 49% partner with Raymond Precision Industries (51%) in ownership of Teleco. Aquitaine did laboratory development work and performed approximately 1,000 hours of field testing on their system before forming the joint venture with Raymond Precision in 1972. Their expenditures to that date are understood to have been on the order of \$6 million. There is no inhouse work on the mud pulse telemetry system at Aquitaine at this time.

Aquitaine developed another system called the "SNAP" Log for measuring drill pipe vibrations on the surface as an indication for downhole parameters. The system measures triaxial accelerations of the drill pipe. A frequency analysis of these vibrations is made to correlate with laboratory measurements of patterns generated by the bit. Correct interpretation of the data gives information as to lithology and to bit condition. Aquitaine has licensed this system to several companies including Dresser in the United States. In our evaluation, new MWD systems will obsolete the "SNAP" Log.

A photograph of the Aquitaine Drilling Lab in Pau, France, is shown in Figure 17.

Figure 17. Aquitaine Drilling Lab in Pau, France

Baroid Petroleum Services
Dr. Kenneth D. Tanner
Director of Research and Development
P. O. Box 1675
Houston, Texas 77001
(713) 527-1298

Baroid has developed computer data processing vans for wellsite use. There are approximately 40 of these units in service. Baroid would like to have a MWD system to couple into this data unit, but at the present time does not have an active hardware development program. They are, however, working at about the 2 man year per year level in following borehole telemetry activity, in assessing markets, and in preparing to incorporate this capability into their data units.

Basic Sciences, Incorporated
Mr. J. Douglas Fitzpatrick, President
P. O. Box 15646, Admiral Station
Tulsa, Oklahoma 74115
(918) 835-7639

Basic Sciences (an affiliated company of Tyler, Dawson Supply Company of Tulsa) has developed an acoustic method of telemetering bottom hole pressure data from producing wells to the surface. At present a 10 second interval is required to transmit this information to the surface ($\pm .25\%$ accuracy), but transmission time could be reduced to 2 seconds per measurement. This system has been tested to 5,000 feet, and they feel that it will work in producing wells to at least 15,000 feet. Discussions have been held on borehole measurements while drilling between Basic Sciences and British Petroleum. Basic Sciences is not working on a MWD system at the present time but feel that their acoustic system is adaptable to the drilling application.

BJ-Hughes, Incorporated
 777 South Post Oak, Suite 333
 Houston, Texas 77027
 (713) 627-8040

Byron Jackson developed the mud pulse system known as 'Teledrift' and 'Teleorienter'. These are hardware systems for measurement of inclination and azimuth and are primarily used with the Dyna-Drill drilling motor. A schematic of the system is shown in Figure 18.

BJ is understood to be working on a combined inclination and azimuth system using the same pulse code transmitter. Work is believed to be at a fairly low level, and work on more sophisticated systems is understood not to be underway.

Figure 18. BJ-Hughes Downhole Pressure Pulse Transmitter

Chevron Oil Field Research Company
LaHabre, California

While Chevron does not have an active inhouse hardware development program, they are providing financial support of approximately \$200,000 to the two joint government/industry borehole telemetry projects, these being the Teleco and GE/Cullen programs.

Continental Oil Company
5 Greenway Plaza East
Houston, Texas 77005
(713) 965-1000

Conoco has contributed \$150,000 to the Teleco program and has been active in testing the Teleco system in some of their wells.

Del Norte Technology Company
Euless, Texas

Del Norte Technology has developed, tested and is marketing an acoustically controlled subsurface production safety valve. Since subsurface safety valves are required on all offshore wells, this constitutes a potentially large market. As far as can be determined, Del Norte is not working on a drilling telemetry system.

A schematic of the Del Norte system is shown in Figure 19.

SPECIFICATIONS

ALL MECHANICAL COMPONENTS OF THE SYSTEM MEET OR EXCEED
API 5,000 POUND SERVICE AND 80,000 POUND TENSILE REQUIREMENTS

DRIVER UNIT ①

FUNCTION:

Contains power supplies and electronics to generate unique pulses of energy to open, close, or lock open the downhole valve in response to local operator commands via a function switch; local pressure, flow or temperature controllers; or remote commands via a supervisory control system.

INPUT POWER: 115/230 VAC, 50/60 Hz at less than 350 watts.

OUTPUT: Pulse to exciter, 50 joules.

CONTROLS: Power — On/Off; Valve — Open/Close/Lock; Remote — Open/Close valve.

ENVIRONMENTAL: Temperature: -25°C to 75°C.

HOUSING: As required

DIMENSIONS: 28 5/16 in. long, 28 5/16 in. wide, 14 1/4 in. deep.

OUTPUT CABLE: 2 Conductor #12 AWG.

EXCITER UNIT ②

FUNCTION:

Converts the pulses from the Driver Unit ① to an acoustical signal without moving parts.

PHYSICAL: API Type N-80 sub with 5 inch diameter

x 4 foot transducer added.

Temperature: 125°C maximum.

Wellhead connection: Supplied with a 20,000 PSI penetrator, 2 inch bull-plug and explosion proof box for 3/4 inch conduit.

BATTERY ELECTRONICS MODULE ③

FUNCTION:

Receive and decode acoustic energy and provide electric power to hydraulic unit upon command.

PHYSICAL: Tubular mounted 1.62 inches O.D. x 149 inches long. Equipped for wireline placement and recovery with DNTI wireline tool ⑤

Temperature: 100°C.

Placement: Locked-in, shear-pin locator.

POWER: Internal battery furnishes 12 volt power for 40 valve cycles with 50% reserve.

CONNECTION: Proprietary molded connector.

CONTROL OF OUTPUT: By acoustic command from wellhead to open or close; operator may lock valve open for tubing or wireline work.

SIDEPOCKET MANDREL ④

FUNCTION:

Receptacle for Electronics Module.

PHYSICAL:

O.D.—4.6 inches x 5.2 inches (Oval).

Length — 32 ft.

Material — API type N80 tubing and 4130 steel.

Weight — 700 pounds, approximately.

Electronic Control Line — Neoprene insulated 4 conductor.

WIRELINE RUNNING TOOL ⑤

FUNCTION:

This DNTI tool allows normal wireline operations and is used to place and retrieve the Battery and Electronics Module.

HYDRAULIC UNIT ⑥

FUNCTION:

Provides hydraulic hold-open control of valve ⑦

PHYSICAL:

Tubing mandrel — 2 3/8 inch EUE joint N80.

Length — 31 ft. nominal joint.

Width — 5.25 inches maximum with module.

Packaging — Sealed module — no communication to bore or annulus.

Material — API type N80 tubing and 4130 steel.

INPUT: No power required unless valve has been operated. 10 watts maximum pumping load and 5 watt-hours maximum load per valve cycle.

OUTPUT CAPABILITY: 12,000 ft./lbs. stored.

1,200 — 800 PSI on release.

OUTPUT LINES: 316 stainless steel.

SAFETY VALVE ⑦

The ACOUSTI-TROL system can be adapted to work with any available tubing or wireline retrievable hydraulic valve.

BALANCE OF HOLE DEPTH:
Packers, nipples, hangers, etc.

Figure 19. Del Norte Subsurface Production Valve

Develco, Inc.
L. H. Rorden
404 Tasman Drive
Sunnyvale, California 94086
(408) 734-5700

Develco has been working under an AEC contract to develop a through-the-earth EM communications system. This system was initially intended to provide data telemetry from a location in close proximity to an atomic blast at a high data collection rate. The system reportedly has been tested with limited success in a cased oilfield hole.

Tests conducted by Develco indicate that EM communications through the earth are feasible but they have not tested offshore. In one test in a cased hole satisfactory signals were sent and received at a depth of 11,000 feet at a data rate of 20 sec/bit. Status of the government contract is uncertain as is the overall level of activity presently underway at Develco. At one time Develco was working with Raytheon to develop an MWD system. This relationship is now terminated.

Table 11 gives available transmission rates (bits per sec) for various values of depth and earth resistivity. Company personnel have stated that the conductive sea water which would overlies earth formations when drilling offshore would actually help an EM system by shielding out atmospheric noise. A photograph of the Develco tool is shown in Figure 20.

TABLE 11
EM TRANSMISSION RATES (BITS/SEC.)
RESISTIVITY (OHMMETER)

DEPTH (ft)	5	10	20	50	100
5,000	2	2	2	2	2
10,000	0.55	1.6	2	2	2
15,000	0.0015	0.05	0.41	1.0	1.5
20,000	--	0.0005	0.01	0.2	0.5

An advantage to the Develco system would be possible higher data rate and the possibility of transmitting during tripping when other systems and the mud pulse and hardwire systems would not be operational. Develco estimates the cost of the downhole tool to be in the range of \$200-300,000 in prototype development. It is questionable whether their system could be competitive with mud pulse systems at this price level.

Although Develco has recently built some borehole magnetometers, work on borehole telemetry system seems to be at a very low level at this time. Develco has sought financial support from several marketers in oilfield services, but to date has not received such support.

Figure 20. Develco EM Borehole Unit

Dornier System GmbH
799 Friedrichshafen
Postfach 648
Hamburg, Germany
07545/83269

Dornier System prepared a survey and evaluation of measurements while drilling systems for the German DGMK. Maurer Engineering prepared an evaluation of the market and research potential of MWD systems for Dornier. This company may be conducting further work on electromagnetic or perhaps other systems but the level of their activity is unknown.

Dresser Industries
R. A. Jackson
P. O. Box 6504
Houston, Texas 77005
(713) 784-8957

Dresser Industries licensed the "SNAP" Log from Aquitaine and pursued limited development work on this system. Dresser is understood not to be working on the "SNAP" Log at the present time.

Dresser is contributing \$25,000 to the support of the GE/Cullen Electrodrill program. It is believed that Dresser hopes to accomplish two ends from an association with GE. The first is to keep up with drilling motor technology which they have closely followed in the past including at one time development and marketing a turbodrill motor; and two, remaining aware of the state-of-the-art of telemetry capabilities.

As far as can be determined, Dresser does not have activity inhouse to develop hardware for a borehole telemetry system although such a system would fit very nicely with wellsite computer data units which are marketed by Magcobar.

Dyna-Drill, Division of Smith International, Inc.
Mr. Wayne Sullivan
P. O. Box 36196
Houston, Texas 77036
(713) 781-2091

Dyna-Drill currently markets 'Teledrift' and 'Teleorienter', mud pulse downhole data telemetry systems. The 'Teledrift' system utilizes mud pressure pulses to signal the inclination of the hole. A separate system called 'Teleorienter' operates on the same basic mud pulse technique and permits orientation of the bent sub for directional drilling. Both systems are marketed under licenses from Byron Jackson. Development work is in progress at B-J to combine the two systems into one package to provide both directional and deviation data.

The B-J pressure pulse system produces a series of from 1 to 7 pressure pulses to indicate the value of coded data. Hence accuracy of the measurement is not great. The system activates each time the drilling fluid circulation is halted, then a series of pulse signals is generated at a rate of 1 pulse every 10 to 20 seconds after fluid circulation is restarted. Pressure transducers in the rotary hose at the surface detect the pulses and provide electrical signal for visual interpretation.

