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Report of the Workshop on Advanced Geothermal Drilling and Completion Systems

Samuel G. Varnado, Editor

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REPORT OF THE WORKSHOP ON ADVANCED GEOTHERMAL DRILLING AND COMPLETION SYSTEMS

SAND79-1195

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Abstract

This report summarizes the discussions, conclusions, and recommendations of the Workshop on Advanced Geothermal Drilling and Completion Systems which was held in New Orleans, Louisiana, January 9-11, 1979. The purpose of the workshop was to identify new drilling and completion systems that have the potential for significantly reducing the cost of geothermal wells, and to provide recommendations to Sandia Laboratories and the Department of Energy as to the research and development tasks that are required to develop these advanced systems.

Participants in the workshop included representatives from private industry, universities, and government who were organized into four working groups as follows: Rock Drilling Technology, Surface Technology, Borehole Technology, and Directional Drilling Technology.

The Panel on Rock Drilling Technology was charged with identifying advanced concepts for breaking rock that could result in instantaneous penetration rates three to five times higher than those of conventional rotary drilling. Three systems were recommended for investigation and subsequent development; namely, high speed downhole motor systems, percussion drilling systems, and high pressure jet drilling systems.

The Panel on Surface Technology discussed improvements in surface equipment and operating procedures that could contribute to reduced well costs. Topics for discussion included fluid and pipe handling systems, instrumentation, training, and equipment required to support advanced drilling systems. It was recommended that high priority be given to the development of improved drilling fluids and fluid handling equipment that would lead to reduced corrosion in drill pipe and casing. Pipe inspection equipment and rig instrumentation for automatic control of the drilling operation were also recommended for investigation.

The Panel on Borehole Technology discussed problems associated with establishing and maintaining a stable borehole for the long-term production of geothermal wells. Topics included in these discussions were drill string design, drilling fluids, lost circulation control, and casing design. Major recommendations included investigations of the chemical and physical behavior of non-bentonitic clays and clay morphology at high temperature; the development of low density, high temperature cements; investigations of casing failure mechanisms; and the development of sealing materials, plugging agents, and mechanical techniques for lost circulation control.

The Panel on Directional Drilling Technology addressed problems encountered in drilling deviated wells in geothermal reservoirs. Recommendations included the development of high temperature downhole motors, high speed bits, techniques for kicking-off in hard rock, and high temperature instrumentation for measuring directional parameters.

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ACKNOWLEDGMENT

The editor wishes to acknowledge the contribution and support of H. M. Stoller, Manager, Geo Energy Technology Department, Sandia Laboratories; and Clifton Carwile, Chief, Advanced Systems Branch, Department of Energy, Division of Geothermal Energy; in organizing and conducting this meeting. A special note of thanks is extended to George Suman, President, Completions Technology Company, for serving as the overall workshop chairman.

EXECUTIVE SUMMARY

I. Introduction

The cost of drilling and completing geothermal wells is currently two to four times that of conventional oil and gas wells of comparable depths. These higher costs occur because of temperature, formation, erosion, and corrosion effects that are found in drilling in geothermal reservoirs. The Division of Geothermal Energy (DGE) of the U.S. Department of Energy (DOE) is funding the development of improved techniques for drilling and completing geothermal wells with the goal of increasing the amount of geothermal power-on-line by reducing well costs. Sandia Laboratories manages the Geothermal Drilling and Completion Technology Development Program for DOE/DGE. Specific programmatic goals are to develop the technology required to reduce geothermal well costs 25% by 1982 and 50% by 1986. Analysis of the costs of existing geothermal wells indicates that the 25% cost reduction goal can be achieved through improvements in conventional rotary drilling technology; however, achieving the 50% cost reduction goal will require the development of advanced drilling and completion systems. For the purpose of the discussions presented here, advanced systems are defined as those that go beyond incremental improvements in current rotary drilling systems.

To assist Sandia Laboratories and the Department of Energy in defining approaches to the development of the required advanced drilling and completion systems, a workshop was convened on January 9-11, 1979, in New Orleans, Louisiana. The workshop was sponsored by Sandia Laboratories and the DOE. The purpose of the workshop was to identify new drilling and completion systems that have the potential for achieving the 50% cost reduction goal. The workshop was also to provide recommendations to Sandia as to the research and development tasks that would be required to develop these advanced systems by 1986. To accomplish these objectives, representatives from private industry, universities, and government laboratories were invited to participate in the workshop. The first day of the workshop was spent in reviewing the current state-of-the-art in geothermal drilling. Then the participants were divided into four panels. These groups were as follows: Rock Drilling Technology, Surface Technology, Borehole Technology, and Directional Drilling Technology. On the second day of the workshop, the four groups met independently to discuss the present state-of-the-art in their respective areas and to discuss ideas and concepts which, if developed, would lead to significant well cost reductions. The third day of the workshop was spent in formulating written conclusions and recommendations which provided the basis for this report. At the end of the workshop, the individual panel reports were collected in rough draft form, and editing was performed by Sandia Laboratories to produce the final report.

In conducting the workshop, the participants were asked to formulate their recommendations with two constraints in mind. The first constraint was that the systems viewpoint should be used, e.g., there is little merit in developing a rock breaking technique that can drill rapidly if supporting surface equipment is not available or cannot be developed to implement the technique. The second constraint was that any proposed advanced system should have a high probability of being developed into a prototype system by 1986 within the funding constraints imposed by the DOE.

With these considerations in mind, the participants formulated the recommendations given in this report. Since the workshop had a significant number of participants from private industry, it is felt that the recommendations presented here are representative of current industry thinking as to the technology that needs to be developed and the Government role in this development. Each panel report contains a statement of the objectives of the panel, state-of-the-art assessments on present techniques for geothermal drilling, conclusions and findings, identification of R&D areas, and recommendations.

II. Panel on Rock Drilling Technology

The Panel on Rock Drilling Technology was assigned the task of identifying advanced techniques for breaking rock and determining which of these techniques have the potential for being developed by 1986 into an advanced drilling system that could lead to a geothermal well cost reduction of 50%. First, the temperature and pressure characteristics of geothermal reservoirs were described, then the questions of drillability and borehole stability of geothermal formations were described and discussed. Typical geothermal reservoirs exhibit temperatures of approximately 250°C. In general, the formations are hard, brittle, and highly permeable due to the fractured nature of the reservoir. Both diamond bits and roller cone bits have been used in geothermal drilling. The roller bits are limited in life because of bearing failure at the high temperatures encountered. Conventional diamond bits used in drilling and coring have had only limited success because of the short life obtained when drilling fractured igneous rock. With these limitations in mind, the discussions then moved to advanced techniques for breaking rock. It was recognized by the panel that in the past ten years over fifty million dollars have been spent on advanced drilling techniques. The techniques which have been investigated include: 1) thermal spalling, 2) melting and vaporization, 3) chemical reactions, and 4) mechanically induced stresses. Many of these techniques have demonstrated the ability to penetrate rock; however, when viewed from a systems perspective, which includes consideration of the surface equipment and the means for transmitting power to the rock breaking system, many of these previously investigated techniques could be eliminated from contention. Systems discussed included abrasive jet drilling, high pressure jet drilling, percussion drills, downhole motors and high speed bits, lasers, electron beams, rock melting drills, flame drills, electric arc drills, explosive drills, spark drills, and implosion drills. These discussions lead to the assignment of a probability estimate to each concept. This estimate, as shown in the following table, represents the panel's judgment as to the probability of the concept being developed into a prototype system by 1986 within the budget constraints set by the DOE. It was felt that instantaneous penetration rates of 3 to 5 times those of conventional drilling systems would have to be achieved in order for an advanced system to significantly reduce well costs. As indicated in this table, there are three systems that were assigned a high probability. These were: 1) high pressure (5000-15000 psi) jets used in conjunction with mechanical rock breaking schemes, 2) high speed downhole motors and bits, and 3) air- or water-driven percussion drills.

Drilling Technique	Power Transmission System			
	Hydraulic	Mechanical	Electrical	Chemical
1) Abrasive jet drilling				
a) Shot	None[1]	NA*	NA	NA
b) Recirculated cuttings	Low	NA	NA	NA
2) High pressure jets with no mechanical augmentation	None	NA	NA	NA
3) High pressure jets with mechanical augmentation				
a) Surface pressure 1000-5000 psi	Med	NA	NA	NA
b) Surface pressure 5000-15000 psi	High	NA	NA	NA
c) Surface pressure > 15000 psi	Low	NA	NA	NA
4) Percussion drill				
a) Air	High	Low	Low	Low
b) Fluid (water)	High	Low	Low	Low
c) Fluid (mud)	Med	Low	Low	Low
5) Downhole motors	High	NA	Low	NA
6) Laser	NA	NA	None[2]	None[2]
7) Electron beam	NA	NA	None[2]	NA
8) Flame	NA	NA	NA	None[3]
9) Subterrene	NA	NA	None	NA
10) Plasma	NA	NA	None	None
11) Electric Arc	NA	NA	None	NA
12) Explosive	NA	NA	NA	None[4]
13) Spark	NA	NA	Low[5]	NA
14) Impact	None	None	NA	NA
15) Implosion (pellets)	None	None	NA	NA

* NA -- technique not applicable with transmission system

1 Technique may be useful in long-term for hot dry rock drilling.

2 Some application for these techniques may be found in the very long term in kerf cutting; however, the probability that they could be used in deep drilling by 1986 is essentially none.

3 This technique has essentially no probability of being used in water filled holes.

4 This technique is limited in temperature capability.

5 Electrode life and insulating materials are the key problems.

PROBABILITY OF SIGNIFICANT CONTRIBUTION TO 50% COST REDUCTION GOAL BY 1986

The panel felt that the use of jet drilling without mechanical augmentation was not feasible in the near-term because of the very high pressures (> 15,000 psi) required to cut the hard rock found in geothermal reservoirs. The best use of jet drilling systems appears to be in conjunction with conventional bits, e.g., roller cone, polycrystalline diamond, or natural diamond bits. The panel felt that the jets should be positioned to cut kerfs in the bottom of the hole, thereby providing for easier mechanical breakage of the remaining rock by the conventional bit.

Downhole motors offer the potential for significantly increasing penetration rates in geothermal drilling provided high speed bits can be developed. The panel felt that hydraulically driven motors have a higher potential for successful development for the geothermal drilling application than electrically driven motors because of temperature problems.

Percussion systems have been investigated previously for oil well drilling, and increases in instantaneous penetration rates of a factor of five were achieved in brittle rock. The system appears to function best when combined with rotary motion. These drills can be used with either air or water as the drilling fluid. Percussion drills have been tested in geothermal drilling at the Geysers, however, the lifetime of the hammer was short. It is felt that the lifetime could be increased through technological improvements. An attractive feature of the air hammer is that no seals are used so that its application at high temperature may be possible with only minor modifications. In addition, no new surface equipment would be required to implement the percussion drilling system.

Recommendations for the high pressure jet augmented drilling system development included the investigation of the use of cavitating jets to reduce the pressures that are required to cut the hard rocks found in geothermal reservoirs and the development of pumps, hoses, and swivels which could be used at pressures of approximately 7500 psi. The development of motors capable of operating at speeds from 300-1000 psi and withstanding a 150°C operating temperature under circulating conditions was recommended. The system must further withstand a twelve-hour soak at 300°C. In conjunction with the motor development, it will be necessary to develop high speed bits which are capable of operating at the rotary speeds which are utilized in the high speed motor. Impregnated diamond bits and polycrystalline diamond bits were recommended as the leading candidates for this development. The development of the percussion drilling system would begin with an evaluation of commercially available percussion drills under high temperature operation. This would include identification of failure modes so that an improved drill with adequate reliability could be designed, built, and tested. There is also a need to develop improved bits to use with the percussion drill in the geothermal environment. Rock mechanics studies were felt to be necessary to support the development of the high speed bit and for defining the system parameters for the jet augmented drilling system.

The panel recommended a total expenditure of thirty-six million dollars over the next seven years to accomplish the development of the systems described above.

III. Panel on Surface Technology

The Panel on Surface Technology was charged with identifying improvements in surface equipment and operating procedures that could make a substantial contribution toward achieving the cost reduction goals of the program. In addition, the developments in surface equipment necessary to support the requirements of advanced drilling systems were to be determined. Topics for discussions included fluid handling and conditioning systems, pipe handling systems, instrumentation systems, crew training, well control, and automated drilling rigs.

The panel identified the need for improving the drilling fluid handling system to reduce or eliminate the problem of corrosion in geothermal wells. It was recognized that innovative techniques for the automatic handling of pipe offer substantial potential for reducing cost, but it was also pointed out that automated systems used in the past have been both expensive and unreliable. Drill pipe inspection procedures were identified as being currently unreliable, and the need to measure cumulative fatigue and to maintain records of the use and the fatigue history of individual joints of pipe was pointed out. The panel felt that significant cost saving potential exists in gathering and utilizing data measured while drilling. Downhole instrumentation and telemetry systems do not exist for geothermal drilling, and there are several sensors which need to be developed for use in gathering information at the surface. The utilization of microprocessors for drilling optimization and control was identified as being worthy of additional investigation. It was further pointed out that drilling simulators for training crews to control high temperature, underpressured wells are not currently available and that the establishment of this capability could lead to reduced well cost. The recommendations of the panel included the development of systems which would reduce the potential for corrosion. Examples are closed fluid handling systems which would prevent the entrainment of oxygen into the drilling fluid and systems for generating inert drilling fluids, e.g., nitrogen. The development of improved pipe inspection methods that minimize operator error and variability was recommended. Finally, the development of surface and downhole instrumentation and closed loop control systems for optimizing the drilling operation was recommended.

IV. Panel on Borehole Technology

The Panel on Borehole Technology discussed problems associated with establishing and maintaining a stable borehole for the long-term production of geothermal wells. Technology development was recommended in the areas of drilling fluids, drill pipe, lost circulation control techniques, completion techniques, and casing and cementing. The conclusions and findings of this panel can be divided into the following six areas:

A. Drilling Fluids -- Basic limitations exist in using bentonitic clays as gelling agents for high temperature wells, and there is little experience with newer clay materials. There are no substitute polymer gelling agents for high temperatures, and experience with non-conventional fluids, such as foams, is lacking.

B. <u>Drill String</u> -- Conventional oil and gas well drill strings are limited in geothermal applications because of corrosion, abrasion, and heat. Borehole stability problems cause pipe sticking and twist-off.

C. <u>Lost Circulation</u> -- Lost circulation problems add significantly to the cost of geothermal wells. These problems are not adequately defined relative to the cause and location of the lost circulation zones, and existing lost circulation control materials and techniques are not adequate to prevent fluid loss and formation damage in geothermal wells.

D. <u>Completions</u> -- Techniques for completing geothermal wells, such as jet perforating and slotted liners, are severely limited due to high temperature, corrosion, and erosion effects. Borehole stability problems are not well defined. Improved cementing procedures are needed to obtain good casing-cement-formation bonding.

E. <u>Casing</u> -- Conventional petroleum industry casing design standards are inadequate for geothermal applications. Available cements and cement placement methods do not produce a long-lasting cement bond between pipe and formation. Wear on the inside of casing strings due to drill pipe rotation cannot currently be prevented because of the failure of rubber drill pipe protectors at high temperature.

F. <u>Cementing</u> -- Effective displacement of mud during cementing is difficult due to gelation, unstable boreholes, and lost circulation zones. Existing cements do not allow flexibility in density control. Low density cements are needed to prevent excessive circulating pressure and breakdown of underpressured zones. Testing methods do not exist to evaluate cements under dynamic downhole conditions involving cyclic temperatures. Existing compositions lack the long-term capability to maintain a strong bond and to resist chemical attack by formation fluids.

The panel recommended that the chemical and physical behavior of non-bentonitic clays and clay morphology be investigated at temperatures of 300-350°C. The purpose of this investigation would be to develop a geothermal drilling mud with good rheological properties. Further recommendations included the development of drill string and casing materials that would be compatible with the temperatures, the pressures, and the corrosion and erosion conditions encountered in drilling geothermal wells. Prior to the initiation of this development, a casing failure mode analysis is required. The development of lost circulation control materials, tools, and procedures was highly recommended because of the current high cost of controlling lost circulation.

V. Panel on Directional Drilling Technology

The Panel on Directional Drilling Technology was asked to identify the problems encountered during the drilling of deviated wells in geothermal reservoirs and to recommend R&D activities which could lead to solutions to these problems. Although directional drilling procedures have been used throughout the oil and gas industry, the direct application of these procedures to geothermal drilling has met difficulties. These difficulties arise because of the effects of elevated temperature and the hard, highly fractured formations which are encountered.

Directional drilling is important to geothermal production because the fractures which contain the steam and hot water have, in most cases, a vertical orientation. The ability to drill highly deviated holes in these fractured formations has the potential to significantly improve the flow rate of the well at little increase in cost.

The panel found that the use of conventional bottomhole assemblies to build hole angle is very difficult in hard rock. Further, hole curvature problems while building angle present the greatest risk in directional drilling in hard rock. Drilling is limited by the lack of orientation devices, downhole motors, and telemetry systems which will operate at temperatures in excess of 150°C. The panel also recognized that bits for use with high speed turbines to drill hot, hard rocks have not been developed.

The panel recommended that high priority be given to the development of drilling bits which would be compatible with high speed downhole motors for directional drilling. They further recommended the development of downhole motors, but this development should be limited to liquid driven motors. The development of sensors, downhole signal conditioning equipment, and telemetry systems that are capable of operating at high temperature and that can be used to measure hole inclination, hole direction, tool face orientation, hole curvature, turbine rpm, weight-on-bit, etc., was recommended.