Further development work by B-J and Dyna-Drill appears to be at a low level. The New Products Division of Smith International is understood to be considering proposals from several developers of MWD systems.

Eastman-Whipstock
Mr. Gordon Richardson
P. O. Box 14609
Houston, Texas 77021
(713) 797-9500

Eastman-Whipstock markets wireline directional surveying equipment as well as single shot and multi-shot tools. They have both gyro and magnetometer systems. The latter is understood to be similar to the technique developed and patented by Scientific Drilling Controls. E-W reportedly is developing and testing high-temperature wireline surveying equipment, but does not have an active program at the present time to develop hardware for measurements while drilling.

ENSCO, Inc.
Mr. Llewellyn A. Rubin
5408A Port Royal Road
Springfield, Virginia 22151
(702) 569-9000

ENSCO has developed a system of side-imaging radar for borehole application in coal mining and tunneling. This system is useful for determining geologic features such as faults and caverns.

ENSCO is primarily interested in systems technology and in signal enhancement methods. Some of their personnel have worked on EM systems for the U.S. Government. In particular they have technology relating to torroidal coupling of EM signals on drill pipe and have reportedly studied a repeater-type EM system using this method.

There is no active hardware development program for measurements while drilling at ENSCO at this time.

Exploration Research Company
Alf Klaveness, President
7476 Harwin Drive
Houston, Texas 77036
(713) 783-5060

Exploration Research Company is a petrophysical company which performs seismographic exploration and surveys. Much of this work is with Intersea Research of La Jolla, California.

Mr. Klaveness has been working toward the development of an an acoustic telemetry system utilizing drill pipe as a conductor for several years. Prototypes have been tested in both test facilities and field wells. Recent work has been at a low level pending issuance of patents, but (according to Klaveness) will be expanding soon under joint effort with a major oil company.

The Exploration Research System reportedly can work to depths of 20,000 feet at a data rate of 10 seconds per measurements. They report this could be reduced to 2 seconds per measurement. Sensor capability is quite broad including systems to look ahead of the bit to detect high pressure zones and geophysical structure. Cost of this system is expected to be modest; market price would likely be in the \$1000-2000/day range. Plans are to complete development, then license the system to someone with broad capability in well-site services.

EXXON Production Research Company
Dr. Leon Robinson
3120 Buffalo Speedway
Houston, Texas 77001
(713) 965-4365

EPRC has periodically conducted borehole data telemetry development projects. These projects have included developing a bottom hole recorder system, supporting GE in the development of cable connectors and working with Gearhart-Owen to develop downhole sensors. Currently an inhouse project is directed toward developing and testing a continuous hardwire system for use inside rotating drillpipe (see Figure 14). This work presently is at a fairly high level with estimated expenditures on the order of \$300,000-400,000 per year.

EPRC is continuing to test their system at facilities near Houston. Reports are that they are pleased with sensors manufactured for them by Gearhart-Owen, but still lack required reliability of the cable system.

Exxon USA of which EPRC is an affiliated company is contributing \$150,000 toward the Teleco project and is allowing tests of the Teleco system on Exxon wells.

EPRC and Exxon have tested and evaluated several proprietary systems for outside firms. A test of Raytheon's EM system was reportedly planned for last year but did not take place. Motorola, Teleco and Develco are understood to have all tested in Exxon's test wells and/or drilling wells.

Exxon is a very strong supporter of the need for measurement while drilling and is quite anxious to see such services offered in the USA and overseas.

Gearhart-Owen Industries, Inc.
Mr. Marvin Gearhart
P. O. Box 1936
Ft. Worth, Texas 76101
(817) 293-1381

Gearhart-Owen is a manufacturer of borehole logging equipment and currently has several borehole telemetry systems under development. The most intense efforts are reportedly aimed at a mud pulse technique. Of their two mud pulse systems one is described as "quick and dirty" and the other as more sophisticated. Tests have been run to depths in excess of 11,000 feet with excellent results.

Gearhart-Owen has worked with Exxon Production Research Company on the development of downhole sensors and other components for the EPRC hardwire system. Several techniques of storing wire inside the drill pipe have been studied. In addition Gearhart-Owen has investigated using a hardwire system from the bottom to near surface, then an EM link to complete the transmission path. This would allow drilling to proceed without adding special lengths of pipe or having to worry about bringing the wire to the well each time a joint is added.

Measurements while drilling are very high priority item at Gearhart-Owen. Total expenditures are believed to be in the range of \$500,000 to \$1 million per year from internal funds, which is a high level considering gross revenues on the order of \$70 million/year. Gearhart-Owen both sells logging equipment and markets logging services. This is a very aggressive company which along with Teleco and Schlumberger will have significant impact on measurements while drilling.

Figure 21 is a photograph of an early prototype of the Gearhart-Owen mud pulse system at the Gearhart plant in Ft. Worth.

Figure 21. Gearhart-Owen Mud Pulse Prototype

General Electric Company
Mr. Peter Taylor
P. O. Box 58408
Houston, Texas 77058
(713) 332-4511

General Electric is pursuing development of the Cullen Electrodrill system. They have incorporated into the system a borehole telemetry system to measure and transmit sixteen parameters over a wire molded as part of the electrodrill power system. Because ample electrical power is available plus a hardwire for data transmission, this telemetry is really an application of wireline logging technology.

Although expenditure and manpower levels on the electrodrill project are high, almost all funding is directed toward further development and testing of the drilling motor itself. Reportedly GE worked with Humphrey, Incorporated to develop directional sensors which will continuously acquire directional data without having to stop drillpipe rotation (or motor rotation), but has now developed their own directional sensor package.

Gentrix Engineering Ltd.
Mr. Clifford Ainsworth
2009 10th Avenue, S.W.
Calgary, Alberta, Canada T3C0K4
(403) 245-2011

Gentrix is primarily an electronics firm. However, they have successfully designed and built several product packages utilized by the petroleum industry. A pressure pulse telemetry system has been under development for several years with support from AMOCO, Cougar Oil Tool and the Canadian Government. The system has been field tested several times with problems reportedly encountered in mechanical subsystems.

The level of effort appears to be at the 3-4 man level. Their plans are to build ten field prototypes within the next year. This seems to be an ambitious goal considering apparent lack of progress since our last conversation with them over a year ago.

Originally Gentrix planned to offer a broad selection of sensors. This has reportedly been changed to plans to develop only a directional package. They are working with Humphrey on the development of directional sensors.

Harnessed Energies, Inc.
Mr. Samuel W. Tishler
63 Great Road, Box J
Maynard, Massachusetts 01754
(617) 897-4715

This company has developed borehole directional sensors for Westinghouse for use in mining instrumentation. The unit is completely electronic and provides continuous reading of azimuth and inclination as the probe is withdrawn from the shaft. Surface readout is directed into a self contained unit.

Two probes were manufactured for Westinghouse and a third for use by Harnessed Energies. The status of further work by this company is unknown.

Helle Engineering, Inc.
David McGhee
7198 Convoy Ct.
San Diego, California 92111
(714) 278-3521

According to a recent news release, Helle Engineering has developed an acoustic system to monitor and transmit corrosion information in production wells to the surface from depths of 10,000 feet. There are no stated plans to develop a drilling data system.

William C. Hooper, Jr.
Consulting and Petroleum Engineer
436 The Main Building
Houston, Texas 77002
(713) 658-8584

Mr. Hooper is a Consulting Engineer and owner of a contract drilling company. He has put approximately \$200,000 to \$300,000 venture capital into an acoustical telemetry system over the past two years. The work was being conducted by individuals as a minimum budget operation. Hooper is reportedly terminating further activity of the group and would like to license technology developed to date.

Institute Francais du Petrole
Jaques Delacour
B. P. 48
92502 Rueil - Malmaison
France

IFP has developed a drilling system based on downhole electric motor on the end of a flexible pipe (see photograph, Figure 15). Molded into the pipe or hose are electrical conductors for downhole communications. The system is currently used for monitoring bit parameters such as weight and torque and motor parameters such as RPM and temperature. This is considered an adaptation of wireline logging technology since a electrical conductors are available for power and data transmission.

Maurer Engineering Inc.
Dr. William J. McDonald
10301 Northwest Freeway, Suite 202
Houston, Texas 77092
(713) 683-8227

Maurer Engineering has made technical surveys and evaluation studies for government and industrial clients. There is no activity which is directed toward developing their own telemetry hardware. Maurer Engineering is involved in developing drilling motor hardware which would utilize telemetry systems.

Mobil Research and Development Corp.
 Dr. Bob Patton
 P.O. Box 900
 Dallas, Texas 75221
 (214) 331-6531

Mobil originally developed and patented the mud "screamer" pressure pulse concept. As discussed in an earlier chapter, this system was taken through prototype stage. Figure 22 shows the Mobil prototype unit stripped of the outer case and undergoing bench testing. Figure 23 shows the system being put together in the Mobil test well.

Figure 22. Mobil Mud Pulse Telemetry Tool
 (Patton, Ref. 15)

Figure 23. Mobil Tool Being Assembled (Patton, Ref. 15)

Three major field test were run by Mobil with the prototype tool after intensive laboratory testing. Field test data results demonstrated; 1) basic mechanical reliability 2) data rate capabilities sufficient to transmit numerous channels of information with good depth resolution and 3) error free data transmission at depths exceeding 20,000 feet for low viscosity, low weight muds, and on the order of 14,000 to 17,000 feet for heavy, viscous muds.

Mobil has worked on sensors and surface processing equipment for the measuring and interpreting well control information. Sandia Laboratories and Mobil have submitted a joint proposal to the Energy Research & Development Administration (ERDA) for funding of a \$1 million project for accurate determination of the annulus/formation ΔP .

Motorola Government Electronics Division
V. J. Yates
8201 East McDowell Road
Scottsdale, Arizona 85252
(602) 949-3033

Motorola has developed an acoustic system for actuating downhole devices. Their system, developed under an ERDA contract with Petroleum Technology Inc., transmits a coded acoustic signal on the production tubing. Attempts to use the system with PTI in explosive fracturing have been unsuccessful. Background noise seems to over-ride the signal in these cases; thus fail-safe features remain activated.

Motorola also tested an acoustic system (understood to be slightly different from the PTI system) to activate a downhole valve in an Exxon test well at Friendswood, Texas, in October, 1975. Background noise and low data appear to limit successful, broad application of the Motorola system.

Another division of Motorola is reported to have developed low frequency (LF) and extra low frequency (ELF) systems for transmitting electromagnetic signals through the earth for defense applications.

Placid Oil Company
Dallas, Texas

Placid Oil Company is contributing \$150,000 toward the Teleco development and demonstration project. They are also providing test wells, when available, for Teleco.

Raymond Precision Industries Inc.
Mr. J. G. Lombardo
217 Smith Street
Middletown, Conn. 60457
(203) 632-1000

Raymond Precision Industries and Aquitaine (SNEA) formed Teleco in 1972. Raymond Precision holds 51% ownership position. The joint venture was to develop and market Aquitaine's mud pulse telemetry system. In late 1976 Teleco completed arrangements for a jointly funded government/industry project to spend approximately \$4 million over the next 2 years for the further development and demonstration of the Teleco system. There are three existing prototypes which have accumulated over 1,500 hours of borehole drilling time to date. In addition 8 tools are being built for extensive field testing and test marketing.

The present Teleco system is a directional unit only. Teleco is reported to have plans to expand the capabilities by incorporating other sensor systems such as gamma-ray and well control sensors.

Field receptiveness to the Teleco system appears to be very good. It is anticipated that Teleco will market this system on a very limited basis by late 1977. Tentative pricing of \$1200-2000/day has been discussed for the directional system. Further discussion of the Teleco system is included under that company.

Raytheon Company
Dr. J. T. deBettencourt
Sudbury, Massachusetts 071776
(617) 443-9521

Raytheon has worked on a very low frequency electromagnetic signaling system for the past three years. This work has been primarily under contract for the U.S. Government. A telemetry system developed by Develco for Raytheon was to undergo field test in 1975, but testing reportedly was delayed due to management decisions. Raytheon has an ERDA contract for the investigation of basic parameters on EM transmission. It is reported that they are working primarily in the 1 Hz range in order to overcome lithospheric attenuation. Even so, the Raytheon system is believed to require repeaters every 3,000 feet.

Sandia Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87115
(202) 264-8920

Sandia Laboratories personnel are investigating MWD as applied to oil and gas wells and to geothermal wells. Two methods are being studied at Sandia. One of the telemetry projects relates to transmission through the earth by electrical currents. The other project area is development of an acoustic coupler to eliminate the slip rings required in a hard wire system. A proposal submitted jointly by Sandia and Mobil Research to ERDA would lead to studies of ways to more accurately determine formation/annulus ΔP .

In addition to MWD, Sandia is studying mapping of fractures by both electrical and seismic methods. This work could yield basic information required for developing an effective borehole telemetry system.

Schlumberger Services Ltd.
Mr. Dennis Tanguy
P. O. Box 1275
Houston, Texas 77001
(713) 928-2511

Schlumberger is actively developing the Mobil "screamer" technique of communicating borehole information for surface interpretation. So far, data telemetry has included (but may not be limited to): gamma logs, temperature logs, E-logs and normal drilling parameters such as bit weight, bit torque and bit condition. The Schlumberger system is reported to be capable of transmitting and receiving at a rate of 3 bits/second (average 10 bits per measurement) with a technical potential for a two-to-four-fold increase if necessary.

Schlumberger has recently completed the fabrication of two new field prototype systems. Reportedly plans are to continue testing with these systems over the next year. According to the reports from several sources, the Schlumberger downhole system is quite expensive, on the order of \$200-300,000 per unit. The total field service system including two downhole packages (one primary and one backup) and surface processing equipment has been stated by the Analysts ¹² to cost on the order of \$1-1.5 million.

Marketing of the Schlumberger tool will be through the Analysts under an agreement reached with them last year by which the Analysts will purchase the downhole equipment from Schlumberger and incorporate MWD as part of their well-site drilling data service. Announcements by the Analysts indicate that the marketing will be directed at a "high end market". Consequently, it will be most applicable to limited use on expensive offshore exploratory rigs. This would indicate that Schlumberger plans to develop their markets over a rather extended period of time.

Although the level of effort on the Schlumberger system is very high, marketing of a fully commercialized system is believed to be at least two years away.

Scientific Drilling Controls
Mr. Bernie Zuvela
4040 Campus Drive
Newport Beach, California 92660
(714) 557-9051

Scientific Drilling Controls markets a magnetic survey system called the "'Eye' Electronic Yaw Equipment." This system which was introduced in 1970 is primarily used for directional drilling. The system requires a continuous single conductor wireline inside the drill string during the drilling operation. Continuous signals are transmitted to the surface indicating magnetic direction of the high side and tool facing of the hole. A compatible tachometer system for use with downhole drilling motors is also available.

Although commercially available for several years, the SDC system has not seen widespread application in drilling. At the present time SDC reports that they have ten field units operating and do not plan rapid expansion of capability at this time. SDC charges on the order of \$4-5,000 per day for the service. At this level, it would appear that they are skimming a very lucrative but rather limited market which best fits the economic constraints of their own organization. Our analysis indicates that to remain competitive, costs will come down and availability and service will have to go up.

SDC is also working on a new system. Although company personnel would not comment, this is believed to be either an EM or combination wire/EM system.

Shell Development Company
Dr. William Montgomery
3737 Bellaire Boulevard
Houston, Texas 77025
(713) 667-5661

Shell has been active in borehole telemetry for considerable time. Recent efforts have been aimed at developing the hardwire system discussed earlier. Their present system consists of a downhole instrument, 3,000 feet of special drillpipe and a slip ring-Kelley assembly, uphole readout equipment and special cleaning equipment. This project is discussed in a recent publication.¹⁷

Modified drillpipe used in the Shell system is shown schematically in Figure 12. The pipe contains a single contact ring in the mating face of each tool joint and an interconnecting conduit through the pipe bore. Contact rings are automatically made-up during joint makeup. To assure electrical isolation, high-pressure water is used to clean each box and pin prior to doping and makeup. A special electrically non-conductive tool joint compound is required; also a special mouse hole is used which can be flushed and cleaned. The downhole instrument package measures borehole azimuth and inclination, annulus pressure, pipe pressure, temperature and accelerations along three axes. Other types of sensors have been designed but not built. Instrument power is supplied down the single conductor; data is multiplexed, digitized and transmitted to the surface on the power line. An eight bit word is transmitted at a data rate of 5,400 bits/second. Presently there are 15 data channels, four channels are sampled 120 times per second and twelve are sampled at 9 times/second.

In the past year Shell has performed a test in which a jumper was used in the lower part of the hole and the special drill pipe in the upper part of the hole. With successful field testing of this system, Shell is now actively seeking to license their system for further development. Concern expressed by those who have reviewed the Shell system indicates there are several major limitations. One is expense since the special pipe is expected to cost on the order of \$400,000 for a 3,000 foot string which may have a life somewhat shorter than that of ordinary drillpipe. At the present time it does not appear that Shell has worked out a licensing arrangement with anyone for this system.

Smith International, Inc.
Jack W. Knowlton
P. O. Box 1860
Newport Beach, California 92660
(714) 752-9000

The Product Development Group of Smith International has considered the licensing of developed MWD systems. To date no agreements have been signed, and as far as can be determined, other than work at SERVECO on an "EYE" - type tool, there is no in-house effort to develop a system.

Efforts of Dyna-Drill apparently are conducted separately from the Smith New Product Group.

Sperry Research Center
Dr. W. D. McBee
Sudbury, Massachusetts
(617) 369-4000

Sperry Research has developed an acoustic transmission system for communicating data on their downhole geothermal pump. They are working on a project to adapt this system to measurements while drilling capabilities. This work is primarily government funded, with some internal funds added. At the present time funding is on the order of \$300,000 per year. However, continued funding is uncertain.

Although an extensive market study was prepared by Harvard Business School for Sperry, it does not appear that Sperry is working toward a tool to market in the petroleum industry.

In addition to their work on acoustics, Sperry is committed to expend part of the government contract funds on research on electromagnetic transmission systems. Electronics for the Sperry geothermal pump acoustic unit are shown in Figure 24.

Figure 24. Sperry Electronics Package

Sperry-Sun
Mr. Charles Hawk
P. O. Box 36363
Houston, Texas 77036
(713) 494-3021

Sperry-Sun has developed and is marketing a system for monitoring bottom hole pressures in production or test wells. The "Permagate" system requires a continuous gas filled capillary tube from the sensor to the surface. Other parameters could logically be monitored under long term test conditions, but the system would be impractical for the drilling situation. In addition, Sperry-Sun is marketing a directional drilling "steering tool" under license from the inventors of the Scientific Drilling Controls system.

Sperry is field testing an acoustic system designed to provide more versatility and capability than their other directional systems. Reports are that the maximum depth capability is approximately 1,500 feet without repeaters. Activity level on the acoustic system is relatively high at the present.

Systems, Science and Software (S³)
Dr. Donald R. Grime
P. O Box 1620
LaJolla, California 92038
(714) 453-0060

S³ is currently working on several development contracts for the Energy Research and Development Administration and the National Science Foundation in the areas of geothermal modeling and temperature studies. In addition they have shown an interest in studying the borehole data telemetry problem (specifically in the geothermal environment).

The level of effort of internally funded work is probably low at this time, but may be increased at a later date (especially if government support is obtained).

Telcom
Dave Hipkins
8027 Leesburg Pike
McLean, Virginia
(703) 893-7700

Telcom is an electronics engineering firm and has worked on data telemetry systems under several government contracts. Two contracts for ERDA were aimed at general data acquisition.

Two additional contracts for USBM under the "Trapped Miner" project (alternate prime/subcontract positions with Fenix and Scisson) were aimed at providing exact location of the borehole bottom. The system which was developed and tested was of the EM type. The work was successful, but was terminated when USBM funding was reduced.

Several unsuccessful attempts have been made to interest oilfield firms in funding further development for drilling applications. As Telcom has no plans to provide in-house funding, no further work is underway.

Teleco Inc.
Ralph Spinnler
217 Smith Street
Middletown, Connecticut 06457
(203) 632-1133

Teleco is a joint venture company formed by Raymond Precision Industries, Inc. (51%) and Societe Nationale des ELF Aquitaine (49%) to develop and market borehole telemetry systems. Several models of an electronic multiplexer and mud pressure pulse signal system have been built and field tested. To date over 1,500 hours of downhole drilling time have been accumulated. Oil company personnel in general seem pleased with system performance.

As reported in a recent World Oil article,¹⁴ system improvements are being made and extensive testing is expected to continue. As described under Raymond Engineering, funding for the next two years will come from a joint government/industry project and will be on the order of \$2 million per year.

They are in the process of establishing a field service center to be located in Lafayette, Louisiana. Plans are to manufacture equipment in Connecticut but to provide field service from the Lafayette location. Minor maintenance will be performed in Lafayette with major maintenance and calibration performed at the Connecticut site. Although proceeding with plans to establish their own marketing and service outlets, Teleco is understood to be discussing marketing arrangements with several oilfield service companies.

Recent reports indicate that Teleco will initiate commercial service in the North Sea in April, 1978. Five complete systems would become available under an arrangement with operating companies advancing approximately one half of the \$3 million required to initiate these operations. Estimated pricing would be \$2,500/day.

Texaco Research
Dr. K. Savage
5901 South Rice
Houston, Texas
(713) 666-0151

Texaco has been relatively active in the evaluation of borehole data telemetry systems over the years (as evidenced by the issue of 11 or more patents assigned to Texaco). The greatest thrust of their work was aimed at bottomhole instrumentation (including recorders). Although their project was terminated about two years ago, some work such as joint field tests has been conducted with companies such as Teleco and Schlumberger. Texaco is understood to have sold bottomhole recorder data measured while drilling to Teleco for use in instrument design.

The level of effort at Texaco is low at the present time.

Texas Dynamics
Dallas, Texas

Texas Dynamics is a small consulting firm which previously worked on downhole borehole telemetry systems and holds several patents in the area.

Union Oil Company of California
Research Department
Dr. James A. Klotz
P. O. Box 76
Brea, California 92621
(714) 528-7201

While Union has no inhouse program for hardware development they are contributing \$25,000 toward financial support of the GE/Cullen project and have offered wells for testing of motors and telemetry systems.