VI. Plans

The remainder of this report provides detailed descriptions of the discussions and recommendations which are outlined above. It is the intent of Sandia Laboratories to use these recommendations to define the future research and development activities for the Geothermal Drilling and Completion Technology Development Program.

REPORT ON THE PANEL ON SURFACE TECHNOLOGY

Panel Members

S. Loy (Chairman)	Progress Drilling Company
L. M. Edwards	Dresser Industries, Inc.
J. Fair	Gulf Research and Dev. Corp.
A. Gangi	Texas A&M University
W. Gravley	Mobil Research & Dev. Corp.
W. Koger	Loffland Brothers Co.
W. McDonald	Maurer Engineering
J. Polito	Sandia Laboratories
R. Ramage	Dresser Industries, Inc.
A. Roberts	WKM Wellhead Systems
B. Wilder	Amoco Production Co.
C. R. Williams	Bartlesville Energy Technology Center

I. Objectives of the Panel

The objectives of the Panel on Surface Technology were to examine the surface equipment and operating procedures used in geothermal drilling and identify areas where technological improvements could result in cost reductions, and to identify new surface equipment that would have to be developed to support the implementation of advanced drilling systems.

A. Fluid handling and conditioning systems
B. Pipe handling systems
C. Instrumentation
D. Training and well control
E. Support for advanced drilling systems

II. State-of-the-Art Assessments

For the purpose of assessing the state of the art, the drilling conditions to be considered were characterized as follows:

Depth	- less than 4 km
Drilling Fluids	- gas, foam, and oil or water based mud (for this discussion, water used as a drilling fluid will be treated as a special case of water based mud).
Lithology	- medium hard to hard, frequently underpressured
Hole Diameter	- sufficient for setting a 7" liner to total depth
Geothermal Fluid Temperature	- up to 350°C

A. Fluid Handling and Conditioning Systems

1. Drilling Solids Removal -- Some of the candidate advanced drilling systems, such as erosion or percussion drilling,

Automated rigs, in particular hydraulically actuated rigs, have been built and tested. They have not been widely accepted because of their high cost, low reliability, and requirement for highly trained technicians.

Efforts have been made to circumvent the problem of drill pipe handling by using continuous, flexible pipe. Such systems eliminate conventional drill pipe connections and offer fast trip speeds. However, the flexible pipes contain elastomers and are made with high strength steels. These characteristics make them unsuitable in their present configuration for use in high temperature, highly corrosive geothermal wells.

2. Pipe Monitoring and Inspection -- Commercial drill pipe inspection services are available to measure wall thickness, pit depth, and crack formation. However, the results of these inspections are very sensitive to operator variability. No field-portable, automated system is available to yield reliable inspections. Also, current technology does not permit measurement of the cumulative fatigue history of the pipe or estimates of the remaining life.

   Maintaining records for each joint of drill pipe would provide data for statistical analysis of drill pipe life, aid in drill stem design, and help to prevent occurrences of parted pipe. Monitoring of individual joints of pipe is not general practice and no statistical models now exist that provide reliable estimates of remaining drill pipe life.

C. Instrumentation

1. Surface Instrumentation -- The current state of surface rig instrumentation is summarized in Table 1. Generally, rig instrumentation is intended to provide information on the physical characteristics of the well, optimize controllable variables to minimize drilling costs, or to detect and prevent potential problems. The panel feels that all of these are important functions and, accordingly, the value of most of the items listed in Table 1 are indicated as "high."

   With the exception of drill pipe fatigue history, continuous pipe inspection, and continuous rheology monitoring, sensors are available to measure the parameters listed in Table 1. However, in those areas where more work is indicated, the instrumentation is characterized by poor accuracy or difficulties with environmental packaging that lead to low reliability. Most of these problems are not directly related to the geothermal environment, but high return temperatures of the drilling fluid may increase the difficulty of some measurement tasks such as pipe inspection and drilling fluid monitoring.

2. Downhole Instrumentation and Data Transmission -- The Directional Drilling Panel at this workshop has considered the needs for downhole instrumentation and sensors for directional monitoring. No other panel has, however, considered the problem of transmission of data to the surface. A variety of Measurement While Drilling (MWD)

may produce finer drilled solids than do most conventional systems. Cuttings produced by these systems may be below 5 microns in size. Accumulation of such fine material in mud systems has several adverse effects, such as

a. Reduced penetration rate
b. Increased mud density
c. Increased annular pressure drop, and
d. Increased difficulty in rheology control.

Micron sized drilled solids are difficult and expensive to remove. Furthermore, no field usable method exists to determine the particle size distribution for drilled solids less than 35 microns in size.

2. Mud Cooling -- High downhole temperatures may heat the return mud to temperatures that make surface handling difficult. The mud must be cooled to less than 80°C to prevent excessive fluid loss in water based systems and to extend the life of pumps and other equipment. Current cooling methods entrain oxygen in the fluid and scavenge corrosion control inhibitors. These effects complicate the difficult task of controlling corrosion in geothermal wells.

3. Corrosion Reduction -- Corrosion is a serious problem in drilling hydrothermal wells because of the high temperatures, the brackish nature of formation fluids, and the frequent presence of hydrogen sulfide. Any oxygen in the drilling fluid seriously aggravates the corrosion problem. Because of the underpressured nature of many reservoirs, geothermal wells are frequently drilled with lightweight fluids such as gas, foam and aerated mud. Currently, air is most often used in the formulation of these drilling fluids. Oxygen can be entrained in the fluid and transported downhole aggravating the corrosion problem. Also, commercially available corrosion inhibitors are designed for use below 175°C and are inadequate for higher temperature operations.

4. Foam -- Foam is an attractive fluid for geothermal drilling because of its high lifting capacity and low density. However, no drilling foam is now available for high temperature use. Also, foams are usually not recirculated, so they must be broken down after a single circulation. Stiff foams that are most suitable for drilling are difficult and expensive to break down for disposal. Oxygen entrainment in the foam also increases corrosion control problems. At present no foam is available that is adequate for use in geothermal drilling and no cost effective means are available for disposing of used foam.

B. Pipe Handling and Hoisting, and Monitoring

1. Pipe Handling and Hoisting -- Conventional pipe handling and hoisting systems are characterized by the following:

a. Slow trip speeds
b. High rig up and rig down cost
c. Close proximity of personnel to high speed moving parts, and,
d. Lack of automated pipe handling operations.

Measurements Required	Value	More Work Needed
Drilling Parameters:		
Rotary Torque	High	Yes
Tool Joint Torque	High	No
Hook Load	High	No
Weight on Bit	High	Yes
Bit RPM	High	No
Hole Depth	Med.	Yes
Drill Pipe Fatigue History	High	Yes
Continuous Pipe Inspection	High	Yes
Block Position and Speed	High	Yes
Penetration Rate	High	Yes
Mud Properties:		
Flow Rate (in/out)	High	Yes
Pump Strokes	High	No
Temperature (in/out)	High	No
Continuous Monitoring of Rheological Properties (density, viscosity, gel strength, filter loss, etc.)	High	Yes
Solids Content and Size Distribution	High	Yes
Rig Mechanical Monitoring	Low	No

Table 1. Status and needs for rig instrumentation at the surface

systems are nearing the commercial stage for oil and gas drilling. None of these systems is adequate for use in geothermal wells, however. Mud pulse telemetry systems transmit signals up the column of drilling mud and utilize complex devices and/or power packs downhole that will not currently survive in geothermal temperatures. Furthermore, these systems are ineffective when air or aerated muds are used as the drilling fluid. It does not appear that these systems will have wide applicability to geothermal drilling.

Hardwired systems exist that utilize a cable lowered through the drill string or conductors imbedded within specially constructed drill pipe. No high temperature cables or cable heads exist that have long lives in geothermal environments. Drill pipe constructed especially for electrical transmission does not seem to be inherently temperature limited, but the special tool joints that are required have been troublesome in conventional drilling. Their performance in geothermal drilling is not known.

3. Data Utilization -- In order to use measured data to minimize drilling costs, it is necessary to identify the important drilling parameters, measure them with appropriate accuracy and frequency, and obtain optimal values of control variables from models that adequately represent the drilling process. Optimized drilling is a goal that has been only imperfectly achieved in practice.

   Current methods rely almost solely on information obtained from offset wells, and models of drilling performance are primarily empirical. Computerized data gathering systems are available, but they generally do little more than display information in an organized fashion and trip alarms when preset limits are exceeded.

   Attempts have been made to completely automate drilling using closed loop feedback control systems. However, their high cost and low reliability have not resulted in economic benefits in field use.

D. Training and Well Control

1. Training -- Many schools and training aids are available to train personnel for oil and gas drilling. These schools are useful in some phases of geothermal drilling, but the areas of high temperature drilling and control of underpressured formations are not addressed. The latter topic is of particular significance, because all current well control training and simulators are directed toward procedures to control high downhole pressures. Geothermal reservoirs are frequently underpressured and are drilled with air or aerated mud. Blowouts can occur in these circumstances, but simulators and instruction programs are not available to train drillers in the control of these situations.

2. Well Control -- Well control equipment is limited by temperature as follows:

Blowout Preventers (BOP)	175°C
Well Heads	275°C
Rotating Heads	175°C
Annular Elements	175°C

These temperature limitations are primarily due to the presence of elastomers. Current practice is to cool the elastomeric elements with water and change them frequently. These procedures are expensive and yield only limited service life for BOP's in the event they must actually be used to control the well.

Furthermore, rotating heads are commonly used in geothermal drilling. This results in a very tall BOP stack which necessitates unusually high substructures for the rig.

E. Support of Advanced Downhole Systems

1. Systems Requiring High Fluid Pressure -- Erosion drilling and some downhole motor systems may require high flow rate, high pressure drilling fluid systems. This topic is discussed in some detail by the panel on rock drilling and will not be considered here. See Subtask 1.5 and Task 3 of the recommendations of the Rock Drilling Panel.

2. Unconventional Drill Pipe -- Flexible drill pipe systems have been constructed and used to drill oil and gas wells. The principal advantage of such systems is in shorter trip time, since the flexible hose can be rapidly coiled and uncoiled. A second advantage is that the continuous pipe systems are compatible with the use of downhole motors and can be fitted with electrical conductors for telemetry and electrical power transmission. The panel feels that the benefits of shorter trip times will not be substantial in geothermal drilling because the wells are relatively shallow. Benefits from telemetry may be significant, but continuous pipe systems suffer from several problems that may limit their use in geothermal drilling. Current designs of armored hose have elastomeric material throughout the length of the hose. Thus the hose, which is the central component of these systems, would require considerable redesign to be compatible with geothermal drilling.

   Also, current hose designs use high strength steels for the armor. These materials are not suitable for the corrosive geothermal environment, unless protected. Finally, the armored hoses may not be compatible with the high pressure drilling systems that may be selected for use in geothermal drilling.

   The panel also considered systems that would spool continuous drill pipe in the same way that continuous tubing is handled. Generally, it was felt that the frequent coiling and uncoiling of the pipe would lead to short life and that the system did not offer sufficient cost saving potential to warrant the extensive development activities that would be required.

   The use of concentric drill pipe offers potential benefit in geothermal drilling for lost circulation control and for use in high pressure erosion drilling or downhole motor systems where an aerated return fluid column is required. Concentric pipe is currently in limited use. No major obstacles prevent it from being used in geothermal drilling, but a quick connect-disconnect tool joint would speed its handling.

III. Conclusion and Findings

The conclusions and findings of the Panel on Surface Technology are:

A. Methods to remove fine drilled solids from drilling mud do not exist, but may be required for certain advanced drilling systems.

B. Current methods for cooling drilling mud entrain oxygen in the fluid and seriously aggravate corrosion control efforts and costs in certain geothermal wells.

C. Corrosion control is a serious problem and a substantial cost item in geothermal drilling. Current corrosion inhibitors are not designed for the high temperatures encountered in geothermal wells.

D. No high temperature drilling foam is now available. Also, methods for recirculation of foam and for breaking foam do not exist or are very expensive.

E. Innovative methods for handling pipe offer substantial potential for reducing costs, but automated systems tried in the past have been expensive and unreliable.

F. Drill pipe inspection procedures are unreliable and no method exists to measure cumulative fatigue. Maintaining records of use and the fatigue history of individual joints of drill pipe has the potential for reducing expensive parted pipe costs.

G. Significant cost saving potential exists in gathering and making good use of data measured while drilling. Downhole instrumentation and information transmission systems do not exist for geothermal drilling. Also, there are several sensors for gathering information at the surface which need to be developed. Further, the utilization of drilling optimization should be examined and improved.

H. Drilling simulators to train crews to control high temperature, underpressured wells are not available. No schools are available to train rig personnel in the special procedures needed for geothermal drilling.

I. Wellhead and well control equipment are limited to temperatures from 175-275°C.

IV. Identification of R&D Areas

A. Fluid Handling and Conditioning Systems

Substantial cost savings can be realized by making improvements to current fluids and fluid handling systems. Methods should be developed to eliminate or reduce the presence of oxygen in all drilling fluids including gas and foam. High temperature corrosion inhibitors need to be developed, and automated monitoring and mixing of corrosion control additives should be investigated.

If the advanced drilling system produces fine drilled solids, methods must be developed to effectively remove them from the drilling fluid.

B. Pipe Monitoring, Handling and Hoisting

Three areas of improved pipe handling offer substantial cost saving potential. Monitoring and modeling the fatigue and corrosion histories of drill pipe will permit optimal drill string design and help to prevent costly instances of catastrophic failures. Development of corrosion resistant drill pipe and coatings will reduce corrosion and erosion of pipe, and automated pipe handling has the potential to save rig time and improve drilling performance.

C. Instrumentation

High temperature sensors and instrumentation for use with a data telemetry system compatible with geothermal drilling can provide information that is useful in drilling optimization and vital for low cost directional drilling. Surface measurements of drilling parameters can enhance drilling optimization and help in detecting impending failures. Sensors are needed that will survive the rig environment and make measurements not currently taken, e.g., real time pipe inspection and continuous monitoring of drilling fluid properties.

Improved algorithms to make optimal use of information are needed.

D. Training and Well Control

High temperature blowout preventers and other wellhead equipment are needed to reduce costs and improve well safety. Also, training must be provided in the control of underpressured wells and in dealing with high temperature geothermal operations.

V. Recommendations

A. Fluid Handling and Conditioning Systems

Task 1. Solids Control and Particle Size Distribution

Characterize the size of the cuttings that will be produced from advanced drilling systems such as percussion and erosion drilling. If a significant fraction of these cuttings will be below 35 microns in size, new separation methods may need to be developed. Also, a field usable method for determining particle size distribution below 35 microns will need to be developed.

Task 2. Mud Cooling

Methods of cooling the drilling mud that do not entrain oxygen in the fluid need to be developed to reduce the severity of corrosion control problems in geothermal drilling.

Task 3. Corrosion Inhibiting Drilling Fluids

Investigate alternate methods for generating inert drilling fluids and select the most cost effective possibilities. Develop the needed systems. Inert variants of aerated mud, air, and foam should all be considered.

Task 4. Corrosion Control Additives

Develop high temperature (350°C) oxygen scavengers and corrosion inhibitors that are quick acting and long lasting.

Task 5. Mud Systems

Investigate the use of closed mud systems to minimize contact of the drilling fluid with air, and develop quick acting, high temperature defoaming agents to prevent aeration of mud in the mud pits.

Task 6. Drill Pipe Coatings

Develop wear resistant, high temperature coatings for drill pipe to reduce corrosion and erosion problems.

Task 7. Automated Fluid Mixing

The cost saving potential of automated mud mixing and automated introduction of mud additives needs to be investigated. If such systems prove to be cost effective, then any needed development should be performed. This task will take on added importance if real time corrosion control monitoring is adopted as suggested in Task 13.

Task 8. Geothermal Drilling Foam

Survey existing surfactants and assess their abilities to generate suitable high temperature drilling foams. Develop new materials if needed. Develop effective methods for generating inert foam, breaking down and recirculating or recovering foam, and disposing of used foam in an environmentally acceptable manner.

B. Hoisting, Pipe Handling and Monitoring

Task 9. Automated Pipe Handling

Investigate the cost effectiveness of alternate automated pipe handling systems. Perform needed development work on these candidate systems if it appears that they can compete economically with conventional methods. Develop automatic or semi-automatic methods for handling and makeup of the BOP stack and special purpose drill pipe as required, e.g., concentric drill pipe.

Task 10. Pipe Inspection

Develop pipe inspection methods that minimize operator error and variability. Investigate techniques for measuring or monitoring the fatigue history of drill pipe. Computerized, on-line inspection as the pipe enters or leaves the well would be particularly valuable. Develop tagging methods for individual joints of drill pipe so records can be maintained on each joint. Machine readable tags would be valuable.

Task 11. Drill Pipe Monitoring and Life Prediction

Modern computing capability makes it possible to maintain records of each joint of drill pipe. Data on wall thickness, pit depth, crack formation, and fatigue history could all be maintained if adequate, cost effective measurement techniques and recording methods were available (see Task 10). Statistical or other techniques to analyze this data and predict remaining pipe life and determine when pipe must be downgraded should be investigated and developed.

Task 12. Drill Pipe Joints and Steel

Develop long-life hard-banding for tool joints in geothermal wells. Also, investigate new formulations of steel for drill pipe that will resist oxygen and hydrogen sulfide corrosion without sacrificing mechanical properties.

C. Instrumentation

Task 13. Surface Instrumentation

Develop rig instruments to measure the parameters listed in Table 1.