Westinghouse Electric Company
Mr. Dick Banta
Baltimore, Maryland

Westinghouse developed and demonstrated a mine rescue communications system for the U.S. Bureau of Mines during the 1960's. This is an EM system with fairly high data rate capability which utilizes a carrier frequency of 100 hz. This system is understood to have a depth capability of at least 2,000 feet. A relatively low level of work is underway at the present time to determine the applicability of their EM technology for measurements while drilling.

Within the last year Harnessed Energies, Inc. of Maynard, Massachusetts built and delivered several directional sensor packages to Westinghouse.

REFERENCES

1. Anon., "Drilling Costs Climbing Faster Than General Inflation," Drilling - DWC, December 1976, p. 26.
2. McDonald, W. J. and Ward, C. E., "Borehole Telemetry System Is Key to Continuous Downhole Drilling Measurements," Oil & Gas Journal, Vol. 73, No. 37, September 15, 1975, pp. 111-118.
3. Raynal, J., et al, "Method and Apparatus for Measuring Mechanical Characteristics of Rocks While They Are Being Drilled," USP 3,520,375.
4. Sullivan, W., "Teleorienter Can Speed Directional Drilling," Drilling Contractor, Volume 30, Number 2, January-February, 1974, pp. 32-35.
5. Heilhecker, J. K., "Telemetry, Drill-Stem Problems, and Hole Control," presented at the 'Drilling For Energy Resources Workshop,' Park City, Utah, June 25-27, 1975.
6. Maurer, William C., "Drilling R&D Underway in the United States," 1977 IADC Drilling Technology Conference, New Orleans, La., March 16-18, 1977.
7. Deily, F. H., et al, "Downhole Measurements of Drill String Forces and Motions," Journal of Engineering For Industry, May 1968, pp. 217-225.
8. Anon., "\$5.8 Billion...During 1975," Drilling - DWC, July 1975, p. 43ff.
9. Meyer, P. K., Research Notes, Eberstadt and Company, Inc., New York, October 15, 1975.
10. Spears, Robert B., "Equipment and Services in the Petroleum Industry," Tulsa, Oklahoma, 1977.
11. Anon., "Results of IADC Questionnaire", Oil and Gas Journal, To Be Published.
12. Anon., "Computerized Oil Well Drilling Systems Coming...", Houston Business Journal, May 9, 1977, pp 18-19.
13. Arps, J. J., "Continuous Logging While Drilling: A Practical Reality," Society of Petroleum Engineers, Preprint No. SPE 710, September, 1963, p. 6.
14. Anon., "New Tool Accelerates Directional Surveying," World Oil, Volume 181, No. 5, October, 1975, pp. 91-95.
15. Patton, B. J., et al, "Development and Successful Testing of a Continuous Wave Logging-While-Drilling Telemetry System," paper SPE 6157, presented at the Annual SPE Meeting, New Orleans, October 3-6, 1976.

16. Anon., "Trapped Miner Location and Communication System Development Program," prepared for Bureau of Mines, PB-235 605, May, 1973.
17. Dennison, E. B., "Making Downhole Measurements Through Modified Drill Pipe," World Oil, Volume 183, No. 5, October 1975, pp. 86ff.
18. Heilhecker, Joe K., "Method For Mounting An Electrical Conductor in A Drill String," USP 3,825,079.
19. Thiery, J., "Report on the Flexorig 3000-1 Drilling Operation in Leemens From October 1974 Till May 1975," Floraflex Technical Report No. 33-R, June 1975, pp. 3 and 12.
20. Cullen, Roy H., et al, "Methods And Apparatus For Mounting Electrical Cable in Flexible Drilling Hose," USP 3,285,629.
21. Russell, M. K., "The Design and Development of a Surface Reading Orienting and Survey Instrument," API Production Division, Pacific Coast District Meeting, Paper No. 801-46R, Los Angeles, California, May 12-14, 1970.

APPENDIX I

CHRONOLOGICAL LIST OF PUBLICATIONS
ON DOWNHOLE MEASUREMENTS WHILE DRILLING

BIBLIOGRAPHY

Reed, P., "Amerada Develops Special Rotary Drill Stem for Simultaneous Electrical Logging and Drilling", Oil and Gas Journal (November 17, 1939), pp. 93-96.

Mills, Brad, "Simultaneous and Continuous Electric Logging and Drilling Achieved", Oil Weekly (January 1, 1940), pp. 16-20.

Stratton, J. A., "Electromagnetic Theory", McGraw Hill Book Co. (1941), p. 554.

Papas, C.H., "On The Infinitely Long Cylindrical Antenna", Journal of Applied Physics, Volume 20 (May, 1949), pp. 437-440.

Goubau, G., "Surface Waves and their Application to Transmission Lines", Journal of Applied Physics, Volume 21 (November, 1950), pp. 1119-1128.

Walstrom, J.E., "Optimum Use of Various Testing Methods in Exploratory Wells", API Dr. and Prod. Prac. (1950), pp. 79-95.

Harris, C.M., Editor, "Handbook of Noise Control", McGraw Hill Book Co. (1957), pp. 33-37.

Chaney, P.E., Mayes, F.M., Jones, J.W., Bennett, J.D. (Sun Oil Co.), "Sun Oil Company's Drill Stem Logging Tool is Successful", World Oil (May, 1959), pp. 191-192, 202.

Lindsay, R.B., "Mechanical Radiation", McGraw Hill Book Co. (1960), p. 194.

Anonymous, "Drill Stem Log Tool Passes Tests", Petr. Week (February 10, 1951), p. 21.

Polyakov, E.A., "The Theory of Wireless Transmission of Electric Signals From the Well Bottom During Drilling", Prikl. Geofiz., Volume 32 (1962), pp. 142-154 (In Russian).

Guy, A.W. and Hasserjian, G., "Impedance Properties of Large Subsurface Antenna Arrays", IEEE Trans. AP-11 (May, 1963), pp. 232-240.

Special Issue, "Electromagnetic Waves in The Earth", IEEE Trans. Ant. and Prop., Volume AP-11 (May, 1963).

Arps, J.J., "Continuous Logging While Drilling: A Practical Reality," Society of Petroleum Engineers, Preprint No. SPE 710, September, 1963, p. 6.

Arps, J.L. (Arps Corporation), "An Introduction to Continuous Electric Logging While Drilling", Trans. Gulf Coast Association of Geol. Soc., Volume 14 (1964), pp. 133-136.

Arps, J.J. (Brit.-Am. Oil Prod. Co.) and Arps, J.L. (Arps Corporation), "The Subsurface Telemetry Problem - A Practical Solution", Journal Petr. Tech. (May, 1964), pp. 487-493.

Arps, J.J. (Arps Corporation), "New Logging-While-Drilling Method Proves Practical", Oil and Gas Journal (September 7, 1964), pp. 154-156.

Anonymous, "Drill String Logging Tool Sees Ahead of Bit", World Oil (August 1, 1964), p. 92.

Anonymous, "New Continuous Logging Tool Unveiled", Oil and Gas Journal (June 22, 1964), pp. 106-107.

Sterrett, E., "Fitting the Bit with Eyes", Drilling (July, 1964), pp. 70-71.

Johnson, H.M. (Tulane University), "Latest Developments in Formation Evaluation", World Oil (April, 1965), pp. 143-150.

Angona, F. A., "Drill String Vibration Attenuation and Its Effect on a Surface Oscillator Drilling System", Trans. ASME J. of Engr., (May 1963), p. 110ff.

Banos, A., Jr., "Dipole Radiation in the Presence of a Conducting Half-Space", Pergamon Press, Oxford (1966).

Cahill, J. (Welex Division, Halliburton Co.), "Use of the Drill Pipe Electric Log", 7th Ann. SPWLA Symp., Tulsa (May 8, 1966 - May 11, 1966).

Cahill, J. (Welex Division, Halliburton Co.), "Drill-Pipe Log is Good Problem Solver", Oil and Gas Journal (September 26, 1966), pp. 106-108.

Cahill, J. (Welex Division, Halliburton Co.), "Frequent Surveys are Economical with Drill Pipe Log System", World Oil (December, 1966), pp. 6-7.

Helander, D.P. (Tulsa University), "Here Are Ways You can Log Formations While Drilling", Oil and Gas Equipment (September, 1966), pp. 6-7.

Rogers, L., "Shale-Density Log Helps Detect Overpressure", Oil and Gas Journal (September 12, 1966), pp. 126, 127, 130.

Cunningham, R.A., "Analysis of Downhole Measurement at Drill String Force and Motions," page 67-PET-12, ASME Pet. Mech. Engr. Cont, Philadelphia, Sept. 17-20, 1967.

Fatuliaev, K.L., "Study of Noise From Measuring Electrodes of Sonde by Modeling with an Electrolytic Bath", Izv. Vyssh. Ucheb. Zavedenii, Neft Gaz, Volume 8 (1967), pp. 89-92 (In Russian).

Gruenberg, E.L., Editor, "Handbook of Telemetry and Remote Control" McGraw Hill Book Co. (1967).

Kengerlinskii, Yu. S., "A Combined System of Electrical Channel Communication", Izv. Vyssh. Ucheb. Zavedenii, Neft Gaz, Volume 10 (1967), pp. 95-98 (In Russian).

Kengerlinskii, Yu. S., "Determination of Variously Distributed Parameters of Electronic Communications Channel in Drilling", Izv. Vyssh. Ucheb. Zavedenii, Neft Gaz, Volume 5 (1967), pp. 103-106 (In Russian).

Long, F.V. (Texas E. Transmission Corp.), "Automation and Telecontrol. PT. 2. Signaling", Pipeline Eng., Volume 39, No. 2 (February, 1967), pp. 37-39.

Litvinov, S. Ya. and Sarkisov, I.K., "The Problem of Logging Wells During Drilling Operations", Razved, Geofiz., Volume 19 (1967), pp. 80-87 (In Russian).

Deilly, F.H., et al, "Downhole Measurements of Drill String Forces and Motions", Trans. ASME, J. Engin. for Ind. (May, 1968), pp. 217-225.

Fedorov, A.S., "Radiotelemetric Channel of a Bond for Transmission of Drilling Parameters from the Face of the Well Being Drilled", Geofiz. App., Volume 36 (1968), pp. 140-146 (In Russian).

Sarkisov, I.K. and Benda, I. Ya., "Apparatus for Investigating Transmission of Electric Signals in Pipes", Geofiz. App., Volume 37 (1968), pp. 90-95 (In Russian).

Chernavin, Yu. V., Fatullaev, K.I. and Leitman, M.B., "Deep Telesurveying Device for Electric Exploration in Drilling with an Electric Drill", Izv. Vyssh. Ucheb. Zavedenii, Neft Gaz, Volume 3 (1969), pp. 81-84 (In Russian).

Sarkisov, I.K., "Investigation of Frequency Characteristics of a Coupling Channel from Transmission of Electric Signals along Pipes", Prikladnaya Geofiz., Volume 56 (1969), pp. 209-214 (In Russian).