Task 14. Closed Loop Control Systems

Investigate the feasibility and cost effectiveness of automatic control systems to completely control drilling operations.

Task 15. Algorithms for Determining Control Variables

This task is concerned with the use of information obtained through instrumentation. Systems engineering studies should be performed to determine whether better algorithms are needed to determine optimal values of control variables. Such studies also will guide instrumentation development by providing insight as to what measurements are needed, what sampling rate is required, and what accuracies are needed.

Task 16. Downhole Telemetry

Develop sensors and telemetry for temperatures up to 350°C and for operation with mud, gas, or foam drilling fluids.

D. Training and Well Control

Task 17. Training

Encourage the development of an orientation program for rig crews new to geothermal drilling and provide mobile facilities for on-site instruction. Provide well control simulation equipment to train crews in the control of underpressured geothermal wells.

Task 18. Elastomer or Seal Development

Develop elastomers or new seal designs for wellhead equipment and BOP's to withstand temperatures of 175-250°C. Study the feasibility of developing elastomers for 250-300°C use. Examine the feasibility of non-elastomer sealing elements for use in BOP's and wellheads.

Task 19. Annular BOP

Develop an annular BOP that will permit rotation of the drill pipe.

Task 20. Downhole BOP

Examine the feasibility of developing a downhole blowout preventer for use in geothermal wells to reduce surface stack requirements.

E. Support of Advanced Drilling Systems

Task 21. Concentric Drill Pipe

If concentric drill pipe is selected for use, develop a quick connect-disconnect tool joint and the needed handling equipment.

VI. Priorities for Recommended Tasks

Task Number	Priority
1	1
2	1
3	1
4	1
5	1
6	1
7	2
8	3
9	1
10	1
11	1
12	2
13	1
14	1
15	1
16	3
17	1
18	1
19	3
20	1
21	3

REPORT OF THE PANEL ON BOREHOLE TECHNOLOGY

Panel Members

B. Nicholson (Chairman)............Republic Geothermal
J. K. Bannerman....................Dresser Industries
J. H. Barnette.....................Sandia Laboratories
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I. Objectives of the Panel

The objectives of the Panel on Borehole Technology were to discuss problems associated with establishing and maintaining a stable borehole for the long-term production of geothermal wells and to recommend areas where technology development is required. Items included in the discussion were drill string design, techniques for cuttings removal, completion techniques, borehole stability, lost circulation problems, and well control. The following headings were used to guide discussions:

A. Drilling fluids
B. Drill string
C. Lost circulation
D. Completion techniques
E. Casing
F. Cementing

The panel established the following assumptions and guidelines for the technical discussion and the organization of recommendations:

A. Actual rock removal methods and hardware (bits, directional tools, etc.) are the responsibilities of other panels.

B. Boreholes are assumed to be located in geothermal reservoirs of three types: 1) vapor dominated, 2) liquid dominated, and 3) hot dry rock. Rock types involved vary from sedimentary to igneous, and include abrasive, highly fractured and vugular formations. Temperatures range up to 350°C and pressures are typically hydrostatic or less in the producing zone (underpressured). Well depth can be as great as 4 km. Formation fluids will be corrosive and may contain H_2S and CO_2. Total dissolved solids may be as high as 200,000 ppm.

C. Geopressured-geothermal conditions were not included in the scope of the discussions.

D. Time and proposed-budget limitations were noted as possible constraints in developing some ideas for advanced systems. Conversely, the panel recognized that simple improvements in existing methods are likely to be ineffective in achieving significant cost reductions. Thus an attempt was made to balance recommendations and anticipated cost of development to fit between these two constraints.

E. While emphasis was placed on advanced concepts, an attempt was made to record all practical ideas for improving existing technology.

II. State-of-the-Art Assessment

A. Drilling Fluids

Reservoir types discussed were primarily water dominated, as in the Imperial Valley. The productive portion of the reservoir in the Geysers is dry steam and is drilled with air. However, some of the concepts discussed would apply to the mud-drilled upper portions of the Geysers' boreholes.

Presently, bentonite-lignite or bentonite-sepiolite-lignite systems are used for drilling geothermal wells. It is necessary to use natural clays for gelling agents since geothermal temperatures exceed the working limits of processed polymer-type viscosifiers. Bentonitic water-based muds thicken excessively above 100°C. Sepiolite (a fibrous magnesium-rich clay) is more temperature resistant, but operators lack experience in its use. Oil-base muds have demonstrated increased temperature resistance in oil and gas well drilling, but they may not be compatible with clean, aqueous systems. Drilling foams are difficult to control and maintain in high intrazonal water flows and are unstable and corrosive at high temperatures.

Specific problems with clay muds caused by excessive gellation include:

1. Circulation difficulties -- Pipe is placed into the hole in stages during drilling, periodically breaking circulation. If excessive pressure is required to restart circulation, the underpressured formations may be fractured, causing lost circulation. Delays in the drilling operation can occur for a variety of reasons. When these delays occur, and circulation is stopped, the recently drilled borehole may swell because of heat induced plasticity, and holes may have to be reamed. Pipe can be stuck if swelling occurs with pipe in the hole.

2. Formation damage -- Within the producing zone, mud lost to fractures of high permeability formations can gel to a near solid condition causing impairment of the producing horizon.

3. Lost circulation -- Low pressure reservoirs are sensitive to mud weight and pressure surges caused by pumping, running pipe too fast, etc. These problems are amplified when the mud thickens or gels because of high temperature.

4. Cement channeling -- Thick mud is difficult to displace during primary cementing jobs. Due to mobility differences, cement slurries may channel through mud leaving large areas of the casing unprotected by cement.

B. Drill String

Steel, tool joints, and coatings designed for oil and gas well drilling are used in geothermal drilling. However, there are basic differences in geothermal wells that cause drill string problems. These include the following:

1. In the Geysers, air drilling causes severe erosion of tool joint shoulders from the jetting action of returning hot, high velocity, sand-laden air and steam. Such erosion problems are primarily limited to the Geysers.

2. Abrasion from hard, volcanic rocks or hard, fractured, metamorphosed sandstones, particularly in crooked holes, may dictate hard banding protection which can damage large diameter casing strings. Rubber drill pipe protectors cannot tolerate high temperatures.

3. Corrosion, both internal and external, and including both general metal loss (thinning) and pitting, is considered a significant problem.

    a. Muds must be aerated for cooling and oxygen is entrained during this procedure. The oxygen combines with natural brine formation fluids to create a corrosive fluid. Different locations have different formation water pH values, so the problems vary geographically.

    b. More formation water is entrapped in the mud in under-balanced drilling and this accelerates corrosion.

    c. Frequent inspections are necessary to avoid trouble. Internal pitting is more difficult to spot in routine visual inspections. Specification API RP7G does not require a special inspection that locates corrosion 3-4 inches from the flash weld.

    d. Wall thinning weakens drill pipe and is a major cause of twist-offs.

    e. Premium drill pipe may have to be replaced after drilling only one hole. Operators pay drilling contractors for pipe damage on the basis of before-and-after inspection.

    f. Sulfide stress cracking caused by H_2S is a problem. Any sulfide source (gypsum, pipe dope, native sulfur) can be converted to H_2S by high temperature reactions, and many geothermal formations contain H_2S.

    g. Aerated fluid systems using inert gas have not been effective to date.

4. Drill pipe coatings (bonded plastics) cannot tolerate extreme conditions in geothermal wells. Coatings are desirable and serve two useful functions: 1) to protect the string from corrosion, and 2) to reduce friction loss in the system (put more horsepower at the bit).

5. Boreholes are not stable in geothermal wells. Rocks tend to behave plastically at high temperatures, even in hard, igneous or metamorphosed sedimentary formations. When holes are static, as during tripping, the hole tends to swell. Reaming is frequently required to return the bit to bottom. Pipe sticking is common, and techniques for freeing the pipe, such as pulling and jarring, can cause severe problems because the pipe is weakened by corrosion.

6. Tool joints must be overtorqued during makeup because high temperatures loosen the coupling. This can actually alter the thread-shouldering stress effect so that the coupling wobbles.

7. Non-conventional drill strings are not yet rugged enough for use in geothermal drilling. Flexible strings of continuous drill pipe which can speed drilling and tripping are not suitable where sticking is likely. Also, geothermal wells are relatively shallow and tripping with conventional pipe is not excessively time consuming.

C. Lost Circulation

With the exception of the producing zone at the Geysers, which is a rare, dry steam reservoir, geothermal reservoirs normally contain hot to superheated water. Reservoir pressures are normally equal to, or slightly less than, hydrostatic pressures. Commercially attractive geothermal rocks have high permeability, either in the form of extensive natural fracturing or loosely consolidated sands. These factors make hydraulic control of drilling fluids difficult and contribute to serious and widespread lost circulation problems. Because of low reservoir fluid pressures, weighted drilling mud needed to support the borehole wall easily overbalances formation pressures, and any pressure surge caused by pump pressure, pipe running, etc., can cause mud loss. Low density fluids such as air, mist, and foam are quickly contaminated by water flows and are difficult to maintain in relation to composition and required back pressure.

Lost circulation can halt drilling progress, leading to further problems as mud continues to gel. The borehole can swell and/or slough causing the pipe to stick. And, within the producing zone, mud lost to fractures can cause significant and permanent plugging due to high temperature effects on the clay particles.

Lost circulation can lower mud support pressure and cause wall failure due to stress. Enlarged boreholes (particularly in conjunction with lost circulation) are difficult to cement effectively, and lack of cement support can allow casing to buckle with thermal expansion.

Lost circulation is frequently associated with high volume water crossflows in which colder, more dense fluids flow into lower zones, even though entire intervals are at hydrostatic pressure. One water flow was reportedly measured at 850 barrels per hour. Cement slurries or lost circulation materials cannot be expected to seal fractures under such prolific flows.

The panel prepared Table I which identifies lost circulation problems, proposed solutions and results for two intervals: 1) above the producing zone, and 2) within the producing zone.

Type of Loss	Remedy	Success	Comments
Above the Producing Zone			
Hydraulic fracturing	Mud weight reduction, lost circulation material, mud property modification, hydraulics modification	Good	Normally successful when properly done
Loss to secondary porosity and large primary porosity (fractures, vugs)	1) Lost circulation material (cotton seed hulls, walnut hulls, mica)	Poor to nil	Success ratio is poor in most areas. Has been successful in some wells.
	2) Cement	Mediocre to nil	Considering cost, success ratio is poor (treatment frequently must be repeated several times)
Vapor Dominated Producing Zone			
Loss to secondary porosity	1) Air drilling	Fair	Some corrosion problems, excessive exterior erosion on drill pipe
	2) Foam drilling	Unproven	Limitations include corrosion, need for high temperature seals on surface for back pressure
Liquid Producing Zone			
Loss to secondary porosity	1) Lost circulation material	Poor to nil	Success ratio varies from good in some areas to nil in others, may damage productivity
	2) Drilling without returns	Fair	Limitations: Obtaining fluid supply (cost/availability); getting stuck; productivity damage from cuttings; no samples for exploratory zone correlation work
	3) Aerated water	Fair	Limitations: Corrosion on drill pipe; handling produced fluids; sloughing

Table I. Lost circulation practices

D. Completions

For geothermal completions, the general procedure is as follows:

1. Locate the top of a commercially viable hot water (or steam) reservoir.

2. Drill enough vertical section to permit commercial flow at existing permeability.

3. Isolate commercial production from cooler waters by effective casing and cement.

4. Remove any drilling fluid damage affecting the permeability of the wellbore.

5. Complete open hole if possible for least cost. If the producing formation is unconsolidated or incompetent, use a slotted liner or cemented casing.

6. Perforate cemented casing with adequate holes to provide commercial flow.

Stimulation by temperature resistant acids, pressure washes, or water injection has been attempted to remove shallow formation damage in the critical flow area immediately around the wellbore. Cased and perforated completions allow greater control for selectively testing and stimulating individual pay zones.

Borehole stability in less competent sands, such as those in the Imperial Valley, may require positive support from cemented casing or gravel packed liners. Compaction within the zone and subsidence of strata above the zone from fluid withdrawal can affect borehole stability, cause casing and/or cement failure, or cause surface problems.

The primary consideration in casing design is to assure an adequate diameter to permit commercial flow from a given depth with a given formation productivity index (barrels per day per psi pressure drop). It is also necessary to keep friction loss through wellheads, flowlines and valves to a minimum to assure maximum flow. Deep-well centrifugal pumps may be needed to increase flow rates. Wellheads are usually simple, consisting of a large valve and a cross of tee to the flowline.

Completion problems can occur in any phase of the producing system. Productivity loss between formation and wellbore can be caused by: 1) formation sand or particle plugging, 2) scale buildup within liner slots or perforations, 3) swelling or dispersion of clay particles in sandstones, and 4) compaction around perforations. Perforations may be ineffective due to limited performance of temperature sensitive charges.

Thermal and corrosion effects can cause failure of liners. Scale buildup and diameter reduction of casing can be significant, particularly in portions of the string where obstructions such as packers, hangers, and pump casings cause turbulence and pressure instability. Mixing of waters from out of the zone can cause scaling. Single diameter strings are desirable, but require special methods to cement effectively above a slotted casing section without contaminating productive zones. Cemented and perforated casing would be the most reliable single diameter system to install.

The master valve is attached to the production casing. Blowout preventers (BOP) are mounted on this valve to allow drilling into the producing zone. When the well is completed, the valve provides control after the BOP's are removed. Geothermal wellheads are subject to severe erosion, corrosion and mechanical damage. The single master valve and wide-open casing system would directly expose the producing zone to the surface in case of valve failure (leakage, cracking). Thus, protection of wellhead components from weakening or damage is a major concern.

E. Casing

Casing in geothermal wells is subject to severe conditions that are not present in oil and gas wells. Thus, design considerations must include more than the conventional concepts of tension, burst (internal yield), and collapse. Unique factors affecting geothermal well casing include:

1. High temperatures -- Metals may be exposed to temperatures up to 350°C which approaches the point where metallurgical strength is affected. Cyclic temperature change, however, is a more severe problem. This is caused by the average string temperature increasing to 250-300°C from static conditions after the wall is placed in production. In the worst case, injection of cool fluids would cause even more extreme variations in temperature. One resulting problem is casing elongation which can buckle unrestrained pipe, particularly in washed out holes where cement support is inadequate. If pipe elongates in a constrained mode, compression and shortening can occur which may cause tensile failure on cooling.

   Current solutions are to: 1) select special buttress thread or premium couplings to withstand the loading, 2) restrain the pipe along its entire length by cement, 3) allow casing to expand vertically within special wellheads, 4) pre-stretch the string (to reduce elongation stress) in conjunction with cementing, and 5) consider the additional stresses in weight and grade selection.

2. Corrosion -- Metal is exposed to aqueous, high temperature fluids containing corrosive CO_2 and H_2S gases, and chlorides (salt). External corrosion may be more prevalent than internal. The exterior is exposed to shallower circulating, ground water which may contain oxygen. Deeper hot water flows will attack the cement sheath, eventually dissolving silica, magnesium and calcium from the cement. Thermal expansion cracks the sheath allowing water contact. Corrosion thinning weakens the pipe's resistance to buckling and collapse.

3. Entrapped liquids -- Between concentric strings, mud or water may become entrapped in cement pockets or above cement tops. During production, these pockets are heated and the liquid expands with great pressure. If this occurs, the internal string is usually collapsed by this expansion before the outer string fails in internal yield. Solutions require effective and complete mud displacement by cement and experienced supervision of wellhead installation and production operations. Positive prevention of this problem may not be possible as 100 per cent mud displacement by cement cannot be guaranteed. In addition, human error will

always be involved in operations; for example, closing casing head valves with water trapped in the annulus.

4. Coupling limitations -- API round thread couplings cannot tolerate extreme compressive and tensile loading. API buttress thread couplings are commonly used, as that thread form does not tend to part under high tension. Neither API thread offers metal-to-metal sealing and shouldering features offered in premium, commercially available couplings. Premium couplings have been used in deeper, higher temperature steam injection wells to solve the compression/tension problem, but they are more expensive than API couplings.

5. Landslides and earthquakes -- Geothermal wells are located in geologic formations associated with vulcanism, dynamic tectonics, active faulting and (in some cases) steep, mountainous terrain. Casing is always subject to ground movements.

6. Drill pipe wear -- When drilling is conducted through production casing, wear of the casing occurs because of contact with the rotating drill pipe and with abrasive cuttings. This problem is very significant in the Geysers where productive zones are drilled with air through cemented production casing. Due to the need for large diameter flow strings, tubing or tied-back liners are not always installed, and the wear-damaged casing serves as the production string.

   One solution is to overdesign the casing with added wall thickness to accommodate wear caused by the drill pipe. The need for hard banding on drill pipe should be carefully evaluated to protect the casing. Rubber protectors do not tolerate the temperatures involved. Calipering for damage evaluation is difficult in hot holes.

7. Casing rating criteria -- Yield values given by API for various casing weights and grades are calculated for non-geothermal environments, considering pressure only. A standard method of rating casing for the special conditions discussed above is presently not available.

8. Scaling -- Buildup of mineral scales from produced water is a function of cooling and pressure behavior. If the water is kept under pressure so that it does not flash, and the flow string does not cause eddies or turbulence which start precipitation, most minerals can be carried to surface. Liner tops, coupling recesses, casing patches and other restrictions can cause problems. Where possible, the ideal string is one of constant diameter. Plastic coating would be ideal if applicable materials existed.