Kennedy, J.L., "Drilling Industry Will Begin the 1970's With New Equipment, Methods", Oil and Gas Journal, Volume 67, No. 51 (December 22, 1969), pp. 157-159.

Thiery, M., "The Flexodrill I.F.P. - Present and Future Status", Rev. Ass. Franc. Tech. Petrol., Volume 198 (November - December, 1969), pp. 48-81 (In French).

Anonymous, A Primer of Oilwell Drilling, Petroleum Extension Service, University of Texas at Austin, Austin, Texas (1970).

Chepelev, V.G., Fetisenko, N.P., Abakumov, V.I., Malykhin, G.A. and Engel, A.S., "Telemetric System for Investigating Drilling String Vibrations and Axial Load on Bit in Electrodrilling", Neft. Khoz., Volume 1 (January, 1970), pp. 14-18 (In Russian).

Hearst, J.R. and Carlson, R.C., "Well-Logging Research for Geonuclear Technology", Nuclear Applications and Technology, Volume 8 (March, 1970), pp. 276-282.

Russell, M.K. (Scientific Drilling Controls), "The Design and Development of a Surface Reading Orienting and Survey Instrument", API Prod. Div. Pacific Coast Dist. Mtg., Paper No. 801-46R, Los Angeles (May 12, 1970 - May 14, 1970).

Kennedy, J.L., "Drilling Porosity Log Proves Accurate", Oil Gas Journal, Volume 68, No. 34 (August 24, 1970), pp. 53-55.

Parfenov, K.A., "A Nomogram for Determining the Depth of Communication with Well Bottom by a Wireless Electric Channel", Neft. Khoz., Volume 9 (September, 1970) pp. 19-20 (In Russian).

Wait, J.R. Editor, "Electromagnetic Probing in Geophysics", The Golem Press (1971).

Lutz, Jr., et al, "Instantaneous Logging Based on a Dynamic Theory of Drilling," JPT, June 1972, pp. 750-758.

Barnes, T.C. and Kirkwood, B.R., "Passbands for Acoustic Transmission in an Idealized Drill String", Jr. Acous. Soc. of Am., Volume 51, No. 5 (Pt. 2) (1972), pp. 1606-1608.

Anonymous, "Trapped Miner Location and Communication System Development Program", prepared for Bureau of Mines, PB -235 605 (May, 1973).

Marshall, Gailen, P., "How to Steer Mud Motors in Ultra-Deep Hot Holes," Drilling-DCW, Volume 34, No. 9 (June, 1973), p. 44.

White, D.E., "Characteristics of Geothermal Resources", Geothermal Energy (ed. by P. Kruger and C. Otte), Stanford University Press, Stanford, California (1973), pp. 69-94.

Loy, Sam, "Master Plan for Drilling Progress", Drilling - DWC, May 1974, pp. 31ff.

Meyer, P.K., Research Notes, Eberstadt and Co., Inc., New York, December 2, 1974.

Scott, J., "Drilling Industry Aims Rigs, Technology At Energy Crunch", Petroleum Engineer, Volume 46 (July 15, 1974), pp. 9, 12-14.

Sullivan, W. (Dyna Drill Co.), "Teleorienter Can Speed Directional Drilling", Drilling Contract, Volume 30, No. 2 (January - February, 1974), pp. 32-35.

Baker, L.E., Campbell, A.B. and Huguen, R.L., Well-Logging Technology and Geothermal Applications, Sandia Laboratories Energy Report No. SAND75-0275, May 1975.

Heilhecker, J.K., "Telemetry, Drill-Stem Problems, and Hole Control", presented at the 'Drilling for Energy Resources Workshop', Park Cities, Utah, June 25-27, 1975.

Thiery, J., "Report On The Flexorig 3000-1 Drilling Operation In Leemans From October 1974 Till May 1975," Foraflex Technical Report No. 33-R, June 1975, pp. 3 and 12.

Brown, T., et al, "What Will We Record and How Will We Do It?", Drilling-DWC, Volume 36, No. 13 (October, 1975), pp. 65-68.

Anonymous, "New Tool Accelerates Directional Surveying", World Oil, Volume 181, No. 5 (October, 1975), pp. 91-95.

Meyer, P.K., Research Notes, Eberstadt and Company, Inc., New York, October 15, 1975.

Garcia, J.A., "Better Computer Input", Drilling-DWC, Volume 36, No. 13 (October, 1975), pp. 61-64.

Meyer, P.K., "Borehole Telemetry - A Survey of the State-of-the-Art," Institutional Investor Report, F. Eberstadt & Co., New York, November 20, 1976.

McDonald, W. J., and Ward, C.E., "Borehole Telemetry System is Key To Continuous Down-Hole Drilling Measurements", Oil and Gas Journal, Volume 73, No. 37 (September 15, 1975), pp. 111-118.

McDonald, W.J., "A Review of Downhole Measurements While Drilling," Sandia Laboratories Research Report SAND 75-7088, November 1975.

Anonymous, "Durchfuhrbarkeitsstudie zur Entwicklung eines Verfahrens zur kabellosen Ubertragung von Messdaten aus tiefen Bohrlochern", DGMK-Projekt 46166, Hamburg, May 1976.

Meyer, Philip K., "MWD Technical Up-date", Eberstadt & Co., Inc., New York, N.Y., July 16, 1976.

McDonald, W.J., "Fernmessung von Bohrloch-Daten Wahren des Bohrens", (Borehole Data Telemetry While Drilling), Erdoel-Erdgas-Zeitschrift, 92.Jg., August 1975, pp. 258-264.

Dennison, E.B., "Making Downhole Measurements Through Modified Drill Pipe", World Oil, Volume 183, No. 5, October 1976, pp. 86ff.

Patton, B.J. et al, "Development and Successful Testing of a Continuous Wave Logging-While-Drilling Telemetry System," paper SPE 6157, presented at the Annual SPE Meeting, New Orleans, October 3-6, 1976.

Pedigo, John et al, "An Acoustically Controlled Downhole Safety Valve (SCSSSV)," paper SPE 6026, presented at the Annual SPE Meeting, New Orleans, October 3-6, 1976.

Meyer, Philip K., "Oilfield Services and Products," Eberstadt & Co., Inc., New York, N.Y., December 2, 1976 and January 10, 1977.

Marshall, Gailen D., "Survey Steering Tool System Provides Savings of Rig Time," Oil and Gas Journal, December 27, 1976, p. 192ff.

Maurer, William C., "Drilling R&D Underway In The United States," 1977 IADC Drilling Technology Conference, New Orleans, La., March 16-18, 1977.

Anonymous, "'Real Time' Data for Downhole Conditions," (Sperry-Sun)", Drilling - DWC, April 20, 1977, p. 78.

Dennison, E.B., "Shell's High-Data-Rate Drilling Telemetry System Passes First Test," Oil and Gas Journal, June 13, 1977, p. 63.

Anon., "Computerized Oil Well Drilling Systems Coming...", Houston Business Journal, May 9, 1977, pp 18-19.

Berger, E.L., "The Electrical Red Time Control and Display System", 52nd Annual SPE Meeting, Denver, Colorado, October 9-12, 1977 - To Be Published.

Rorden, L.H., "Single Hop Electromagnetic Telemetry for Drilling", 52nd Annual SPE Meeting, Denver, Colorado, October 9-12, 1977- To Be Published.

Taylor, P.D., "Electrodrill, A Drilling System for the Future", 52nd Annual SPE Meeting, Denver, Colorado, October 9-12, 1977 - To Be Published.

APPENDIX II

U. S. PATENTS RELATING TO
DOWNHOLE MEASUREMENTS WHILE DRILLING

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
959,977	Electrical Connector	F. L. Washburn, et al	
1,063,625	Apparatus for Measuring the Axial Thrust Acting Upon a Shaft	P. Wagner	General Elec. Co.
1,411,896	Boring Device and Method for the Production of Vertical Boreholes	H. Anschutz- Kaempee	Anschutz & Co.
1,855,647			
1,905,299	Instrument for Recording Inclination	W. I. McLaughlin, et al	Std. of Calif.
1,927,664	Method and Apparatus for Exploring Bore Holes	J. C. Karcher	
1,963,090	Apparatus for Detecting Excessive Deviation of Drill Holes	J. J. Jakosky	MacClatchie Manufacturing Co.
1,979,481	Device for Indicating Inclination	T. L. Lynch, et al	
2,085,664	Method and Apparatus for Determining Porosity of Rock Formation	J. C. Karcher	Geophysical Service Inc.
2,096,279	Insulated Pipe Connector	J. C. Karcher	Geophysical Service Inc.
2,096,359	Apparatus for Subsurface Surveying	D. G. Hawthorn	Geophysical Research Corp.
2,150,169	Method and Apparatus for Continuous Exploration of Bore Holes	J. J. Jakosky	

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,151,201	Thermostatic Control for Fluid Meters	C. P. Griffith	S. F. Bowser & Co.
2,153,802	Method and Apparatus for Continuous Exploration of Bore Holes	J. J. Jakosky	
2,161,256	Apparatus for Determining the Hardness of Subsurface Formations	J. C. Karcher	Geophysical Service Inc.
2,181,601	Method and Apparatus for Continuous Exploration of Bore Holes	J. J. Jakosky	
2,189,900	Drill Stem Circuit Tester	D. G. Hawthorn, et al	Geophysical Research Corp.
2,196,314	Method of Measuring the Inherent Terrestrial Magnetism of the Earth's Crust	R. E. Lee	Joseph H. Reynolds
2,197,392	Drill Stem Section	D. G. Hawthorn	Geophysical Service Corp.
2,208,147	Photoelectric Inclinator	J. D. Eisler	Stanolind Oil & Gas
2,214,786	Apparatus for Logging Holes While Drilling	B. P. Bishop	
2,230,999	Method of Indicating Spontaneous Potentials in Shallow Wells	H. G. Doll	Schlumberger
2,232,360	Apparatus for Surveying Bore Holes	A. R. Barnett	Technical Oil Tool Corp.
2,247,417	Electrical Logging	D. Silverman, et al	Stanolind Oil and Gas Co.
2,249,769	Electrical System for Exploring Drill Holes	E. G. Leonardon	Schlumberger
2,255,721	Well Control Device	H. W. Mattingly, et al	
2,295,829	Vibration Dampener	B. G. Carlson	Weatherhead Co.
2,300,827			