F. Cementing

Geothermal cementing problems may be divided into emplacement problems and long-term problems. Deep oil and gas well completions have similar emplacement problems, and they have not yet been solved. Thick drilling muds are difficult to displace completely in the pipe/borehole annulus, and cement slurries tend to finger through or bypass pockets of mud. Displacement of mud from areas where pipe rests against the wall is almost impossible; thus, proper casing centralization is a key requirement for effective cement placement. Cement slurries also become thick and tend to set up prematurely in hot boreholes without proper retardation. Unstable boreholes that swell or slough can reduce pipe-wall clearances and produce thin, ineffective sheaths. Lost circulation zones also cause cement loss. In some cases, the washed out, oversized hole sections are not properly displaced because cement velocity is greatly reduced.

Where an adequate cement sheath is not initially emplaced, the casing is not uniformly supported, and, with thermal loading, it will tend to buckle. The pipe is also exposed to formation fluids which rapidly corrode the hot, bare metal.

Long-term cement problems are primarily caused by cement deterioration from the effects of hot water leaching, thermal shock (cyclic temperature changes), cracking caused by pipe expansion (ballooning) and/or longitudinal movement from elongation and shrinkage. These problems are not as prevalent in oil and gas wells, and the limited geothermal market has not created a demand for the development of new compositions for such severe long-term conditions.

At this time, cements used in geothermal wells are based on stable formulations as determined by compressive strength properties under downhole conditions of 200-300°C. Such systems are basically Portland cements (Class G in most cases) with added silica in a quartz form. Density reduction to 13 pounds per gallon is accomplished by the addition of perlite, a volcanic glass which may be obtained an in expanded glass-bubble state. Perlite is used in conjunction with bentonite to maintain a non-segregating slurry. This type cement system shows desirable properties when tested in a <u>static</u> environment at geothermal temperatures and pressures. An additional benefit from such a system is that a degree of lost circulation control is obtained due to perlite bridging and bentonitic effects.

As mentioned, this cement system is based on static design which does not compensate for variations under actual, dynamic use. Problems which develop in such cements are primarily the result of thermal shock of a repeated and uncontrollable nature. The first effects noticed are usually a loss of bond between casing and cement, or stress cracking and possible borehole-to-cement separation. Further development of these effects usually permits well fluid migration behind the casing and subsequent casing corrosion and cement erosion. Failure of the cement and casing can be expected after two or three years, if thermal shocks of several hundred degrees are frequent. Squeeze cementing of such damaged areas has had very limited success because of the large volume of brine fluids present and the overall deteriorated state of the casing and remaining cement.

III. Conclusions and Findings

The Panel on Borehole Technology considered six aspects of borehole technology which, if improved, could lead to significant reductions in geothermal well costs by the year 1986. The conclusions and findings of the panel are listed below.

A. Drilling Fluids

1. Basic limitations exist in using tentonitic clays as gelling agents for high temperature wells, and there is little experience with newer clay materials (sepiolite).

2. There are no available substitute polymer gelling agents for high temperatures.

3. Experience with utilizing nonconventional fluids such as foams and oil emulsions is lacking.

B. Drill String

1. Conventional oil and gas well drill strings are limited in geothermal applications.

2. Corrosion which occurs due to combined effects of O_2 entrainment, aqueous (brine) type formation fluids, abrasive rocks, heat, and inadequate plastic coating protection, causes many drill string failures.

3. Continuous reel (flexible) pipe is not yet rugged enough for most geothermal applications and is presently not cost effective for geothermal drilling.

4. Borehole stability problems (swelling and hole reduction) cause pipe sticking and twist-offs.

5. Tool joint makeup problems, such as the over-torque required to prevent wobbling and resulting belling of the joint, are basic joint design limitations in geothermal applications. Improved, high temperature thread compounds are needed.

C. Lost Circulation

1. Lost circulation problems in geothermal wells are not adequately defined relative to the type of permeability and the sensitivity to overbalance to be expected in various geologic environments.

2. Existing fluids, lost circulation materials, and techniques are not adequate to prevent fluid loss or formation damage after loss.

D. Completions

1. Methods are not commercially available to accurately measure temperatures and otherwise define commercial productive zones.

2. Underpressured (compared to hydrostatic) producing zones are easily impaired by incompatible fluids and solids. Stimulation methods to remove near-wellbore damage have not been fully developed for geothermal wells.

3. Explosives for application in jet perforating, wireline back-off tools, etc., are not reliable at high temperatures.

4. Plugging agents to seal off unwanted production or thief zones do not tolerate high temperatures and high fluid flows.

5. Slotted liners are subject to corrosion, erosion (slot enlargement), plugging by scale and formation particles, and collapse and buckling from thermal stress or formation instability.

6. Borehole stability problems are not well defined. Accurate geologic descriptions are needed. Effects of borehole stress, compaction/subsidence, casing/cement support, and inflow velocity need to be investigated for geothermal conditions.

7. Methods for drilling and completing wells to obtain large, single-diameter flow strings (no diameter change to cause scale precipitation) have not been evaluated for cost effectiveness.

8. Improved cementing and/or operational procedures to obtain and maintain casing-cement-formation bonding is needed to: 1) protect pipe, 2) prevent unwanted fluid entry, and 3) maintain casing system strength and resistance to thermal movement.

9. The wellhead is a point of vulnerability from the standpoint of safety and well control. Present systems are subject to weakening or failure by mechanical damage, erosion and/or corrosion.

10. Elastomeric seals are unreliable in contact with hot steam or water. This places a severe limitation on the use of rubber drill pipe protectors, bridge plugs and packers, testing, and logging and treating tools. The problem is acute in dry steam areas.

E. <u>Casing</u>

1. Conventional petroleum industry casing design standards based on API ratings are not adequate for geothermal applications.

2. Conventional methods are ineffective in preventing internal and external corrosion.

3. Available cements and cement placement methods do not produce a long lasting cement sheath between pipe and formation that will give the string sufficient structural strength and protect the metal surface from corrosion.

4. Concentric string configurations are susceptible to entrapment of liquids which can cause internal string collapse.

5. Wear on the inside of casing strings due to drill pipe rotation cannot be prevented. Better methods of measuring wear and accurately evaluating the problem are needed.

6. Casing design to minimize scale buildup is not fully understood.

7. Ensuring the integrity of the casing and liner is necessary to reduce workover costs and to minimize the risk of blowout. Restrictions imposed by downhole repairs or installation of smaller liners or tubing should be eliminated.

F. Cementing

1. Mud gelation, unstable boreholes, and lost circulation zones prevent effective displacement of mud during cementing. This tends to preclude the emplacement of a uniformly thick, channel free, uncontaminated cement sheath.

2. Existing cements do not allow flexibility in density control to prevent excessive circulating pressure and breakdown of underpressured zones.

3. Testing methods do not exist to evaluate cements under dynamic, downhole conditions involving cyclic temperatures, changing pipe stresses, and active leaching systems with varying chemical contents.

4. Existing compositions lack long-term capability to: 1) retain a strong bond to pipe and formation, and 2) resist chemical attack by formation fluids.

IV. Identification of Research and Development Areas

A. Drilling Fluids

In water dominated, underpressured reservoirs in which low density air, mist or foam cannot be used, the following needs have been identified:

1. An economical, high temperature viscosifying agent to replace clays should be developed.

2. Improved formulation, handling, and applications procedures for sepiolite clay should be developed. Long-term effects of downhole geothermal conditions on sepiolite muds should be evaluated; e.g., for shutdowns of weeks or months, or for use in temporary plugging or abandonment.

3. Other non-bentonitic clay muds should be investigated to: 1) improve compatibility with cement, 2) reduce gelation and fluid loss, 3) reduce formation damage, and 4) improve lubricity.

B. Drill String

The areas of need which exist for drill string used in geothermal environments and for which no commercial source is available, are as follows:

1. Specifications for and evaluation of concentric drill pipe.

2. Specifications for drill collars and drill pipe joint compounds.

3. Requirements for materials and techniques for internal coatings which can withstand geothermal environments.

4. Rapidly coupled, non-threaded tool joints and high pressure tool joint seals.

C. Lost Circulation

Listed below are suggested research and development areas related to lost circulation control.

1. Tools to locate and describe permeability conditions causing lost circulation are needed. Vug configuration and/or fracture density, widths, and locations need to be described. Inflow, outflow, or crossflow of natural fluids should be identified. Data would be used to help design lost circulation materials, volumes, and placement techniques. Casing and cementing programs could be modified to improve protection through lost circulation zones. Such a tool would also aid in describing major production zones to permit more efficient casing design/completion operations.

2. Within the producing zone, improvements in the following areas would be desirable.

   a. Controlled-density drilling fluids -- A stable fluid with density between that of air and water would enable closer balancing of formation pressures to prevent formation breakdown.*

   b. Non-damaging plugging materials -- Methods to allow temporary and economical plugging of a problem zone need to be developed. The techniques would have to be reversed at a later time (or would have to self-destruct with time or temperature) to reduce productivity impairment. Mechanical sealing techniques or new lost circulation materials should be considered.*

   c. Concentric drill pipe use -- In this concept, mud is pumped down the pipe-wellbore annulus, gas is pumped down the drill pipe annulus, and returns come up the center tube. The wellbore remains pressurized to maintain stability, but mud velocity is low. The cuttings can be efficiently lifted by the high velocity fluid comprising a mixture of gas and mud which comes up the center pipe.*

3. Above the producing zone, improvements or innovations in sealing materials are needed. Three types of materials or plugging methods are as follows:

   a. A mud which is mixed with a chemical and then rapidly solidifies.

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*These items may also be applicable to uphole problems providing they can be applied and the well can still be cased and properly cemented.

b. A separate material which 1) solidifies upon contact with formation fluids, or 2) contains two components which react to form a solid plug.

   The above fluids would have to be thermally stable to 350°C, immiscible and insoluble in wellbore/formation fluids, rapid setting, able to set and seal under dynamic conditions (while moving due to cross flow), and have strength to withstand differential pressure between wellbore and formation.

c. A mechanical seal or open hole patch could perhaps be utilized by placing some material, such as metal, across the lost circulation zone. The patch must not interfere with casing installation or cementing.

D. Completions

Initiation of efforts, or additional efforts, should be programmed for the following subjects.

1. An investigation of formation damage and resulting productivity impairment should be conducted. This project should include identification and prevention of possible permeability damage around the wellbore from various sources. Improved stimulation methods to remove such damage should be developed.

2. Plugging agents to seal off unwanted fluid entry should be developed.

3. Potential problems with sand control should be evaluated. There are indications of problems in the Imperial Valley.

E. Casing

1. Casing failure -- The basic mechanisms contributing to the failure of casing in geothermal wells should be investigated. This study may identify the need for improved logging and evaluation tools.

2. Coatings -- Requirements for plastic or metallic coatings to minimize internal and external corrosion should be established.

3. Cementing -- Casing string problems caused by inadequate cementing should be described. Possible cementing advances should be evaluated and alternate solutions should be proposed where necessary.

4. Buckling -- Additional data should be obtained to study casing buckling. Additional definition is needed to separate collapse and buckling failure and to identify conditions that cause each failure mode.

5. Coupling design -- The cost effectiveness of API buttress threads should be determined for geothermal wells. The additional cost for providing positive protection of premium threads should be analyzed on a cost/benefit basis. The industry need for a special geothermal coupling should be determined.

6. Casing hanger -- A constant tension casing hanger would be a welcome addition to the suite of downhole completion tools.

7. Design standards -- A Recommended Practice should be submitted to API for geothermal casing rating. The objectives would be to simplify design and to specify standards for producing special geothermal materials.

8. Elastomer needs -- New developments are needed in methods to seal casing strings in hangers, improve life of seals in expanding wellheads, provide reliable protection from drill pipe wear, and to improve the reliability of downhole packers and tools needed to test, evaluate, repair and properly install casing.

9. Scaling -- The causes of scaling as a function of location should be defined. Cleanout frequency and cost, and productivity impairment should be evaluated vis-a-vis modified completion methods that eliminate precipitation points. This study should include future surface system designs that keep fluid under pressure to minimize scale dropout. Chemical inhibition should be considered.

F. Cementing

The following items indicate research and development areas that will improve geothermal cementing.

1. New materials are needed, but their cost must not be excessive. The Panel felt that a reasonable cost goal for new materials would be about twice that of current costs, which average $4-5 per cubic foot.

2. The performance of cements under dynamic, simulated geothermal conditions should be studied. Present compositions being tested include 1) variations of Portland cement by admixtures, 2) non-Portland, inorganic cements, and 3) high polymer ratio systems, both inorganic and organic.

3. Methods for utilizing extenders to cut slurry costs should be investigated.

4. Possible methods for chemically treating drilling mud for alteration into cement should be investigated. This study should be coordinated with drilling fluid research and would likely involve a non-conventional mud composition.

5. Cost effective modifications to existing cements or development of new compositions to improve any or all of the following properties should be investigated.

   a. Placement ability -- The slurry should respond to retarders so as to achieve pumpable viscosity at bottomhole temperature, but it must set up properly uphole.

   b. Thermal stability -- Cured cement should retain strength and integrity at high temperatures for long periods (years).

c. Shear strength -- After setting, cement must restrain shearing loads imposed by casing movement in response to cyclic temperature changes. There is evidence that bonding presently is inadequate and that restraint is achieved only by positive gripping of collars.

d. Density control -- Slurries should be capable of being tailored to individual well conditions by reducing density to as low as 8 pounds per gallon.

e. Low permeability -- To prevent corrosive formation fluid attack on pipe surfaces, cured cement should have a long-term permeability of less than one millidarcy.

f. Self-healing features -- In conjunction with low permeability, the cement should seal itself when formation fluids enter micro-cracks.

V. Recommendations

The Panel on Borehole Technology summarized their assessments, conclusions, and recommendations into five major tasks as outlined below.

Task 1. Investigation of the Chemical and Physical Behavior of Non-Bentonitic Clays and Clay Morphology for Geothermal Utilization

Task 2. Development of Drill String and Casing Materials Compatible with Geothermal Environments

Task 3. Development of Lost Circulation Materials, Tools, and Procedures

Task 4. Development of Completions Plugging Agents

Task 5. Development of Geothermal Cements

Task 1. Investigation of the Chemical and Physical Behavior of Non-bentonitic Clays and Clay Morphology for Geothermal Utilization

Subtask 1.1 Non-Bentonitic Clays

Investigate the use of non-bentonitic clays in various continuous-phase media to provide thixotropy and fluid loss control with minimum residual formation damage. Bentonite and sepiolite are currently being used as viscosifying agents along with lignite and polymers. Each clay should be evaluated along with the various combinations of the two clays. In addition, other approaches such as the use of non-aqueous fluids should be evaluated. Alternatively, temperature-stable fluid loss control agents and thixotropic agents should be evaluated. This study should utilize the following procedures:

1. Test fluids in cores under downhole conditions for return permeability behavior.

2. Determine rheological properties under downhole conditions.

3. Determine static and dynamic filtration rates under downhole conditions.

4. Determine lubricity of fluids and filter cakes.

Subtask 1.2 Clay Morphology

Investigate clay morphology (structure and structural changes with temperature) under hydrothermal conditions. This study should

1. Define basic mechanisms of the bentonite gelation problem,

2. Determine how sepiolite clays behave differently than bentonite, and

3. Investigate the behavior of bentonite-sepiolite mixtures.

Task 2. Development of Drill String and Casing Materials Compatible with Geothermal Environments

Subtask 2.1 Drill String

1. Concentric drill pipe -- The technical feasibility and cost effectiveness of using concentric drill pipe in geothermal applications should be investigated. Disadvantages of special handling and running needs versus the possible reduction of lost circulation problems should be considered. Design and construction of a concentric string for geothermal drilling should be undertaken.

2. Thread compounds -- Available materials should be investigated and tested under geothermal conditions to develop specifications for drill collars and drill pipe joint compounds.

3. Internal coatings -- Available materials and techniques should be evaluated, and requirements for internal coatings to withstand geothermal environments should be developed.

4. Tool joints -- The feasibility and economics of new types of tool joints that can be rapidly coupled without use of threads should be investigated. Such a breakthrough would reduce coupling failure problems and reduce trip time. Development should proceed if investigation results are positive.

5. High pressure drilling -- Improved tool joint sealing ability, either metallic or elastomeric, is needed for deeper drilling involving high pressure. Potential drilling requirements should be evaluated and current sealing capability investigated to determine project scope.

Subtask 2.2 Casing

Investigate the performance of casing strings in geothermal wells. This should include the following activities:

1. Determine casing failure mechanisms.

2. Identify conditions causing internal and external casing corrosion. Factors such as metallurgy, local fluids, depth, geology, temperature, completion/cementing methods, producing methods, and flow rates should be considered. Requirements for special plastic or metallic coatings should be identified. The cost effectiveness of prevention

methods compared to alternative programs such as well replacement, workover and exotic alloy use, should be defined. Monitoring and evaluation needs should be defined.

3. Submit a recommendation to API to modify casing specifications and ratings to be more applicable to geothermal conditions. Additional data would allow consideration of temperature and pressure effects. Manufacturer participation should be encouraged.

Task 3. Development of Lost Circulation Materials, Tools, and Procedures

Subtask 3.1 Sealing Materials

1. Develop a material that will solidify upon contact with formation fluids or one which contains two components which react together to form a solid plug in-situ.

2. Develop a mechanical seal or openhole patch which will allow bridging of a lost circulation zone.

Subtask 3.2 Controlled-Density Fluid

Develop a stable fluid with a controlled density between that of air and water which would enable closer balancing of formation pressures.

Subtask 3.3 Lost Circulation Tool(s)

Develop a tool to locate and describe permeability conditions causing lost circulation.

Subtask 3.4 Reverse Circulating Concentric Drill Pipe

Develop a reverse circulating concentric drill pipe compatible with the geothermal environment such that mud is pumped down the pipe-well annulus and gas is pumped down the pipe annulus with both recirculating to the surface through the center tube.

Task 4. Development of Completions Plugging Agents

Identify or develop plugging agent(s) to prevent unwanted non-commercial fluid entry into a production well.

Task 5. Development of Geothermal Cements

Subtask 5.1 Study of Present Cements

Study and investigate the performance of present cements under simulated, dynamic geothermal borehole conditions to precisely define the behavior of these cements.

Subtask 5.2 Develop Specifications for a Geothermal Cement

Based on the studies and investigations of Subtask 5.1, develop a specification for geothermal cement.

BOREHOLE PANEL RECOMMENDATIONS

Major Category	Specific Task	Estimated Expenditures (dollars in thousands)
1) Casing failure analysis	a) Failure mechanism determination	$ 500 - 1000K
	b) Corrosion control surface treatment	1000 - 1500
	c) Design specifications	100
	d) Cement placement techniques	*
2) Lost circulation control techniques	a) Sealants, materials and mechanical	2500
	b) Identification methods (tools)	3000 - 5000
	c) Controllable density fluids	**
	d) Concentric drill pipe	**
3) Cementing	a) Large ΔT cement	Preliminary work underway in industry
	b) Self-heating cement	4000 - 5000
	c) Low density cementing	
4) Drilling fluids	a) Non-bentonitic fluids	500
	b) Morphological clay mineralogy	500
5) Drill string	a) Internal coating	500
	b) Quick connect joint	3000
	c) Thread compound	100
	d) Inert gas generation	1500 - 3000
	e) Tool joint for high pressure drilling 10,000 psi	250 - 500
6) Downhole completions	a) Unidiameter wellbore	***
	b) Plugging agents	750 - 1000
	c) Slotted line failure analysis	***
	d) High-temperature explosives	***
	e) Packers	***
7) Wellhead design	a) Coatings, metallurgy or surface corrosion	****
	b) Metallic seals	****

* Addressed in cementing industry research
** Not recommended under budget and time restraints as a priority item
*** Addressed in existing research projects or by industry
**** Solutions to other problem areas will address these tasks

REPORT OF THE PANEL ON ROCK DRILLING TECHNOLOGY

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I. Objectives of the Panel

The objectives of the Panel on Rock Drilling Technology were to identify advanced techniques for breaking rock and to determine which of these techniques has the potential for being developed by 1986 into an advanced drilling system that could lead to a geothermal well cost reduction of 50%. Advanced drilling systems are herein described as new systems that go beyond incremental improvements in present rotary systems, yet are thought to be achievable within the time and funding constraints stated for the DOE/Sandia Drilling Technology Development Program.

II. State-of-the-Art Assessments

A. Characteristics of Geothermal Reservoirs

The three geothermal reservoir types considered in the panel discussions were dry steam, hot water, and hot dry rock.* Reservoir characteristics for five typical fields (Table 1) indicate that, aside from differences in specific rock types and geologic framework, the reservoirs are distinguished primarily on the basis of formation fluid pressure. Dry steam reservoirs are inherently abnormally low-pressured, the hydrothermal reservoirs are modestly under- to hydrostatically-pressured; and the hot dry rock reservoirs ideally are dry, so that the influence of the fluid pressure is negligible. Generalized drilling problems associated with geothermal reservoirs are listed in Table 2.

Natural fractures (joints) are an essential feature of dry steam and most hydrothermal reservoirs. They are required to convey fluids to the wellbore in that (with possible exception of the Imperial Valley) initial integranular porosity and permeability are low or the natural circulation of hot waters has degraded them via solution and cementation. Most of the fractures tend to be vertical, and mineralization along their upper reaches contributes to reservoir sealing.

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*Abnormally high-pressured (geopressured) hot waters commonly found in petroleum provinces such as the Gulf Coast were not included in the scope of this workshop.

Reservoir Type	Example	Fluid Pressure	Primary Reservoir Rock	Reservoir Temperature °C	Reservoir Depths (Km)	Porosity and Permeability
dry steam	Geysers	abnormally low	metagraywacke	250	2-4	fractures
hydrothermal	Imperial Valley	hydrostatic	sandstone and metasediments	180-370	1-2	integranular and fractures
hydrothermal	Valles Caldera	under hydrostatic	extrusive igneous tuff and andesite	> 250	2-3	fractures
hydrothermal	Roosevelt Hot Springs	hydrostatic	granitic	280	2-3	fractures
hot dry rock	Jemez Mtns. New Mexico	N/A	granitic	200	3-4	hydraulic fracturing required

Table 1. Characteristics of typical geothermal reservoirs

I. Low Penetration Rates

* Low rates are caused by drilling dense, abrasive, fractured rocks; conventional bits at high temperatures give short runs.

* Directional control sometimes requires slower drilling and conventional tools often fail in the geothermal environment.

II. Lost Circulation and Borehole Stabilization

* Control is attempted by use of conventional lost-circulation materials.

* Cement plugs are frequently required.

* Casing strings are required to shut off the lost circulation zones and must be cemented from shoe to surface.

III. Corrosion in Circulating Equipment

* Oxygen in the system along with naturally occurring non-condensible gases and salts causes severe corrosion problems.

* High temperatures enhance the corrosivity.

Table 2. Generalized problems in drilling geothermal wells

Negatively, the fractures complicate drilling by causing lost circulation, loss of gauge, and hole deviation (Table 2). The hot dry rock reservoir needs to be hydraulically fractured to permit communication between injection and production wells. Directional drilling to intersect natural or artificial fractures is helpful in most geothermal reservoir development.

B. Rock Mechanics Considerations in Geothermal Drilling

1. Introduction

Geothermal drilling and completion problems involve the mechanical behavior of a wide variety of fractured rocks at temperatures to 350°C and at depths to 4 km where overburden and borehole pressures may reach 150 MPa (22,000 psi) and 40 MPa (5800 psi), respectively, and where the rocks are in a chemically active aqueous environment. In addition, the rocks are deformed over a wide time range such that their failure needs to be evaluated at the high strain rates existent during drilling and at the slower rates that occur during the lifetime of the well.

The mechanical properties of primary interest in rock deformation are the instantaneous strength and failure mode, the strain at failure, and time-dependent transient flow of intact rock and of the frictional sliding of rock-on-rock. A wealth of experimental data has amply verified the generalities that for any given rock type:

a) strength and ductility are enhanced by effective confining pressure,

b) strength is decreased and ductility is increased by increasing temperature, decreasing strain rate and porosity, and by the existence of fractures and other planes of mechanical discontinuity which relate to the size of the body, and

c) strength is increased and ductility decreased by decreasing grain size except in the case of shales and other rocks with load-bearing frameworks composed of clays, micas, serpentinite, chlorite, etc.

During drilling, the environmental parameters are dominated mainly by the following:

a) borehole pressure and effective pressure in the rock along the bottom of the hole,

b) rock permeability, which governs the rate of equilibration of borehole and pore fluid pressures,

c) mechanical stress concentrations produced by the cutter on the bit or the power input of other drilling methods,

d) the rate of impact of the cutter, abrasive, jet, etc., and

e) any gross stress changes introduced by kerfing, heating, etc.

	Rock Behavior		
	Brittle	Semi-brittle	Ductile
Fracture (cataclasis)	a) Precursive micro-fracturing minimal b) Discrete macroscopic tensile or extension fractures predominate over shear fractures, side cracking minimal c) Deformation requires least input energy d) All rock types	a) Precursive micro-fracturing increases b) Macroscopic shear fractures with gouge predominate c) Fracture surface area greatly increased d) All igneous rocks, sandstones, dolomites	a) Deformation is by precursive micro-fracturing b) Pervasive cataclastic flow c) Stress corrosion cracking can be creep mechanism. This requires low energy input, but increases in importance with increasing time d) All igneous rocks, sandstones, dolomites
Grain boundary sliding	a) Minimal	a) In igneous rocks and sandstones, grain boundaries are broken and frictional sliding along them contribute to deformation b) In argillaceous shales, serpentinites, and some metasediments slip takes places along flat surfaces of clays, micas, serpentinites	a) This is the major deformation mechanism in all rocks dominated by clays, serpentinite mica, chlorite, etc.
Intra-granular gliding flow	a) Minimal	a) Becomes major mechanism in limestones and evaporites b) Begins to operate in dolomites	a) This is the major mechanism of deformation in limestones, dolomites, and evaporites

Table 3. Deformation mechanisms and the brittle-ductile transition

After drilling, borehole stability is largely controlled by the borehole pressure and borehole stresses, by the quality of the borehole wall (irregular boreholes set up stress concentrations), and by temperature gradients around the borehole. With regard to the latter, cooling the borehole will help to stabilize it by increasing rock strength, decreasing ductility, and decreasing the tangential stress which drives the deformation at the borehole wall.

2. Deformation Mechanisms and the Brittle-Ductile Transition

Under the pressure, temperature and time regimes of geothermal drilling stated above, the deformation mechanisms (failure modes) are fracture (cataclasis), grain boundary slip, and intergranular gliding flow. The mechanisms that will operate in any given situation are dependent on rock type and the ambient physical conditions. These are outlined in the matrix of Table 3. Under any set of conditions those deformation mechanisms requiring the least energy will be favored. Thus, for example, in the semi-brittle and ductile regimes it takes less input energy to cause limestones to deform by twin or translation gliding than to fracture them.

3. Drillability

In general, rock drilling involves deforming the rock to create a chip or fragment and then removing that fragment from the bottom. Drilling bits or devices designed to fracture the rock work best when the rock is mechanically brittle. Available data, largely on dry rocks, indicate that many remain brittle or semi-brittle at geothermal well pressures and temperatures; these include all crystalline igneous rocks, siliceous tuffs, siltstones and shales, most sandstones and metagrawackes, and some serpentinites. While remaining brittle or semi-brittle, their strengths decrease with increasing temperature so their drillability should actually increase with depth provided the borehole pressure is held constant.

Rocks apt to be ductile include argillaceous shales (i.e., those containing clay minerals), limestones, evaporites, greenstones, some serpentinites, and unconsolidated sediments. There, materials are invariably weak, and they are easily indented by elongated cutters such that bit changes are required to drill them efficiently.

4. Borehole Stability

Stable boreholes occur when instantaneous or time-dependent rock strengths exceed the differential stresses existent at the borehole walls. From stress-strain test data it is known that under many physical environments there is a nearly linear or slightly curved relationship between ultimate strength (differential stress at failure) and mean stress. Accordingly, plots of rock strength and mean strength at failure can be superimposed on a plot of borehole stresses versus depth to assess the likelihood of borehole failures or stability. A different set of borehole stresses and corresponding depths are needed for various rock conditions.

C. Conventional Drilling Techniques

1. Roller Bits for Geothermal Drilling

Tri-cone roller bits currently used in geothermal drilling can be placed in two categories, (1) sealed, and (2) unsealed. The type of bit used is determined by the type of drilling fluid used and the formation temperature. Although the bearings are different, the cutting structures are identical. An explanation of the roller bit characteristics is as follows:

a. Cutting Structure

Because the majority of the geothermal reservoir systems are found in either igneous or metamorphic rocks, the drilling is usually in hard and abrasive formations. Therefore, sintered tungsten carbide insert type bits are generally used. The geometric cutting structures used are the same as those currently used in the oil fields. They differ only in the tungsten carbide insert grade used. Geothermal bits use harder, more wear resistant grades, especially for the gauge row inserts.

b. Bearing Types

The well temperature and the circulation media control the bearing selection. Two bearing types are commonly used and are described as follows:

Unsealed, Open Bearing, Air Circulation Bits -- The air or mist cooled open bearing bits use what is called an "RBF" bearing (roller, ball, friction). The air or mist is used to cool and help clean the bearing. Although new material changes are planned in the open bearing bits, standard air bearings have been used to date, and they are limited by wear problems and tempering limits of the current materials.

Sealed Bearing Bits -- Today, sealed bearing bits use oil field seals that are limited to 125°C to 150°C. There are two sealed bearing systems available, those using rollers and those using the friction journal concepts. There are differences between these two bearing types that should be noted. The roller bearing bit is somewhat easier to seal than the journal bearing bits because the anti-friction bearing runs slightly cooler. This could be a factor where marginal temperature increases are encountered. The journal bearing bit generally has longer life as long as the seal remains effective.

c. Other Features

i. Lugs and/or additional leg hardfacing are used to help maintain bit stability and reduce leg wear to prevent bearing or seal damage.

ii. The nozzles on bits using air bearings should be sized to divert 30% of the air supply through the bearings for cooling and cleaning purposes.

iii. Improved, high temperature elastomers have been used in a few products with some bit life improvement.

iv. Increased journal angles are used on some open bearing designs to reduce gauge wear and improve the inner bearing life.

2. Diamond Bits for Geothermal Drilling

Diamond bits of three distinct types suitable for geothermal drilling are being used today in drilling and coring applications in sizes up to 17-1/2 inches diameter. These are as follows:

a. Conventional, surface set diamond drill and core bits, each employing hundreds of industrial diamonds (e.g., sizes of 4 or 8 stones per carat) individually set in a cast matrix to cover the bit drilling surface,

b. Bits employing sharp, polycrystalline, synthetic diamond and tungsten carbide cutters, like Stratapax[R], with surface-set diamond gauges at the O.D. (and I.D. for core bits), and

c. Impregnated bits, employing synthetic and natural diamond grits dispersed in powder metal matrix "inserts." These diamond grits are similar to those used in diamond sawing. The powder metal inserts are arranged on the bit drilling surface to bring all of them into contact with the formation. Usually, in impregnated bits, the gauge dimension of the hole is drilled with surface-set diamonds.

Diamond bits are generally manufactured in powder metal infiltration processes and joined with alloy steel shanks. Sometimes additional steps involving hot pressing or sintering operations are used for segment production. This process yields drilling tools having no moving parts, great strength, high reliability and extreme durability.

Applications for diamond bits of these three types range from medium hardness formations, in which polycrystalline diamond cutters and surface-set diamond bits are used; to the most abrasive, hard, and tough formations where impregnated diamond bits are used. Drilling rates with diamond bits in oil and gas drilling currently range from 90 feet per hour on mud-motors in soft formations, down to 1 to 3 feet per hour in abrasive, dense, hard, and cemented sandstones. Diamond bits are usually run with mud circulation which provides 3.0 hydraulic horsepower per square inch of bit drilling surface. Air and gas circulation have been successfully (but infrequently) utilized in diamond coring in limestones and dolomites.

Weight-speed practices with diamond drills depend on the formation being drilled and the drilling techniques. In conventional rotary drilling, it is standard practice to use 4000 to 8000 pounds of applied bit weight per inch of bit diameter and rotary speeds of 50 to 120 rpm. On the other hand, in turbo-drill or mud-motor diamond bit applications where depth of cut per diamond per revolution can be reduced, weight applied is usually less and the rotational speed is correspondingly increased. Here, bit weights of 2000 to 5000 pounds per inch of bit diameter are commonly used at bit rotary speeds of 300-375 rpm with mud motors and 400-650 rpm with current turbo-drills.

[R]Registered trademark of the General Electric Company

Stabilization of the bottomhole assembly (BHA) is important in diamond drilling to maintain control of the bit hydraulics flow distribution and the uniformity of drilling stresses.

In minerals exploration, diamond bits drill igneous, metamorphic and sedimentary formations, and in oil and gas development wells they drill sedimentary formations with bit life ranging up to 350 drilling hours.

Currently, diamond bits are designed for deep hole rotary and downhole motor drilling in sedimentary formations for petroleum exploration. Geothermal drilling often takes place in stronger, fractured, igneous rocks, and requires new diamond bit designs which incorporate suitable cutting elements. These elements must withstand the high impact loads and abrasion produced in the geothermal formations.

Conventional diamond bits used for geothermal drilling and coring have had limited success. The bits have used surface-set natural diamonds in a "ridge set" pattern for maximum resistance to diamond failure. Nevertheless, the bits have had short life when drilling fractured granite. Possible solutions are to use an impregnated diamond bit (IDB) or polycrystalline diamond bits (PDB) (e.g., with Stratapax^{R} cutters). The use of these bits can lead to improved drilling rates and bit life, particularly in downhole motor drilling at high rotary speeds. However, the proper combination of grit size and concentration and predictable matrix wear characteristics must be achieved to realize improvements in performance with the IDB. Polycrystalline diamond bits offer the potential for use in high speed drilling, but problems of bit hydraulics and cutter attachment need to be addressed.

D. Power Transmission Systems

When considering means for transmitting power from the surface to the drill in geothermal holes, there are the following possibilities:

1. Hydraulic
2. Pneumatic
3. Mechanical
4. Electrical
5. Chemical
6. Thermal
7. Electro-magnetic
8. Dynamic
9. Combinations of two or more of the above

From a pratical standpoint, hydraulic and pneumatic methods are closely related. Transmission of energy by thermal means will involve temperature as well as pressure considerations, but can be considered a special case of hydraulic transmission. Chemical techniques, on the other hand, will be considered separately.

Electro-magnetic wave concepts for power transmission fail to provide for high power rates. EM waves, fibre optics, etc., are satisfactory data links but are not now capable of power levels above a few horsepower of continuous operation. It is concluded that electromagnetic power transmission is not presently practical for consideration in geothermal drilling work. It is also felt that it would not be practical to expect development of EM transmission techniques to a usable form by 1986.

Dynamic transmission (stress wave, or dynamic mass) will be considered as a low interest version of mechanical transmission.