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,309,877	Device for Determining Inclination of Well Bores	D. H. Weinstein, et al	Cooperative Development Co.
2,310,611	Electrical Exploration of Geological Strata	E. E. Blondeau	Geophysical Research Corp.
2,313,384	Mean for Determining the Tectonics and Nature of Subsurface Geology	R. E. Lee	Joseph H. Reynolds
2,329,732	Signaling Deviation Detector	F. M. Varney, et al	
2,337,296			
2,339,274	Electrical Connecting Means for Well Bore Apparatus	G. L. Kothny	Sperry-Sun Well Surveying Co.
2,345,766	Deflecting Tool	L. C. Miller	Eastman Oil Well Survey Co.
2,352,219	Vibration Measuring System	R. C. Olesen	Consolidated Engineering Corp.
2,352,833	Choke Valve Borehole Indicating System	G. L. Hassler	Shell Develop. Co.
2,354,887	Well Signaling System	D. Silverman, et al	Stanolind Oil and Gas Co.
2,354,957	Electrical Surveying	N. Douglas	Stanolind Oil and Gas Co.
2,365,999	Bore Hole Inclinator	F. G. Boucher	Standard Oil Develop. Co.
2,370,188			
2,370,818	Well Measurements	D. Silverman	Stanolind Oil and Gas Co.
2,379,800	Signal Transmission System	D. G. C. Hare	The Texas Co.
2,379,996	Transmitting System	D. Silverman	Stanolind Oil and Gas Co.
2,380,520	Borehole Indicating Apparatus	G. L. Hassler	Shell Develop. Co.
2,388,141	Electrical Logging Apparatus	G. G. Harrington	Reed Roller Bit Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,398,241	Well Logging	D. Silverman	Stanolind Oil and Gas Co.
2,400,170	Time Cycle Telemetering	D. Silverman	Stanolind Oil and Gas Co.
2,406,859	Communication in Pipe Lines	E. W. Smith	Submarine Signal Corp.
2,407,299	Communication in Pipe Lines	E. W. Smith	
2,408,001	Gain-Control System for Seismic Amplifiers	E. J. Shimak, et al	Secony-Vacuum Oil Company
2,411,696	Well Signaling System	D. Silverman, et al	Stanolind Oil and Gas Co.
2,414,719	Transmission System	R. T. Cloud	Stanolind Oil and Gas Co.
2,428,034	Electrical Propsecting Apparatus	C. R. Nichols, et al	Sperry-Sun Well Surveying Co.
2,435,934	Signalling Clinograph	F. M. Varney, et al	
2,436,563	Well Logging	A. Frosch	Standard Oil Develop. Co.
2,438,293	Means for Bottom Hole Operation	H. G. Livingston	Eastman Oil Well Survey Co.
2,438,518	Circuit for Measuring Voltage of an Alternating Source	R. G. Piety	Phillips Petroleum Co.
2,452,515	Method of Making Geophysical Explorations	L. F. Athy	Continental Oil Co.
2,479,518	Recording Apparatus for Correlating Measurements in Accordance with Depth	S. A. Scherbatskoy	
2,507,351	Transmitting of Information in Drill Holes	S. A. Scherbatskoy	Wells Survey Inc.
2,518,001			

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,524,031	Apparatus for Logging Wells	J. J. Arps	
2,539,618	Vibration Responsive Apparatus	W. A. Good, et al	U. S. Navy
2,544,569	Signaling System	D. Silverman	Stanolind Oil and Gas Co.
2,557,168	Continuous Electric Logging While Drilling	J. J. Arps, et al	
2,568,241			
2,568,441	Apparatus for Logging	P. W. Martin	
2,569,390	Well Logging	B. W. Sewell	Standard Oil Develop. Co.
2,572,332	Apparatus for Determining Angular Positions of Objects in Wells	J. S. Goodwin, P. Campbell	
2,584,983	Centrifugally Operated Switch	G. J. Butterworth	Sperry-Sun Well Surveying Co.
2,627,392	Control Circuit	W. L. Morris	Phillips Petr.
2,650,067	Apparatus for Logging Wells While Drilling	P. W. Martin	
2,658,284	Continuous Directional Drilling	J. J. Arps	
2,658,728	Warning System for Controlled Rotary Drilling	J. J. Arps	
2,658,725	Signal Transmission System for Use in Logging Drill Hole Formations	J. J. Arps	
2,659,046	Geophysical Exploration Using Radioactive Material	J. J. Arps	
2,677,790	Borehole Logging by Intermittent Signaling	J. J. Arps	

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,679,757	Apparatus for Recording Subsurface Measurements	C. H. Fay	Shell Develop. Co.
2,681,567	System for Obtaining and Transmitting Measurements in Wells During Drilling	M. B. Wides	Stanolind Oil and Gas Co.
2,700,131	Measurement System	R. M. Otis, et al	Lane-Wells Co.
2,700,897	Continuous Electrical Logging	J. J. Arps	
2,706,616	Conductor Line Jar	D. W. Osun	
2,728,893	Flowmeter	J. A. Bartelink	National Luchtvanrilaboratorium
2,732,518	Bore Hole Detecting Circuit and Bore Hole Firing Circuit Utilizing a Common transmission Channel	J. M. Bricaud	Borg-Warner Corp.
2,748,358	Combination Oil Well Tubing and Electrical Cable Construction	D. S. Johnston	Signal Oil and Gas Co.
2,755,067	Method and Apparatus For Insulating a Drillstem in Continuous Exploration of a Bore Hole	S. H. Williston	Sperry-Sun Well Surveying Co.
2,755,431	Logging While Drilling	S. A. Scherbatskoy	
2,755,432	Logging While Drilling	J. J. Arps, et al	
2,759,143	Earth Borehole Investigation Signaling System	J. J. Arps	
2,762,132	Signaling Drift Indicator	J. A. Varney	
2,775,887	Load Cell Type Dynamometer With Overload Protection Means	F. F. Hines	Baldwin-Lima-Hamilton Corp.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,775,889	Torque Determining Method	E. L. Decker	Martin-Decker Corporation
2,780,438	Device for Drilling Wells	Q. J. Bielstein	Esso Research & Eng. Co.
2,787,759	Apparatus for Logging Wells	J. J. Arps	
2,791,398	Core Signalling Device	W. M. O'Reilly, et al	Esso Research & Eng. Co.
2,795,134			
2,806,139	Pulse Reshaper	B. M. J. LeClerc	Compagnie Des Machines Bull
2,810,546	Drill Tool Telemetering System	B. G. Eaton, W. W. Boynton	
2,851,785	Inclinometer	A. L. Gaudin	Jersey Prod. Research Co.
2,859,013	Borehole Logging Signaling System	E. W. Peterson	Dresser Ind. Inc.
2,866,896	Pulse Converting Circuit	R. A. Stampfl	U.S.A. (Army)
2,876,434	Indicating and Control System	L. M. Oberlin	Phillips Petroleum Co.
2,877,646	Dynamometer	H. J. Dudenhausen	Intavex Inc.
2,887,298	Well Bore Inclinometer	H. D. Hampton	
2,890,019	Earth Borehole Logging System	J. J. Arps	
2,898,088	Earth Borehole Logging System	R. L. Alder	Dresser Industries Inc.
2,901,685	Apparatus for Earth Borehole Investigating and Signaling	R. L. Alder	Dresser Industries Inc.
2,905,885	Generator Voltage Regulator	D. A. Burt et al	Westinghouse Electric Corp.
2,910,133	Method of Continuous Well Logging During Drilling	R. B. Hudson, et al	

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,917,704	Earth Formation Logging System	J. J. Arps	
2,924,432	Earth Borehole Logging System	J. J. Arps	
2,925,251	Earth Well Borehole Drilling and Logging System	J. J. Arps	
2,930,137	Earth Borehole Crookedness Detection and Indication	J. J. Arps	
2,933,144	Well Logging Method and	J. G. Scott,	American Percussion Tool Co.
2,938,708	Simultaneous Drilling and Electrical Logging of Hydro-Carbon Contents of Formation	J. J. Arps	
2,940,039	Well Bore Electrical Generator	L. Yost, et al	Calif. Research Corp.
2,941,784	Logging While Drilling	J. L. Martin	The Atlantic Refining Co.
2,949,544	Switching Apparatus	E. R. Hill, et al	Westinghouse Electric Co.
2,957,159	Measuring Device	J. Fitchette	Phillips Petroleum Co.
2,958,511	Earth Borehole Drilling Apparatus and System	G. H. Pfefferle	Dresser Industries Inc.
2,958,821	Turbo Drill Tachometer	D. L. Webb	Dresser Industries Inc.
2,964,116	Signaling System	E. W. Peterson	Dresser Industries Inc.
2,973,471	Analysis Techniques Based on Nuclear Magnetic	F. C. Armistead, et al	Texaco Develop. Corp.
2,976,520	Matrix Selecting Net Work	W. A. Reenstra	Bell Telephone Laboratories
2,978,634	Apparatus for Logging Wells	J. J. Arps	