Therefore, the following four major methods and combinations remain:

1. Hydraulic
2. Mechanical
3. Electric
4. Chemical

1. Hydraulic Transmission of Energy

Hydraulic systems utilizing high pressure, high flow rate pumps are capable of transmitting large amounts of energy from the surface to the drill bit. Abrasive jet drills operating at approximately 5000 hp have been tested. The Panel feels that power transmission levels of up to 10,000 hp could be achieved by 1986 with hydraulics. Hydraulic power can be used directly in jet erosion drilling applications or converted into rotational energy by turbines or other motors.

The advantages of hydraulics are therefore high power transfer and relative simplicity. Most of the components are either state-of-the-art or nearly so. The system is not strongly affected by geothermal temperatures provided elastomeric seals are not required.

Disadvantages are that "dirty fluids" cause rapid wear of nozzles and actuators. Some applications would require high temperature seals that are not currently available.

Pneumatic systems are much more limited in power transfer capacity. Due to inefficiency and flow conductor effects, pneumatics are limited to 300 to 500 hp at the present time. However, since much geothermal drilling is done with air or mist, hammers and other pneumatic tools may be well suited for the geothermal drilling application.

2. Mechanical Transmission of Energy

Conventional rotary drilling utilizes the transmission of power by mechanical means. Drill pipe can deliver up to about 500 hp. Higher speed rotation (with lower torque) would deliver approximately the same power.

Advantages are simple construction with directly usable rotary action. Disadvantages are fatigue and surface wear in drill pipe (especially in geothermal wells). In addition, materials of construction are subject to temperature degradation and corrosion. Nevertheless, the state-of-the-art is well advanced, and systems of this type are economically competitive.

3. Electrical Transmission of Energy

Power transmission by electrical conductor is limited to approximately 1000 hp. High voltage-low current systems tend to have bulky connectors and insulation. At lower voltages, the conductor is large.

The advantages of electrical power are significant. The power link also provides for a data up-link. Speeds of electric motors are controllable by varying electrical frequency. Using electrical power for the drilling operation allows for independent hydraulic flow as required for other uses, such as cleaning.

The complexity of conductor coupling and conductor handling make the system difficult to use, and coupling failures are frequent. At the present time, flexible conductor insulation and virtually all seals use elastomers and are therefore temperature limited. The same is generally true for the downhole motor. These factors would appear to severely limit the use of electrically driven systems in the geothermal application.

4. Chemical Transmission of Energy

The transfer of energy by chemical means must be coupled with a physical transport system, such as hydraulics. But with reasonable volumes of liquid, chemical power transfer rates of greater than 20,000 hp appear to be possible. The high power rate is the major advantage of this form of transmission.

Many chemical conversion systems are, however, strongly affected by exposure to high temperature. The bottomhole environment may limit the use of chemical systems.

E. Advanced Drilling Systems

In the past ten years over $50 million has been spent on advanced drilling systems. These advanced systems remove rock by four basic mechanisms: 1) thermal spalling (370-600°C), 2) melting and vaporization (1100-2200°C), 3) chemical reactions, and 4) mechanically induced stresses. Devices which thermally spall rock (e.g., flame jets and rocket drills) have limited application because most rocks will not thermally spall. Rock melting drills (e.g., electron beams and lasers) have low drilling rates because of the high energy requirement for melting and vaporizing rock and because of the low thermal conductivity of rock. Electron beams and lasers can efficiently melt narrow kerfs in rock and therefore may eventually find application in conjunction with mechanical cutters (e.g., on tunnel boring machines). High temperatures and severe space constraints will preclude the use of these devices in geothermal wells by 1986.

Several advanced drills which mechanically remove rock have been used to drill deep oil wells. These include the following: 1) abrasive jet drills, 2) high pressure jet drills, 3) explosive drills, 4) percussive drills, and 5) downhole motors. High drilling fluid densities are required for abrasive jet drilling. These densities limit the use of abrasive jet drills in geothermal wells because of the severe lost circulation problems encountered in these wells. Cavitating jet drills and high pressure jet drills have the potential for increasing drilling rates in geothermal wells three- to four-fold when used in conjunction with mechanical cutters (e.g., roller or drag bits). Explosive techniques drill soft rock at high rates, but their application in hard rock is limited by low drilling rates and safety problems. Percussive drills have demonstrated three- to five-fold increases in drilling rate in hard rock, but severe mechanical problems currently limit the application of these tools in geothermal wells.

High speed downhole motors and bits have demonstrated that they can drill hard rock three to four times faster than conventional rotary drills. Improved high speed bits and improved motor seals and bearings will have to be developed before downhole motors find widespread application in geothermal wells. New polycrystalline diamond bits have also demonstrated high drilling rates in hard rock. These bits may be suitable for use with downhole motors, and the combination may yield very high drilling rates.

F. Geothermal Drilling Test and Simulation Capabilities

Laboratory testing can provide quantitative technology evaluation beyond the standard field performance assessment. It is desirable in component development work to perform repetitive testing which is time and cost efficient. Similar capabilities are needed to assess the performance of the final tool. For example, development of a new seal may require 20 to 100 iterations of tests on different seals. Or, a modified roller bit which might require fifty or more bit field runs to assess the effect of the change, may be evaluated with a few correctly simulated laboratory tests drilling into a control rock sample.

Test facilities are available to provide general simulation of downhole conditions, and for full-scale testing of tools. Laboratory pressure simulators can create a full-scale borehole with over burden stress, horizontal stresses (by subjecting large rock samples to high confining pressures), and pore fluid pressure to simulate 30,000 ft well depths. Wellbore fluid pressure is accomplished by pumping water, brines (at modest concentrations), or mud with large mud pumps.

Limited elevated temperature capability exists, but no full-scale capability exists for handling hydrogen-sulfide and other such corrosive environments. Laboratory hot-air drilling test facilities (8-3/4" bits) are available to 300°C. High temperature test stands are available for specific seal tests under simulated downhole pressures and temperatures. Full-scale mud motor test stands for simulating downhole pressure and temperature, and for providing some dynamic-vibratory loadings are becoming available.

In general, it is now possible to simulate the different geothermal reservoir types, except when circulation is required at elevated temperatures.

G. Specialty Tools

While the topic of specialty tools is not particularly related to rock breakage, some panel members felt that the following information should be included in this section of the report.

1. Fishing Tools

Major problems arise when drilling conventional wells in determining the configuration of the "fish" on bottom. This is complicated in high temperature wells by the changes occurring in length of the fish as it is cooled or heated. If the complications of directionally drilled segments of the well, fractures, and vugular formations are added, the problem is compounded. To reduce the magnitude of the problem, the following developments would be useful:

a. high temperature drilling muds,

b. downhole surveying tools to determine "attitude" of "fish," and

c. mills, jars, washovers, etc., that are capable of withstanding temperature variations encountered during fishing operations.

2. Downhole Gas/Water/Mud/Foam Separators

Downhole fluid separators are needed to allow the use of fluid driven motors while permitting use of aerated muds and foams for reducing borehole pressures while drilling in fractured formations.

3. Underreamers

The problems associated with conventional underreamers are greatly complicated by the hardness, temperatures, and corrosiveness of geothermal wells. An underreamer designed specifically for geothermal applications is needed.

III. Conclusions and Findings

The Panel on Rock Drilling Technology considered three basic aspects of an advanced drilling system; namely, surface equipment, transmission of power from the surface to the drilling tool, and efficient use of the power at the rock face (rock drilling technology). The Panel recognized that improvements in penetration rates by themselves could not result in the 50% cost reduction goal; however, it was pointed out that increased rates would lead to other cost savings in addition to reduced rig charges. It was felt that increases in instantaneous penetration rate of a factor of 4 to 5 would be an attainable goal, and the discussions were intended to define systems which had a high probability of achieving these increases.

A. Surface Equipment

The Rock Drilling Panel felt that there were very few constraints on surface equipment in terms of space or power requirements. It was recognized, however, that certain technology limitations do exist, e.g., in terms of high pressure pumps, but that these problems would be addressed by the Surface Technology Panel. Discussions of this technology was, therefore, brief, and it was assumed that any practical rock breaking technique would not be precluded by the lack of surface equipment.

B. Power Transmission Systems

The Panel felt that the four major power transmission methods; hydraulic-pneumatic, mechanical, electrical, and chemical, are all potential methods for use in geothermal drilling. All have advantages and limitations. Combinations of techniques are possible. In the remaining parts of the report, drilling techniques will be discussed, and the transmission system required to implement the rock breaking technique will be identified.

C. Rock Drilling Technology

The Panel discussed both advanced and novel techniques for breaking rock and the potential for using these techniques in a practical drilling system by 1986. The criteria used in evaluating the potential for these various concepts were: 1) the probability that the required technology could be developed by 1986, and 2) the probability that the technology, if developed, would contribute to the 50% cost reduction goal. It was decided to assign an overall probability, either none, low, medium, or high, to each technique

Drilling Technique	Power Transmission System: Hydraulic	Mechanical	Electrical	Chemical
1) Abrasive jet drilling				
a) Shot	None[1]	NA*	NA	NA
b) Recirculated cuttings	Low	NA	NA	NA
2) High pressure jets with no mechanical augmentation	None	NA	NA	NA
3) High pressure jets with mechanical augmentation				
a) Surface pressure 1000-5000 psi	Med	NA	NA	NA
b) Surface pressure 5000-15000 psi	High	NA	NA	NA
c) Surface pressure > 15000 psi	Low	NA	NA	NA
4) Percussion drill				
a) Air	High	Low	Low	Low
b) Fluid (water)	High	Low	Low	Low
c) Fluid (mud)	Med	Low	Low	Low
5) Downhole motors	High	NA	Low	NA
6) Laser	NA	NA	None[2]	None[2]
7) Electron beam	NA	NA	None[2]	NA
8) Flame	NA	NA	NA	None[3]
9) Subterrene	NA	NA	None	NA
10) Plasma	NA	NA	None	None
11) Electric Arc	NA	NA	None	NA
12) Explosive	NA	NA	NA	None[4]
13) Spark	NA	NA	Low[5]	NA
14) Impact	None	None	NA	NA
15) Implosion (pellets)	None	None	NA	NA

* NA -- technique not applicable with transmission system

[1] Technique may be useful in long-term for hot dry rock drilling.

[2] Some application for these techniques may be found in the very long term in kerf cutting; however, the probability that they could be used in deep drilling by 1986 is essentially none.

[3] This technique has essentially no probability of being used in water filled holes.

[4] This technique is limited in temperature capability.

[5] Electrode life and insulating materials are the key problems.

Table 4. Probability of significant contribution to 50% cost reduction goal by 1986

considered. This assigned probability represents the panel's assessment of the potential contribution of that drilling technique to the DOE programmatic goals. Table 4 presents these assigned probabilities for each drill type and power transmission system.

As shown in this table, the Panel felt that there were three systems which had a high probability of being developed by 1986 and which could increase instantaneous penetration rates by factors of 4 to 5 in geothermal wells. These are percussion drilling, high pressure water jets combined with mechanical techniques, and high speed downhole motors and bits.

Percussion systems have been investigated previously for oil well drilling, and increases in penetration rates of factors of 5 were achieved in brittle rock. The system appears to function best when combined with rotary motion. These drills can be used with either air or water as the drilling fluid. Percussion drills have been tested in the Geysers, and increases in penetration rate were obtained; however, the lifetime of the hammer was short. It is felt that the lifetime could be increased through technological improvements. An attractive feature of the air hammer is that no seals are used, so that its use at high temperature may be possible with only minor modifications. In addition, no new surface equipment would be required.

The development of a high pressure water jet drilling system was also given a high probability of success for geothermal drilling. However, the panel felt that the use of high pressure jet drilling without mechanical augmentation was not feasible in the near-term because of the high pressure (> 15,000 psi) required to cut the hard rock found in geothermal reservoirs. The best use of these systems appears to be in conjunction with conventional bits, e.g., roller cone, polycrystalline diamond, or natural diamond bits. The Panel felt that the water jets should be positioned to cut kerfs in the bottom of the hole, thereby providing for easier mechanical breakage of the remaining rock by the conventional bit.

Considerable discussion was conducted relative to the abrasive jet drilling system developed by Gulf Research and Development. This system shows promise for deep oil and gas drilling, but does not appear to be promising for geothermal applications because of the high mud weights required. Since most geothermal reservoirs are subnormally pressured, lower density fluids must be used for drilling. Further concern was voiced relative to the cost of the steel shot required to create the abrasive action. It was pointed out, however, that it may be possible to utilize recirculated cuttings from the bit rather than the steel shot for abrasion. The Panel indicated a "low" probability of success for this idea. It was also recognized that the steel shot abrasive system might have application in cutting kerfs in drilling hot dry rock reservoirs. The panel felt strongly that the high pressure pumping technology developed by Gulf for this system could be extremely useful in high pressure jet cutting without abrasives.

Downhole motors offer the potential for significantly increasing penetration rates in geothermal drilling, provided high speed bits can be developed. The panel felt that hydraulically driven motors have a higher potential for successful development than electrically driven motors for the geothermal drilling application because of temperature problems. It was emphasized that high speed bits (300-1000 rpm) would need to be developed to fully utilize the motor capability. Impregnated diamond bits and polycrystalline diamond bits were felt to be strong candidates for this application.

The remaining drilling techniques, which could be considered novel, appeared to have practical difficulties which would make the probability of their development by 1986 essentially zero.

During the discussion of novel systems, it was pointed out that rock melting drills might have some applicability to the problem of sealing the borehole to prevent loss of drilling fluids and cement. While this problem was specifically the province of the Borehole Technology Panel, it was suggested that rock melting devices should be evaluated for use in this application.

D. Rock Mechanics Investigations

In general, optimum bit designs have been obtained in the past primarily by trial and error methods. It is essential to speed the development and optimization of advanced drilling systems by a supportive rock mechanics effort. For each advanced system, the rock mechanics effort should include characterization of needed rock properties, finite element analyses of the stress field at the bottom of the hole and how it is perturbed by the drilling system, and observational analysis of damage created by the system under controlled testing at simulated downhole conditions.

IV. Identification of Research and Development Areas

A. Areas for Improvement in Roller Bits

1. Problems

The principal roller bit problems resulting from the geothermal environment are as follows:

a. High downhole temperatures cause a loss in mechanical properties in bearings and prevent the use of conventional elastomeric seals and lubricants.

b. The rock formations encountered in most geothermal applications cause severe abrasive wear on the bit cutting structure, especially on the gauge row.

c. Corrosion problems occur, primarily in hot brines, that can shorten bearing life, attack cemented carbides and weaken areas of high stress (stress corrosion).

2. Assessment of Immediate and/or Short Term Solutions

While the Panel concentrated primarily on advanced techniques, it was felt that several improvements in conventional roller bits could be made, and that these should be pointed out here.

a. Immediate improvements in mechanical properties can be achieved through materials substitution. For example, materials with higher hot hardness can improve bearing life. Due to the time span required for developing new seals for sealed bits, the substitution of new materials in unsealed bits appears to be the fastest intermediate solution to improving bearing life. The seal development work should concentrate on metal-to-metal seals or non-elastomer types only.

b. The immediate gains in the gauge or cutting structure wear problems are being accomplished through the use of more wear resistant tungsten carbide insert grades. Future improvements should come from the use of polycrystalline diamond cutters either on the gauge itself, e.g., inserts using diamond implants, or polycrystalline diamond cutters used as reamers, either at the bit or above the bit. Elimination of the current bit reaming problem will allow significant reductions in well cost.

c. The corrosion problem in cemented carbides can be reduced by using nickel binder materials instead of cobalt. Recent tests in this area look encouraging.

d. Other areas for near-term improvements include designing nozzles to provide for proper air distribution to the bearings of open bearing bits, and increasing the journal angle on all tungsten carbide insert designs to reduce gauge wear and inner bearing radial thrust wear.

3. Long-Term Roller Bit Improvements

Longer term improvements in roller cone bits for high temperature operation would include the development of metal-to-metal seals; high temperature, high load bearing lubricants, hybrid bits, kerf-cutting bit designs, and improved bit designs capable of carrying higher weight and operating at higher rpm.

B. Areas for Improvement in Diamond Bits

The performance of current diamond bits is limited by abrasive wear of the diamonds due to frictional heat. This heating effect is accelerated by excessive bit speeds and/or inadequate flow of coolant and leads to progressively reduced drilling rates. In addition, the use of surface-set diamonds for drilling fractured formations leads to diamond breakage and rapid wear. These conditions may, however, be offset through the use of fine, strong, diamond abrasive grits in segments. Diamond wear is aggravated when formation, mud, or friction-generated temperatures reach approximately 200°C, and metallurgical instabilities may arise at temperatures above 300°C.

The development of new geothermal diamond bits with high impact and abrasion resistance for both drilling and coring operations needs to be pursued. Specific areas for R&D include the following:

1. Single Cutter Evaluation

Single point wear tests on hard, strong, abrasive rocks such as granite with impregnated diamond matrix compositions and polycrystalline diamond drill blanks should be carried out to determine the mechanisms of heat transfer, stress distribution, and wear. Then, if needed, materials of suitable wear resistance and cutting ability for geothermal drilling should be developed.

2. Bit Hydraulics Investigations

Fluid flow and heat transfer models especially for high speed diamond drill bits should be developed, in conjunction with laboratory flow and thermal tests, to determine the relationship among cutter wear, temperature, and fluid velocity across the cutters.

3. Laboratory Bit Testing

Laboratory drilling experiments with selected impregnated and polycrystalline diamond bit designs to determine performance in strong abrasive rocks should be considered. This program can be expected to yield bit technology suitable for commercialization within several years.

4. Field Test and Evaluation

Selected drill and coring bit designs, incorporating either impregnated or polycrystalline diamond cutters, should be field tested in both steam and hot water areas.

C. Identification of R&D Areas in Rock Mechanics

1. Tool/Rock Interactions

Little information is available on tool/rock interactions for conventional drilling techniques and even less is available for advanced drilling concepts. Studies are needed to allow optimization of each advanced drilling system.

2. Rock Properties

The experimental investigation of the mechanical properties of rocks under geothermal conditions provides background information on the dry, instantaneous strength and ductility of intact specimens. These data permit assessment of drillability and borehole stability for several classes of rock types. It is now necessary to investigate site specific rocks that are apt to be troublesome. Frictional sliding strengths and the role of interfering fractures needs to be investigated. Time-dependent, transient creep data are needed for both intact and fractured rock, if unsupported boreholes are to be maintained for long time periods. A scheme is now available to predict borehole stability from experimental data and assumptions on, or knowledge of, borehole stresses. It is therefore appropriate to conduct laboratory investigations of site specific rock samples to assist in understanding borehole stability questions.

3. Effects of Formation Fluids on Rock Strength

Too few data exist on the effects of chemically active, high temperature aqueous fluids on rock strength. Studies should be conducted to determine rock drillability under simulated downhole conditions.

D. Geothermal Drilling Test Capabilities

Geothermal test facilities that simulate downhole drilling conditions and allow full-scale simulation for component development and complete tool evaluation are presently available. However, additional temperature capabilities are required, particularly for air-foam drilling with large amounts of water and for water, brine or mud drilling. Specific drilling experiments may require simulation of drilling dynamics for fractured formations. The experiments may also require testing of the complete system, for example, the mud motor, the shock sub, the drill bit, and the rock.

V. Recommendations

The Panel on Rock Drilling Technology decided to summarize their discussions, conclusions, and recommendations into five major tasks as follows:

Task 1. Development of a High Speed Motor/Bit Drilling System for Geothermal Applications

Task 2. Development of a Percussion Drilling System for Geothermal Applications

Task 3. Development of a High Pressure Jet Augmented, Rotary Mechanical Drilling System

Task 4. Supporting Rock Mechanics Studies

Task 5. Advanced Studies

Task 1. Development of a High Speed Motor/Bit Drilling System

Downhole drilling mtors and high speed bits have the potential to drill at rates three to five times faster that conventional rotary drills because of their high rotary speeds (300 to 1000 rpm). Severe mechanical problems with these motors and with the bits currently prevent widespread use of motors for geothermal drilling. The objective of this task is to develop high temperature, medium speed (200 to 300 rpm) motors for use with roller bits and high speed (300 to 1000 rpm) motors for use with diamond bits. Motors are needed for use with 6 inch, 8-1/2 inch, and 12-1/4 inch diameter bits. A further objective is to develop roller bits and diamond bits which will work effectively at these high rotary speeds.

Subtask 1.1. Medium Speed Motor Development (200-300 rpm)

A need exists to develop a high temperature downhole motor that operates at 200-300 rpm. The need for a motor in this medium speed range is in part due to the greater probability of obtaining bits capable of running at these speeds and also the greater probability of solving some of the more complicated sealing and metallurgical problems prevalent with the higher speed motor. The medium speed motor must be capable of transmitting loads to the bit of up to 8000 lbs per inch of bit diameter. It must be capable of transmitting up to 1500 psi pressure drop through the bit. It must withstand a soak temperature of 300°C and a continuous operating temperature of 150°C. The tool should further be capable ofsupplying sufficient torque to effectively drive the bit in order to achieve the desired increases in pentration rates.

Subtask 1.2. High Speed Motor Development (300-1000 rpm)

The need exists to develop a high speed motor suitable for use under geothermal conditions. Primary consideration should be given to the use of axial-flow, mud-driven reaction turbines for this application. The speed of the motor should be changeable by varying the blading. Torque output must be sufficient to rotate the bit (probably diamond) loaded at 2000 to 4000 pounds per inch of bit diameter. The turbine must have a bit pressure drop capacity of 1500 psi, a continuous operating temperature capability of at least 150°C, and be equipped with a tachometer to enable the driller to determine output shaft speed periodically. Materials used must withstand a twelve-hour soak at 300°C, followed by cooling to 150°C with drilling mud. Drilling operations must be resumable within ten minutes after circulation is started.

Subtask 1.3. Medium Speed Bit Development (200-300 rpm)

1.3.1 -- Roller bits need to be developed to run at high temperatures (300°C), bit weights of 4000 to 8000 pounds per inch of bit diameter, and rotary speeds up to 300 rpm. The bits to be developed must achieve increased rates of penetration of up to five times normal and achieve twice the normal footage. Areas requiring development in order to achieve these goals are improved insert grades capable of higher impact and wear resistance, high temperature mechanical seals, new materials, and hydraulic improvements. Based on the present state-of-the-art, a considerable effort will be required in order to accomplish this task by 1986.

1.3.2 -- Diamond bits capable of operating at 200-300 rpm in geothermal formations may exist. However, careful selection and testing of existing designs will be required to verify that improved penetration rate and bit life are obtainable in these formations. The bits must be capable of operating at 150°C and soaking at 300°C in a corrosive environment. Bit weights of up to 8000 pounds per inch of diameter will be utilized. If no suitable bits are found in the existing products, then a second phase of this task would be to develop geothermal diamond drilling bits (surface-set or impregnated natural diamonds, polycrystalline diamond bits, or combinations) to meet the stated performance objectives.

Subtask 1.4. High Speed Bit Development (300-1000 rpm)

Diamond drill bits capable of operating at 300 to 1000 rpm rotary speed and delivering twice the footage and three to five times the penetration rate of conventional tools in hard, abrasive and broken geothermal formations need to be developed. These bits should operate at bit weights of 2000 to 4000 pounds per inch of diameter. Drilling and wear characteristics must account for a 300°C 12-hour soak, followed by circulating a 150°C mud, with up to 1500 psi bit pressure drop. Impregnated diamond bits and polycrystalline diamond bits appear to be the leading candidates for this development.

Subtask 1.5. High Pressure Pump Development

Conventional geothermal rotary rig pumps are normally operated at pressures of 1500 to 3000 psi. Higher pressures will be required to operate downhole motors. Pressure drops of 1000 to 2000 psi will be required across new high torque motors capable of operating at high bit weights. Bit pressure drops up to 1500 psi will be required to adequately cool and clean diamond bits at these high weights and high rotary speeds. These high motor and bit pressure drops will therefore increase the required pump operating pressures to the range of 4000 to 6000 psi. Although conventional triplex mud pumps are rated to operating pressures of 5000 to 5500 psi, severe maintenance problems are encountered with piston plungers and valves when these pumps are operated for extended periods at pressures above 4000 psi. Rig pumps therefore need to be upgraded so that they will operate reliably at pressures up to 6000 psi with drilling mud.

Subtask 1.6. High Temperature Downhole Tool Development

The capabilities of existing collar string shock absorbers and drill collar stabilizers should be evaluated to determine if any are suitable for 300°C and 150°C service operating temperatures in geothermal drilling applications to 15000 feet. This evaluation must take into account all known abrasive and corrosive environmental aspects. Candidate products must meet survival criteria of 500 hours inhole service life between overhauls while transmitting required torque and bit weights. Weights of up to 8000 pounds per inch of diameter are anticipated.

If no conventional products meet these nominal survival criteria while simultaneously performing their shock absorbing or stabilizing functions, the needed downhole tools will have to be developed.

Subtask 1.7. Thruster/Guidance System Development

Means for guiding downhole motors are essential when they are used for directional drilling. Downhole thruster systems will be needed in highly deviated holes where wellbore drag on the drill pipe prevents the application of the high bit weights needed for fast drilling. The thruster system should be designed so that it can also be used to assist in removing the drill string from these high angle holes.

Subtask 1.8. Lost Circulation Considerations

Due to the characteristics of geothermal reservoir systems, lost circulation is always a threat. Turbines must either be capable of passing lost circulation material or means to by-pass the lost circulation material to the formation must be incorporated above the turbine. The technique used to pass the material must not limit or reduce the normal operating capability of the turbine. Large scale work on this task should not be undertaken until the turbine design is set in order to see what limitations may exist.

Task 2. Percussion Drilling System Development

Penetration rates from 3 to 5 times that of conventional rotary drilling techniques in brittle rock have been achieved by percussion drilling systems driven by water or drilling mud. However, mechanical failures in the drill have generally limited the lifetime of the system. Since much of the drilling for geothermal energy is done in hard, brittle rock, the percussion system appears to offer the potential for significantly increasing penetration rate. In addition, it appears to be possible to use low density fluids, e.g., air or mist, to power percussion drills. Since these fluids are commonly used in geothermal drilling, the percussion drill could be utilized with little change in existing surface equipment. The objective of this task is to develop a percussion drilling system capable of achieving high penetration rates and long life in the geothermal environment.

Subtask 2.1. Development of a Reliable Air/Fluid Percussion Drill

Commercially available percussion drills should be evaluated under geothermal drilling conditions. Failure modes should be identified so that an improved drill with adequate reliability can be designed, built and tested. The evaluation must take into account the drilling fluids, temperature, and formation characteristics normally encountered in the geothermal environment. It is anticipated that improvements in seals and pneumatic or hydraulic valves will be required to achieve a successful tool.

Subtask 2.2. Development of Improved Percussion Bits

2.2.1. Roller Bits -- The work that has been done by industry indicates that improvements in the metallurgy of roller bits used for percussion drilling are required to prevent fatigue and cracking of the tool joints, legs, welds, and bearings of the bits.

2.2.2. Solid Head Bits -- The work that has been done by industry indicates that improvements in the metallurgy and design of these bits is required, since fatigue and cracking of the pins and body have been observed in addition to severe wear on the gauge portions of the bit.

2.2.3. Timing -- To insure the reliability of this tool, it will be necessary to design the bit, the geometry of the tool, and the velocity of the percussion stroke to match the nature of the rock to be penetrated. The short tests performed to date have indicated that severe deviation of the hole direction may occur unless these design parameters are properly adjusted.

Task 3. Development of a High Pressure Jet Augmented Rotary Mechanical Drilling System

The objective of this task is to develop methods to increase geothermal drilling rates by factors of 4 to 5 by augmenting the mechanical drilling of rock with high pressure water jets. The best use of hydraulic energy appears to be in cutting a kerf in the rock. This allows for easier mechanical breakage with conventional bits. This may be accomplished with the use of low pressure (less than 7500 psi) cavitating nozzles, and existing drilling fluids and rig equipment. If and only if, higher pressure (7500-15000 psi) is required at the nozzle, new high pressure pumps, drill bits, fluids and miscellaneous rig equipment would have to be developed. Therefore, the task plan is given in two pressure regimes, a) 1000-7500 psi, and b) 7500-15000 psi. Specifically excluded are pressures greater than 15,000 psi.

Subtask 3.1. Low Pressure Cavitation Jet Drilling

The purpose of this task is to explore the use of cavitating nozzles to clean, kerf, and otherwise increase the drilling rates with conventional and modified mechanical drilling devices.

3.1.1 -- Conventional drilling hardware should be used to evaluate cavitating fluid streams for increasing drilling rates. Existing mud pumps may require minor modifications to achieve greater reliability at pressures approaching 7500 psi.

3.1.2 -- Cavitating jet nozzles should be placed in conventional roller and diamond drill and coring bits for laboratory and field testing; performance should be compared to that of the same drilling bits with conventional nozzles.

3.1.3 -- Single nozzle fluid dynamics, and rock drilling and kerfing tests should be conducted in the laboratory to develop increased jetting efficiency in terms of specific energy and specific kerfing energy as they relate to the drilling process. These data can be used to optimize system design.

Subtask 3.2. High Pressure Jet Drilling

Use of high pressure (7500-15,000 psi) jets for drilling will require the development of reliable and safe pumps, swivels, and rotary hose. This development will be expensive. Prior to initiating this development, a go-no-go decision should be made based on the threshold pressures required to drill geothermal formations. If high pressures (over 7500 psi) are required, the following tasks are needed.

3.2.1 -- Develop pumps, roller and diamond drill and core bits, swivels, drill pipe, rotary hose and other support equipment for high pressure service.

3.2.2 -- Determine the maximum pressure required to suitably increase the drilling rates in laboratory and field trials of new drill bits augmented with jet nozzles.

Subtask 3.3. Special Applications

Evaluate the benefits of cavitating jet nozzles in specialized drilling and completion operations at pressure to 7500 psi. For these applications, the threshold pressures required in geothermal formations should be determined, then development should be initiated as appropriate. The special applications are as follows:

3.3.1 -- Underreaming

3.3.2 -- Directional Drilling

3.3.3 -- Stimulation

3.3.4 -- Scale Removal

3.3.5 -- Perforation Cleaning

Task 4. Supportive Rock Mechanics Studies

The objective of this task is to provide basic understanding or rock breaking mechanisms in order to optimize the design of each advanced drilling system. Rock properties measurements and analyses of the mechanics of rock drilling are required to gain a better understanding of a) tool/rock interaction, and b) borehole stability at the bottom of the drilled hole.

Development of the advanced drilling concepts will be enhanced by analyses of macroscopic stress, fracture mechanisms and fluid flow characteristics and of the microscopic observations of rock deformation. These analyses will be of the mechanics of the rock breakage and removal system. Without such analyses, advanced drilling concept development will be done by trial-and-error design, greatly increasing time and costs. The borehole analysis will require definition of rock properties, including strength and deformation characteristics in a chemically active aqueous environment, at downhole pressures, temperatures, pore-fluid conditions, and at realistic strain rates. Thermoelastic effects should be included.

Each of the subtasks below requires a) rock testing to acquire needed rock properties under suitable ambient conditions, b) finite element analyses of stress and deformation fields at the bottom of the drilled hole as it is perturbed by the tool, and c) microscopic observational analyses of damage produced by the tool under controlled test-drilling. A variety of rock types typical of geothermal drilling will have to be tested in each subtask at ambient conditions.

Subtask 4.1. Rock Mechanics Support for High Rotary Speed Drilling Systems

This subtask should concentrate on assessing the effect of high velocity impacts resulting from roller cone drill bits run at speeds of 200-300 rpm, and on assessing the rock removal characteristics using drag-bit concepts at rotational speeds of 300-1000 rpm.

Subtask 4.2. Rock Mechanics Support for Percussion Drilling System

This subtask should concentrate on assessing the effect of impacts from vibratory rock breakage systems in connection with roller cone and diamond rotary drilling. It is envisioned that percussive drilling will be done in connection with modified roller cone or diamond bits, as opposed to pure vibratory drilling concepts.

Subtask 4.3. Rock Mechanics Support for Jet-Augmented-Rotary Mechanical System

This subtask should concentrate on assessing the effect of high velocity fluid jets in connection with modified roller cone and diamond bits on rock removal rates. Pure water-jet erosion is probably not of interest, because of the high pressures required; however, threshold pressures to "cut" rocks typical of geothermal drilling need to be determined when used with roller and drag bits.

Subtask 4.4. Rock Mechanics Support for Advanced Studies

It is difficult to estimate needed tasks for advanced studies until such studies are formulated. The Novel Borehole Sealing Subtask 5.1 and Subtask 5.5 to explore kerfing concepts for advanced roller cone bits will certainly require rock mechanics support.

Task 5. Advanced Studies (Small Scale)

The items listed here as advanced studies are areas of concern in which the feasibility of the concept or an understanding of the benefits to accrue from success are not well understood. Introductory studies are being proposed which should determine the potential benefits accruing to a success oriented program and develop the plan of activities required for the program. Continued funding would then be predicated on a better understanding of the concept.

Subtask 5.1. Borehole Sealing Techniques

Lost circulation is a prevalent and costly problem in geothermal drilling and completion. On numerous occasions, only low density drilling fluids can be utilized. Subpressured reservoirs are numerous. Standard approaches to lost circulation control are marginal at best in geothermal applications. The Panel on Rock Drilling Technology recommends the following studies:

a. Investigate the feasibility of using rock melt techniques to seal off inflow or thief zones

b. Investigate the feasibility of using temperature expanded sealants for thief zone shut off.

Subtask 5.2. Downhole Intensifiers

Surface equipment pressure constraints and transmission losses may result in the need for downhole intensifiers to increase hydraulic horsepower to bottomhole tool assemblies to enhance penetration rates. Several possibilities exist for achieving this pressure amplification:

a. Turbine type pumping/compression systems

b. Pulse type intensifiers (water hammer)

c. Chemical type intensifiers (explosives/chemicals)

Spin-off from fluid pressure amplification at the point of use could provide reduced annular pressures by aeration (chemical type intensifiers), increased pressure drops across bits while obviating the need for high pressure seals when downhole motors are present (intensifier below motors), and increased cuttings removal by aeration/pulsing of fluid below motors. Feasibility studies of these concepts are recommended.

Subtask 5.3. Explosives Concepts

Feasibility studies should be directed at methods of fracturing and/or reducing borehole pressures in advance of the tool face. Possibilities include the following:

a. Bubble formation with explosives (large gas volume producing explosives) resulting in stressing and aeration of mud

b. High velocity (directional) explosions (tuned to formation) to rubblize (fracture) in advance of mechanical shearing systems

c. Low velocity explosives for pulsing to increase horsepower to tool/rock interface

d. Review of present explosive drilling techniques to determine applicability in geothermal drilling.

Spin-off from this area could perhaps be utilized for reducing lost circulation, development of new downhole motor systems, etc.