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
2,985,829	Method and Apparatus for Determining Drill Bit Speed	G. Swift	Dresser Industries Inc.
3,007,134	Remote Telemetry and Recording System	R. H. Kolb	Shell Oil Co.
3,007,534	Electric Cable Drum for Rotary Drilling	I. S. Salnikov, et al	Jersey Prod. Research Co.
3,009,255	Horizon Indicating System	J. J. A. Robillard	Motorola Inc.
3,014,282	Inclinometer	E. B. Wise	Shell Oil Co.
3,015,801	Drill Pipe Module Data Collection and Transmission System	D. C. Kalbfell	
3,016,963	Apparatus for Bore Hole Drilling and Logging	J. D. Bennett, et al	Sun Oil Co.
3,037,295	Process and Means for Determining Hole Direction in Drilling	B. J. Roberson	Alvin R. Allison
3,046,474	Bore Hole Logging System and Method	J. J. Arps	Arps Corp.
3,047,794	Bore Hole Logging Methods and Apparatus	J. Bennett, et al	Sun Oil Co.
3,047,795	Bore Hole Logging Methods and Apparatus	J. M. Pearson	Sun Oil Co.
3,047,796	Bore Hole Logging Methods and Apparatus	J. Bennett, et al	Sun Oil Co.
3,052,309	Apparatus for Orienting Well Drilling Equipment	H. J. Eastman	Eastman Oil Well Survey Co.
3,052,838	Bore Hole Logging Apparatus	J. Bennett, et al	Sun Oil Co.
3,058,532	Drill Bit Condition Indicator and Signaling System	R. L. Alder	Dresser Industries Inc.
3,062,052	Apparatus for Measuring Variable Physical Conditions Employing a Sensing Device Generating a Variable Frequency Signal	R. H. Kolb	Shell Oil Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,062,302	Indicator Device for Bearing Failures in Drill Bits	F. J. Toth, et al	Shell Oil Co.
3,065,404	Bore Hole Logging Apparatus	F. M. Mayes, et al	Sun Oil Co.
3,065,406	Bore Hole Logging Apparatus	F. M. Mayes	Sun Oil Co.
3,071,689	Nuclear Measuring System	S. A. Scherbatskoy	
3,072,843	Abrasion Resistance Coating Suitable for Borehole Drilling Apparatus	R. J. Clements,	Texaco Inc.
3,074,493	Apparatus for Bore Hole Drilling and Logging	J. D. Bennett	Sun Oil Co.
3,077,233	Bore Hole Declinometer	A. P. Armstrong	
3,078,922	Apparatus for Controlling the Movement of a Tool Through a Tubular Structure	J. D. Bennett	Sun Oil Co.
3,079,549	Means and Techniques for Logging Well Bores	Philip W. Martin	
3,086,167	Bore Hole Logging Methods and Apparatus	P. E. Chaney, et al	Sun Oil Co.
3,090,031	Signal Transmission System	A. H. Lord	Texaco, Inc.
3,103,625	Bore Hole Logging Apparatus Providing a Pulse Space Modulated Record	F. M. Mayes	Sun Oil Co.
3,103,643	Drill Pipe Module Transmitter Transducer	D. C. Kalbfell	
3,103,644	Plural Channel Time Sharing Multiplex System	R. G. Burton	Well Surveys Inc.
3,104,809	Directional Survey Computer	G. Swift	Dresser Industries Inc.
3,105,194	Timing Recovery Circuit	M. A. Rappeport	Bell Telephone Laboratories Inc.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,112,422	Photo-Electric Cell for the Automatic Exploring of Curves		
3,115,774	Magnetostrictive Drill String Logging Device	R. H. Kolb	Shell Oil Co.
3,115,942	Method of Earth Borehole	J. J. Arps	Arps Corp.
3,123,939			
3,134,069	Well Logging Apparatus Having Detector Means in a Rotable Casing Mounted Within a Drill String for Simultaneous Drilling and Logging	R. J. Clements, et al	Texaco Inc.
3,141,126	Motion Detection Apparatus and Method for Use in Bore Hole Logging	J. D. Bennett,	Sun Oil Co.
3,141,126			
3,141,127	Bore Hole Logging Apparatus with Means for Providing a Pulse Space Modulating Record of Detecting Potentials	F. M. Mayes	Sun Oil Co.
3,149,277	Borehole Logging Apparatus Including Flexible Detector and Weighing Means	J. D. Bennett, et al	Sun Oil Co.
3,149,490	Well Logging Apparatus	R. J. Clements, et al	Texaco Inc.
3,149,683	Geophysical Prospecting Apparatus	R. J. Clements, et al	Texaco Inc.
3,150,321	Buried Pipe Communication System Utilizing Earth Polarization Phenomenon	H. C. Summers	Harvest Queen Mill & Elevator Co.
3,158,923	Method for Making a Seal and Coupling Assembly	H. L. Reinsma	Caterpillar Tractor Co.
3,163,816	Geophysical Prospecting Apparatus with Fluid Operated Electrical Generator for Logging While Drilling	R. J. Clements,	Texaco Inc.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,170,137	Method of Improving Electrical Signal Transmission in Wells	H. Brandt	California Research Corp.
3,176,407	Drift Indicator	R. L. Alder, et al	Varney Eng. Corp.
3,180,034	Drill Hole Indicator	G. McDonnell	
3,182,735	Method and Means for Locating Subsoil Formations During Drilling	G. Bartolini Salimbeni, et al	
3,184,698	Drill String Transmission Circuit	R. H. Kolb, et al	Shell Oil Co.
3,186,222	Well Signaling System	P. W. Martin	McCullough Tool Co.
3,187,301	Telemetry System for Use in Borehole Logging to Control Downhole Tool From Surface	G. C. Summers	PGAC Develop. Co.
3,189,881	Pulse Producing Means	T. R. Reinhart	Shell Oil Co.
3,195,660	Drilling Bit	G. M. McKown	
3,205,447	Pulse Detector	G. L. Richards	General Dynamics Corp.
3,209,323	Information Retrieval System for Logging While Drilling	G. J. Grossman, Jr.	Texaco Inc.
3,219,971	Method and Apparatus for Maintaining Phase Relation	J. R. Cole	Continental Oil Co.
3,223,184	Bore Hole Logging Apparatus	J. W. Jones, et al	Sun Oil Co.
3,227,945	Borehole Logging Apparatus Including Means for Producing a Pulse Time Modulated Linear Record	Fred M. Mayes, et al	Sun Oil Co.
3,227,946	Borehole Logging Apparatus of the Focussed Current Type for Providing a Pulse Space Modulated Record	F. M. Mayes	Sun Oil Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,233,214	Apparatus for the Production of Bore Hole Logs	J. Bennett, et al	Sun Oil Co.
3,237,093	Bore Hole Logging Apparatus Having Rate of Descent Controlling Means and a Flexible Cable Member Carrying a Detector Element	J. Bennett, et al	Sun Oil Co.
3,237,153	Detection of Acoustic Signals	R. B. Blizzard	Schlumberger
3,252,225	Signaling Generator Indicating Vertical Deviation	E. L. Hixson	Ed White
3,253,245	Electrical Signal Transmission for Well Drilling	H. Brandt	Chevron Research
3,255,353	Apparatus for Nuclear Well Logging While Drilling	S. A. Scherbatskoy	
3,268,801	Apparatus Having a Pair of Spaced Electrodes for Measuring Spontaneous Potentials in a Well Bore While Drilling	R. J. Clements, et al	Texaco
3,274,694	Apparatus for Measuring the Azimuth and Inclination of a Borehole	A. B. Hildebrandt	Esso Prod. Research Co.
3,275,983	Ultrasonic Inclination Meter	Tetsuichi Kaneko	Oyo Chishitsu Co. Ltd.
3,285,629	Methods and Apparatus for Mounting Electrical Cable in Flexible Drilling Hose	R. H. Cullen, et al	Roy H. Cullen
3,293,542	Electrical Well Logging Apparatus Including a Drill Collar Having Spaced Electrodes Mounted Thereon for Making Resistivity Measurements While Drilling	R. G. Piety	Phillips Petroleum Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,302,457	Method and Apparatus for Telemetering in a Bore Hole by Changing Drilling Mud Pressure	F. M. Mayes	Sun Oil Co.
3,303,573	Binary Position Indicator	J. A. Varney, et al	
3,305,771	Inductive Resistivity Guard Logging Apparatus Including Toroidal Coils Mounted on a Conductive Stem	J. J. Arps	Arps Corp.
3,305,771			
3,305,825	Telemetering Device and System for Pumping Wells	J. K. Godbey	Mobil Oil Corp.
3,309,656	Logging-While-Drilling System	J. K. Godbey	Mobil Oil Corp.
3,316,651	Inclinometers	J. K. Godbey	
3,320,803	Self-Contained Well Logging Apparatus with Magnetic Storage of Information	A. H. Lord	Texaco Inc.
3,324,717	System and Method for Optimizing Drilling Operations	W. B. Brooks, et al	Mobil Oil Corp.
3,327,230	Regenerator	R. Konian	Radio Corp. of America
3,327,527	Fluid Temperature Logging While Drilling	J. J. Arps	Arps Corp.
3,333,239	Subsurface Signaling Technique	D. Silverman	Pan American Petroleum Corp.
3,340,500	System with Electrical Utilization Device Having Main Energization Conductors over which Information Signals are also Transferred	C. A. Boyd, et al	Borg-Warner Corporation
3,345,867	Method and Apparatus for Measuring Rock Bit Wear While Drilling		

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,346,067	System for Determining Acoustic Reflection Coefficients	M. R. Schroeder	Bell Telephone Laboratories
3,353,612	Method and Apparatus for Exploration of the Water Bottom Regions	C. B. Bannister	
3,363,702	Rock Bit Dullness Indicator	W. J. Bielstein	Esso Production Research Co.
3,376,921	Completion of Wells	C. W. Manry, et al	Esso Production Research Co.
3,377,549	Coil Assembly Structure and Mounting Forming on Annular Chamber to be Mounted and Sealed on a Drill Collar	J. L. Newman, et al	Arps Corp.
3,385,392	Ultrasonic Siren Applied on Seagoing Ships for Defogging the Ranges of Vision	M. Vios	
3,387,599	Vacuum Indicating Device	J. T. Cruse	Atlantic Richfield Co.
3,407,886	Apparatus for Wellbore Telemetry	J. D. Bennett	Sun Oil Co.
3,408,561	Formation Resistivity Measurement While Drilling Utilization Physical Conditions Representative of the Signals from a Toroidal Coil Located Adjacent the Drilling Bit	F. H. Redwin, et al	Arps Corp.
3,427,580	Electrical Methods and Apparatus for Well Tools	G. W. Brock	Schlumberger Technology Corp.
3,431,654	Signalling Orientation Indicator	R. L. Alder	Byron Jackson Inc.
3,440,730	Centrifugally Controlled Signalling Drift Apparatus	R. L. Alder	Byron Jackson Inc.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,448,612	Method of and Apparatus for Transmitting Information From a Subsurface Well Tool to the Earth's Surface	M. P. Lebourg	Schlumberger Technology Co.
3,455,158	Logging While Drilling System	A. P. Richter, Jr., et al	Texaco Inc.
3,457,654	Pendulum Release System for Signalling Drift indicator	R. L. Alder	Byron Jackson Inc.
3,465,582	Bore Hole Logging System	A. P. Richter, Jr., et al	Texaco Inc.
3,465,834	Guided Subterranean Penetrator Systems	H. Southworth, Jr.	Bell Telephone Laboratories
3,466,597	Logging While Drilling System	A. P. Richter, Jr., et al	Texaco Inc.
3,466,755	Mainspring Force Transfer Means for Signaling Drift Indicator	R. L. Alder	Byron Jackson Inc.
3,471,936	Apparatus for Measuring the Spherical Coordinates of a Luminous Point	R. Jean-Baptiste Clavet	Société d'Applications Générales d'Electricité et de Mécanique
3,475,722	Method and Apparatus for Acoustic Core Hole Logging Using Acoustic Signals of Controlled Direction	J. E. White	Marathon Oil Co.
3,486,375	Apparatus for Lithologic Logging of Underground Formations by Acoustic Vibrations	F. H. Redwine, et al	Core Laboratories Inc.
3,488,629	Pressure Wave Noise Filter with Reflection Suppression	J. R. Claycomb	Schlumberger Technology Corp.
3,498,393	Well Control Method	A. G. West, et al	W & H Production Drilling Inc.
3,518,608	Telemetry Drill Pipe with Thread Electrode	M. N. Papadopoulos	Shell Oil Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,518,699			
3,520,375	Method and Apparatus for Measuring Mechanical Characteristics of Rocks While They are Being Drilled	J. Raynal, et al	Societe Nationale des Petroles d'Aquitaine
3,526,285	Angularly Adjustable Auger Head	D. E. Adkins, et al	American Gas Association Inc.
3,555,504	Pressure Wave Noise Filter	Roger Q. Fields	Schlumberger Technology Corp.
3,571,936	High or Low Fluid Flow Signalling Apparatus	Raymond G. Taylor, Jr.	Byron Jackson Inc.
3,581,564	Method for Detecting Roller Bit Bearing Failure	Farrile S. Young, Jr.	Esso Production Research Co.
3,588,804	Telemetry System for Use in Boreholes	Jacob Robert Fort	Globe Universal Science Inc.
3,588,908	Borehole Instrument	James M. Lindsey	Sperry-Sun Well Surveying Co.
3,593,810			
3,603,923	Signaling System	William B. Nelligan	Schlumberger Technology Corp.
3,627,356	Directional Drilling Apparatus with Retrievable Limiting Device	Edwin A. Anderson	
3,633,688	Torsional Rectifier Drilling Device	Albert G. Bodine	
3,635,081	Diagnostic Method for Subsurface Hydraulic Pumping Systems	Sam G. Gibbs	Shell Oil Co.
3,659,259	Method and Apparatus for Telemetry Information through Well Bores	Preston E. Chaney, Jr., et al	Halliburton Co.
3,668,926	Apparatus for Indicating Torque Applied to Pipe Rotated by Rotary Table	Leo A. Bell	Shell Oil Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,673,559	Pulse Resolution System	Robert J. Schwartz	Schlumberger Technology Corp.
3,675,113	System for the Generation of Electrical Power Having a Spring Powered Prime Mover Responsive to Output Voltage	Clifford J. Bader	Burroughs Corp.
3,682,262	Oil Well Drilling Apparatus	William Guier	
3,686,942	Drilling Column Comprising a Device for Measuring Stresses Exerted on the Column	Michael Chatard, et al	Institut Francais du Petrole, des Carburants et Lubrifiants
3,691,363	Method and Apparatus for Bore Hole Directional Logging	Fontaine C. Armistead	Texaco Inc.
3,693,428	Hydraulic Control Device for Transmitting Measuring Values from the Bottom of a Well to the Surface as Pressure Pulses through the Drilling Mud	Jean Pierre Le Peuvedic, et al	
3,696,332			
3,697,940	Signaling System for Bore Logging	Bohdan Jiri Berka	
3,699,510	Borehole Data Transmission System	James M. Lindsey	Sperry-Sun Well Surveying Co.
3,700,049	Device for Connecting a Drill Bit to a Drill String Provided with a Penetrometer	Wladimir Tirosposky, et al	Institut Francais du Petrole, des Carburants et Lubrifiants
3,703,096	Method of Determining Downhole Occurrences in Well Drilling Using Rotary Torque Oscillation Measurements	Albert L. Vitter, Jr., et al	Chevron Research Co.
3,704,406	Gyro Servo Control System and Structure	James M. Lindsey	Sperry-Sun Well Surveying Co.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,704,407	Gyro Servo Control System and Structure	James M. Lindsey	Sperry-Sun Well Surveying Co.
3,705,603	Drive Train for Logging While Drilling Tool	Daniel E. Hawk	Mobil Oil Co.
3,711,825	Data-Signaling Apparatus for Well Drilling Tools	Jackson R. Claycomb	Schlumberger Technology Corp.
3,713,089	Data-Signaling Apparatus for Well Drilling Tools	Jackson R. Claycomb	Schlumberger Technology Corp.
3,713,500	Drilling Devices	Michael King Russell	
3,714,831	Device for Suspending Measuring Instruments Inside Drilling Assembly	Claude Quichaud, et al	Societe Nationale des Petroles d'Aquitaine
3,716,830	Electronic Noise Filter With Hose Reflection Suppression	D. J. Garcia	Schlumberger Technology Corp.
3,718,194	Method and Apparatus for Orienting a Borehole Device	D. R. Hering, et al	Sperry-Sun Well Surveying Co.
3,719,239	Up-Hole Signaling Device	Albert P. Richter	Texaco Inc.
3,736,558	Data-Signaling Apparatus For Well Drilling Tools	Walter E. Cubberly, Jr.	Schlumberger Technology Corp.
3,732,728	Bottom Hole Pressure and Temperature Indicator	J. R. Fitzpatrick	Fitzpatrick, Dawson, Tyler
3,737,843	Hydraulically Controlled Device for Modulation the Mud	J. P. LePeuvidic, C. Quichaud	Societe Nationale des Petroles d'Aquitaine
3,742,443		B. J. Patton, et al	Mobil Oil Corp.
3,743,034	Steerable Drill String	Wm. B. Bradley	Shell Oil Co.
3,753,296	Well Mapping Apparatus and Method	D. E. Van Steenwyk	Applied Technology Association
3,764,968	Well Bore Data Transmission Apparatus with Debris Clearing Apparatus	Ronald A. Anderson	Schlumberger Technology Corp.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,764,969	Well Bore Data Transmission Apparatus with Debris Clearing Apparatus	Walter E. Cubberly, Jr.	Schlumberger Technology Corp.
3,764,970	Well Bore Data Transmission Apparatus with Debris Clearing Apparatus	Kenneth G. Manning	Schlumberger Technology Corp.
3,770,006	Logging-While-Drilling Tool	James H. Sexton	Mobil Oil Corp.
3,771,118	Borehole Orientation Tool	Henry P. Lichte, Jr., et al	Sperry-Sun Well Surveying Co.
3,776,032	Method and Appartus for Detecting an Inflow of Fluid into a Well	Charles B. Vogel	Shell Oil Co.
3,777,560	Method and Apparatus for Measuring the Rate of Penetration in Well Drilling	Jean-Hubert Guignard	Schlumberger Technology Corp.
3,786,413			
3,789,355	Method of and Apparatus Logging While Drilling	Bobbie J. Patton	Mobil Oil Corp.
3,789,510	Borehole Deviation Measurement While Drilling	Albert P. Richter, Jr. et al	Texaco Inc.
3,789,936	Method and Apparatus for Simultaneously Drilling and Logging	Ira J. McCullough	
3,790,930	Telemetry System for Oil Wells	Arthur E. Lamel, et al	American Petrosience Corporation
3,792,428	Method and Apparatus for Controlling the Downhole Acoustic Transmitter of a Logging While Drilling System	John W. Harvell, et al	Mobil Oil Co.
3,792,429	Logging-While-Drilling Tool	Bobbie Joe Patton, et al	Mobil Oil Corp.
3,793,632	Telemetry System for Drill Boreholes	W. L. Still	

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,800,277	Method and Apparatus for Surface-to-downhole Communication	Bobbie J. Patton, James H. Sexton, John W. Harrell	Mobil Oil Corp.
3,801,816			
3,805,606	Method and Apparatus for Transmission of Data from Bit in Wellbore While Drilling	Roland B. Stelzer, et al	Texaco, Inc.
3,807,502	Method for Installing an Electric Conductor in a Drill String	Joe K. Heilhecker, et al	Esso Production Research Co.
3,813,656	Methods and Apparatuses for Transmission of Longitudinal and Torque Pulse Data From Drill String in Well While Drilling	Joe R. Fowler	Texaco Inc.
3,818,319	Regulator Turn-on Overshoot Elimination	John W. Harrell, et al	Mobil Oil Corp.
3,820,063	Logging-While-Drilling Encoder	James H. Sexton, et al	Mobil Oil Corp.
3,825,079	Method for Mounting an Electric Conductor in a Drill String	Joe K. Heilhecker	Esso Production Research Co.
3,837,223	Method and Apparatuses for Transmitting Data Up a Drill String	A. P. Richter, Jr. W. R. McEvers	Texaco Inc.
3,845,837	Gravity Force Operated Apparatuses for Generation of Longitudinal Pulse Data From the Bottom of a Well	W. R. McEvers, P. T. Cox, A. P. Richter, Jr.	Texaco Inc.
3,860,902	Logging Method and System	E. M. Galle	Hughes Tool Co.
3,860,960	Magnetic Recording and Reproducing Apparatus with Tape Extraction	Takenori Akamine	Matsushita Electric Industrial Co.
3,863,203	Method and Apparatus for Controlling the Data Rate of A Downhole Acoustic Transmitter in a Logging-While-Drilling System	B. J. Patton, et al	Mobil Oil Corp.

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
3,865,201	Acoustic Emission in Drilling Wells	E. L. Haden	Continental Oil Co.
3,866,678	Apparatus for Employing a Portion of an Electrically Conductive Fluid Flowing in a Pipeline as an Electrical Conductor	John D. Jeter	Texas Dynamics, Inc.
3,867,714	Torque Assist for Logging-While-Drilling Tool	B. J. Patton	Mobil Oil Corp.
3,879,097	Electrical Connectors for Telemetering Drill Strings	Don H. Oertle	Continental Oil Co.
3,886,495	Uphole Receiver for Logging While-Drilling System	B. J. Patton	Mobil Oil Corp.
3,896,667	Method and Apparatus for Actuating Downhole Devices	John D. Jeter	Texas Dynamics, Inc.
3,904,840			
3,949,354	Apparatus for Transmitting Well Bore Data	J. R. Claycomb	Schlumberger Technology
3,964,558	Fluid Activated Downhole Drilling Device	S. F. Fagle	Texas Dynamics
3,967,201	Wireless Subterranean Signaling Method	Louis H. Rorden	Develco Inc.
3,968,473	Weight-on-Bit and Torque - Measuring Apparatus	B. J. Patton, et al	Mobil Oil Corp.
3,68,844	Determining the Extent of Entry of Fluids into a Borehole During Drilling	H. C. Walther, Jr. and G. M. Myers	Continental Oil Co.
3,992,928	Measuring the Strength of a Rock Formation in situ.	R. L. Thomas	

APPENDIX III

NON U. S. PATENTS RELATING TO
DOWNHOLE MEASUREMENTS WHILE DRILLING

The following is a list of non-U.S. patents relating to downhole measurements while drilling obtained from a limited search of foreign patent literature. This list should provide a guide to some of the important patents and perhaps a basis for more exhaustive patent review.

FOREIGN PATENTS

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
<u>FRANCE</u>			
1,498,615	A New Process for Transmitting Information To the Surface of the Ground From the Lower End of a Drill String and Apparatus For Application of This Process	F. Besnard, et al	Soc. Nat'l. Petr. Aquitaine
1,584,951	A New Method for Geologic Control of Drilling	M. Guy	Inst. Francais du Petrole
1,590,327	Process for Instantaneous Logging During Drilling and Apparatus for its Application	C. Quichaud, et al	Soc. Nat'l. Petr.
2,096,920	Automatic Hydraulic Control Apparatus for the Transmission of Measurements Made at the Bottom of a Borehole	C. Quichaud, J. P. LePeuvedic	Soc. Nat'l. Petr.
<u>GREAT BRITAIN</u>			
1,316,617	Method and Apparatus for Improving Signal-To-Noise Ratio in a Closed Fluid System	-	Mobil Oil Corporation
<u>WEST GERMANY</u>			
1,224,678	Apparatus for Transmitting Signals	B. A. Gratschew, et al	USSR Agency
P24,16,063	Cableless Transmission of Data from Deep Drilling Holes	E. Krebs	
<u>PORTUGAL</u>			
51,330	Procedure for Measuring the Mechanical Characteristics of Rocks During Drilling	-	Soc. Nat'l. Petr. Aquitaine

<u>PATENT NO.</u>	<u>TITLE</u>	<u>INVENTOR</u>	<u>ASSIGNEE</u>
<u>U.S.S.R.</u>			
150,952	Device for Logging Boreholes During Drilling	I. K. Sarkiso	-
205,981	Arrangement for Geo-physical Investigation in Drilling Wells	I. K. Sarkisov, et al	-
221,606	Arrangement for Well Logging During Drilling	I. K. Sarkisov, S. G. Komarov	-
221,608	Oscillator for Automatic Logging Station	V. M. Denikin, B. A. Malin	-
224,438	Arrangement for Mounting Well Logging Instruments	A. Kh. Siraev, et al	-
226,739	Arrangement for Well Logging During Drilling	A. A. Popov, et al	-
233,516	Arrangement for Logging During Drilling	N. I. Karabanov, et al	-
235,631	Arrangement for Geophysical While Drilling	I. K. Sarkisov	-
240,626	Pickup System for Remote Control of an Automatic Device	I. K. Sarkisov	-
251,102	Turbogenerator Apparatus For Well Testing During Drilling Process	I. K. Sarkisov, A. I. Talalyan	-
<u>CANADA</u>			
978,176	Method and Apparatus for Simultaneously Drilling and Logging	Ira J. McCullough	-