Subtask 5.4. Downhole Cooling Studies

Many of the advanced concepts for geothermal drilling are severely limited by the formation or circulation temperatures. For example, attempts to find higher temperature elastomeric seals have been almost entirely unsuccessful. All seals, cutting surfaces, bearing surfaces or other areas of high temperature generation would benefit from cooling. The cooling might be derived from down flowing fluid or from bottomhole heat sinks. With adequate power, downhole cooling systems and the associated heat transfer may offer a method for tool life improvement. Some work along this line has been done with instrumentation. A study should be initiated to determine the feasibility of developing a cooling system sufficient to extend seal life, bearing life and drag cutter life. The limitations of heat transfer, source isolation and required cooling capacity should be analyzed.

Subtask 5.5. High Pressure Downhole Motor/Jet Bit System (5000 psi)

A long-standing limitation for downhole motor use, whether sealed or unsealed, is the low jet cleaning pressure range of 500 psi. This is not adequate for cleaning purposes for roller bits or diamonds. Since kerf cutting jets are a strong candidate to improve drilling rates, and since downhole motors are expected to be used, much higher pressures are needed. If bottomhole intensifiers can be run below the downhole motor, high pressure can be supplied to the bit while obviating the need for high pressure seals in the motor. There are possibly other means to provide for high jet pressures. Studies should be initiated to:

a. Develop an understanding of the limitations of seals for downhole motors with pressure capabilities of up to 5000 psi

b. Investigate novel means for providing 5000 psi jet pressure when using downhole motors and define a development program.

Subtask 5.6. Bottomhole Fluid-Steam/Air/Products-of-Combustion Motor Systems

The objective of these feasibility studies is to generate increased rotary horsepower downhole by utilizing or converting fluids not heretofore found practical for downhole power. Possibilities include the use of:

a. The Sandia downhole steam generator coupled to steam engines and turbines

b. Downhole separators allowing liquids to be used in the turbine but bypassing gas to the bit for cuttings removal and aeration of drilling fluid to reduce annular pressures

c. Combustion of pumped final mixtures

d. Stiff foams for use in turbodrill motors

Spin-off from these tasks would have a direct bearing on the ability to control lost circulation while increasing horsepower to bits.

The Panel on Rock Drilling Technology estimates the recommend program to cost as follows over the 1980-1986 time frame:

ESTIMATED TOTAL PROGRAM COSTS

			Totals $ x 10^6
Task 1.	High Rotary Speed Motor/Bit Drilling System		
	a. Motors	$7	
	b. Bits	5	
	c. Accessories	3	
			$15M
Task 2.	Percussive Drilling Systems		3
Task 3.	Fluid Jet Augmented Rotary Mechanical Drills		
	a. Low Pressure	5	
	b. High Pressure	8	
	c. Special Applications	3	
			16
Task 4.	Supporting Rock Mechanics Studies		1
Task 5.	Advanced Studies		1
	Total		$36M

REPORT OF THE PANEL ON DIRECTIONAL DRILLING TECHNOLOGY

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I. Objectives of the Panel

The objectives of the Panel on Directional Drilling Technology were to identify the problems encountered during the drilling of deviated wells in geothermal reservoirs and to recommend R&D activities which could lead to solutions to these problems.

II. State-of-the-Art Assessments

A. Introduction

Although directional drilling procedures have long been in use throughout the oil and gas industry, the direct application of these procedures to the emerging geothermal field has met difficulties. The principal difficulties result from the effects of: 1) elevated temperature, and 2) hard, highly-fractured formations.

The importance of directional drilling in the development of geothermal energy resources is made evident by the following facts:

1. The completion of multiple wells from a single pad will be nearly universal due to limited site availability resulting from terrain considerations and environmental regulation. The drilling of reinjection wells will also benefit from development of directional drilling procedures.

2. The costs associated with the drilling and completion of geothermal reservoirs require that on-line wells be of the highest reasonable productivity in order to enhance the economic viability of the resource. It has been found that the recoverable volume of hot water and/or steam is dependent upon the successful intersection of the borehole with the maximum number of fractures in the reservoir. Since these fractures usually lie in near vertical planes, some type of deviated drilling to intersect them will be required. Near-horizontal trajectories in the reservoirs are frequently desirable.

B. Scope of Discussions

For the purposes of the Panel on Directional Drilling Technology, the following problem areas were identified for discussion:

1. Building and maintaining deviated boreholes,

2. Drilling high angle holes, kick-off, hole existing and entry, and hole straightening, and

3. Guidance, sensing and steering.

In many instances new concepts will be required to generate the desired near-term solutions to the problems associated with directional drilling in geothermal reservoirs.

C. Current Techniques

Tools used in deflecting the borehole of a geothermal well are positive displacement mud motors, turbodrills and standard or circulating whipstocks. The use of a positive displacement motor is presently limited to circulation temperatures of 125°C or less due to the use of rubber parts and seals in the motor. Turbodrills can withstand higher temperatures; however, roller bits have very short life at high turbine speeds. Diamond bits have been used on turbodrills with mixed results. Short life is observed because of heat generated from the high speed of rotation and from the high temperature of geothermal wellbores.

Whipstocking is another deflection technique that is usable at high temperature and can operate with air or mist. However, lost rig time is high since four round trips are necessary to utilize a whipstock.

Measurements of hole deviation are necessary in any directionally drilled well, but they are especially important in geothermal drilling because of the need to accurately control the hole position in order to intersect fractures. Unfortunately, conventional systems cannot function at the elevated bottomhole temperatures encountered in geothermal drilling. Standard single shot survey devices fail at temperatures above 125°c. The use of a thermal shield can extend this range to about 200°C. When running a guidance tool with any downhole motor, instruments and electric cable are currently limited to use at temperatures below 200°C.

To minimize drill string torque, drag, and wear, the rate of angle build-up in the well must be kept nearly constant. This rate of increase must be maintained from the well kick-off point up to the programmed maximum angle. After hole angle and direction are established, the high formation temperatures contribute to high rates of bit wear and to stabilizer problems. An under gage bit and/or near-bit stabilizer can seriously effect the ability to control the trajectory of the wellbore.

Sidetracking out of old wellbores in an effort to hit a specified geologic target is a problem; particularly when attempting to sidetrack from the low-side of the hole and simultaneously turn the hole direction by a high angle.

D. Downhole Drilling Motors

1. Low Speed Motors

Three positive displacement motors of the Moineau type are commercially available; Smith International's "Dyna-Drill," Christensen's "Navi Drill," and Baker's downhole drilling motor. The Dyna-Drill has been commercially available for over ten years; the others since 1978. Approximately characteristics of their 6-3/4" (or 6-1/2") motors are as follows:

Directional Drilling Motors

	Dyna-Drill	Christensen	Baker
Pumping rate (gpm)	325	350	350
Operating ΔP (psi)	250	375	250
Operating torque (ft-#)	470	900	1200
Operating speed (rpm)	410	400	175
Maximum pressure drop across bit (psi)	300	600	1000
Motor geometry	1 lobe in 2	1 lobe in 2	3 lobes in 4
Maximum operating temperature (°C)	150	150	150

The application of these motors to geothermal drilling is limited because of the elastomeric material used in the motor stator.

Other low speed motors are under development including Moineau and vane type; however, their operating characteristics and commercial availability are uncertain.

The Russians are also utilizing Moineau motors of the multi-lobed type.

2. High Speed Motors

Several manufacturers have high speed turbines commercially available. NEYRPIC turbines have been used extensively in Western Europe. These motors have very low torque output resulting in unstable operating speeds and frequent stalling problems. Also, operating pressures across the bit are limited. Dyna-Drill has a high speed (720 rpm) version of its positive displacement motor, but the allowable pressure drop across the bit is limited.

Other turbines are under development (including a 7-3/4" Turbodrill by Maurer Engineering with a torque objective of approximately 1400 ft/lbs); however, their operating characteristics and commercial availability are uncertain. An electric motor is also under development by GE. This motor has both high speed and low speed capability. Because of the electrical conductor cable and the use of elastomeric seals, etc., it has a temperature limitation that would severely restrict its application to geothermal drilling.

E. Bits for Downhole Motors

This Panel feels that currently available bits are inadequate for use with motors in the geothermal environment and encouraged the Panel on Rock Drilling Technology to address this topic.

F. Borehole Instrumentation

Instrumentation required to meet desired directional drilling goals for geothermal applications must include real time measurement of downhole drilling and borehole parameters. Parameters necessary to optimize directional drilling include:

1. Hole inclination (angle)
2. Hole direction (azimuth)
3. Borehole curvature
4. Reaction torque of turbine or motor
5. Tool face orientation (bent sub)

6. Downhole temperatures
7. Turbine rpm
8. Weight on bit
9. Bit under gage warning

Measurements of these parameters should be transmitted to the surface for on-line analysis.

Currently, technology allows for downhole measurements of:

1. Inclination
2. Direction
3. Tool face orientation
4. Temperature

through the deployment of a downhole instrument package that locks into the bottomhole assembly. This data can be transmitted to surface readout equipment via a conductor line. The state-of-the-art is presently limited to downhole temperatures not exceeding 125°C. The conductor line is also temperature limited. The necessity of pulling the instrument package to make a connection increases drilling time. Advances in wireless data telemetry systems (e.g., acoustic, mud pulse) are expected to be marketed in the near-term. These systems will, however, still be temperature limited.

Sensors to measure the parameters listed above must be incorporated into the bottomhole drilling assembly, and steering sensors should be located as close to the drill bit as possible. To meet the goals outlined for directional drilling in the geothermal environment, both sensor devices and transmitting systems must be upgraded to operate continuously at temperatures up to 300°C.

Consideration should be given to utilizing the measurable parameters on a real-time basis during the actual drilling operation. This can be accomplished by employing computer techniques provided the downhole data can be interfaced to surface equipment for on-line analysis. Certainly the transmission of the bottomhole directional drilling parameters on a wireless system would eliminate cumbersome operations encountered with armored conductor line equipment. However, data rates, accuracy and sensitivity must be made compatible with surface computational and readout systems. Wireless transmission systems must be carefully evaluated for optimum on-line analysis. The availability of downhole electronic circuitry would allow sensor signal processing and improved sensitivity, accuracy, and data rates for numerous transducers (multiplex) and insure surface computer compatibility. Electronics, however, presently do not operate in the severe temperature environment, and data output will probably require a conductor line for transmission to the surface. Therefore, downhole electronic systems require the development of temperature-hardened components (perhaps heat sinks and dewars for near-term operations) and high temperature armored conductor lines or more sophisticated wireless telemetry systems.

III. Conclusions and Findings

In formulating a set of conclusions, the problems of directional drilling in hot, hard, fractured and unfractured formations were discussed. It was assumed that high hole angles (> 45°) would be required, and that the drilling fluid would be either water or mud. Since the maximum rate of anglebuildup was assumed to be 1.5"/100 ft, long intervals of angle building are required. It was concluded that it is highly desirable to do angle building in non-fractured, rather than in fractured formations. The resulting, recommended strategy is to build angle (when necessary) in competent rock and work to maintain angle and direction when drilling in fractured rock. When it is necessary to build angle near the surface in fractured rock, a slant-hole rig is recommended.

Current directional drilling technology does not provide for efficient angle building in hard rock. The problems in drilling high-angle geothermal wells in hard rock consist of the following:

A. Kicking-off
B. Building angle at constant rate
C. Drilling fast
D. Closely controlling hole angle, direction and curvature
E. Knowing when crooked hole problems develop, and
F. Correcting problems when they occur.

Further conclusions and findings of the Panel on Directional Drilling Technology are as follows:

A. Maximum curvature change for the buildup of hole angle should not exceed 1.5°/100 ft in hard rock because of pipe extraction problems.

B. The use of bottomhole assemblies to build hole angle with rotary drilling is not an economical method, and in most cases is not feasible in hard rock.

C. The use of an active orientation device (deflecting sub or whipstock device) is necessary for all methods excluding high-pressure, hydraulic jet drilling.

D. Hole curvature problems while building angle present the greatest risk in directional drilling in hard rocks.

E. Mud motors capable of economically drilling hard geothermal reservoirs above 125°C do not exist.

F. Telemetering systems to transmit the required directional data to the surface at temperatures above 125°C do not exist. Other systems to measure directional data are unreliable at high temperatures and cause lost rig time.

G. Bits for use with high-speed turbines to drill hot, hard rocks have not been developed.

H. There is no reliable way to slow a turbine down so that conventional low speed bits can be used.

I. There is no reliable system or method to kick-off a well in hard rock in an open hole.

J. Directional drilling using air or mist is not practical in most hard rock drilling situations.

K. Kicking off in fractured hard rocks is an expensive operation.

L. The use of bottomhole assemblies with conventional (rotating) stabilizers is an impractical way to maintain angle in fractured hard rocks.

M. Complex geology has a strong influence on the trajectory of directional holes infractured, hard rocks.

N. There are no means for correcting detrimental hole curvatures in a directional well in hard rock.

O. Trained manpower does not exist to consistently drill high-temperature directional wells.

P. The plausible systems that offer the potential for enhanced capability in directional drilling between now and 1986 have been judged by the Panel to be:

1. A high-speed turbine system
2. A low-speed downhole motor system
3. A percussion system

IV. Identification of R&D Areas

A. Directional Drilling Systems

The Panel on Directional Drilling Technology identified the following areas requiring R&D.

1. System I -- High Speed Turbodrilling

The components needed for a geothermal turbodrilling system including the following:

a. High speed, long life, high temperature bits to kick-off and build angle

b. High temperature, high speed and torque, long-life turbines

c. Adjustable orienting or bent subs that can be controlled and reoriented at will from the surface

d. Downhole sensors to measure

1) Hole inclination (angle)
2) Hole azimuth (direction)
3) Orientation or bent sub orientation (tool face)
4) Weight-on-bit
5) Turbine reaction torque
6) Hole curvature
7) Turbine rpm
8) Bottomhole temperatures
9) Gage condition of bit (tell-tale would be adequate)

e. Moderate to high data rate telemetry system capable of long life in the geothermal environment

f. Surface pumps that can provide adequate fluid power (pressure and volume) to drive the turbines, and to cool, and clean the bits

g. Surface equipment and software to receive and process the telemetry data to provide information in a form for efficient decision making

h. Trained personnel to efficiently operate and maintain the system and to make correct decisions using the computer printout.

Most of the above needed components do not exist today. The recommended tasks to develop them are discussed in subsequent sections.

2. System II -- Low/Moderate Speed Drills/Turbines/Motors

The use of low or moderate speed drills would reduce the bit problems which are encountered in turbodrilling. The following systems are identified as deserving attention:

a. Percussion (Hammer) Drill

This technique is currently being used in certain special drilling situations. Hardware problems exist, but it has considerable potential for geothermal drilling. The components needed for such a system include:

1) Long life, high temperature percussion bits for kicking-off and building angle

2) Long life, high temperature percussion drills (fluid hammers) that can be used in kicking-off and building angle

3-8) Same as for System I, except the word "turbine" is replaced by "percussion drills" in No. 6.

b. Low-Moderate Speed Turbines

At the present time there is no effective way of reducing turbine speed. The components needed to implement this approach are:

1) Long life, high temperature, low/moderate speed bits for kicking-off and building angle

2) Long life, high temperature brakes or speed reducers

3) High temperature, high speed, high/low torque, long-life turbines (torque requirement depends on whether brake or gear box is used to reduce speed)

4-9) Same as 3-8 for System I

c. High Temperature Vane Motors

These tools are currently under development for oil/gas well drilling. There is some feeling that their temperature capability can be extended to the geothermal range. The components needed to implement this approach are:

1) Long life, moderate speed, high temperature bits to kick-off and build angle

2) Long life, high temperature and torque, vane-type motors

3-8) Same as for System I except the word, "turbine," is replaced by "vane motors" in No. 6.

Most of the above needed components do not exist today. The recommended tasks to develop them are discussed in subsequent sections.

3. System III -- Hydraulic Jet Drilling

Considerable work has been done to develop high pressure, clear water jet drilling and moderate pressure, abrasive-fluid jet drilling for oil/gas well drilling. The state-of-the-art is such that the Panel does not believe abrasive jetting could be developed for application in geothermal drilling within the next six years; however, it is felt that high pressure, clear water jetting has a potential application. The components needed for such a system are:

a. High pressure hybrid (jet plus mechanical cutters) bits for kicking-off and building angle

b-d. Same as 3-5 for System I

e. Surface pumps that can provide pressures and flow rates adequate to kick-off and build angle

f-g. Same as 7-8 for System I

Most of the above needed components do not exist today. The recommended R&D tasks to develop them are discussed in subsequent sections.

B. Downhole Drilling Motor Components

Several areas for R&D in geothermal downhole motor components were identified as follows to provide additional detail for task definition:

1. High temperature elastomers -- For motors of the Moineau type to be utilized, a high temperature elastomer for the stator would be required. In view of the attempts made through the years to improve the temperature capability of elastomers, the probability of success appears remote.

2. Sealed bearing systems without elastomers -- If high pressure drops across the bit are to be achieved on either high or low speed turbines, a sealed bearing system is required. Because of temperature limitations, metallic or plastic seals should be investigated.

3. Mud-lubricated bearings -- Currently available mud lubricated bearing systems should be upgraded with flow restrictors capable of withstanding a bit pressure drop of 500-1000 psi. These bearing systems should be totally void of elastomeric materials.

4. Turbine brake -- The technical feasibility of developing low speed turbines utilizing a braking system (similar to Russia's) or speed reducer should be investigated.

5. Percussion drill -- The application of percussion drills to directional drilling should be investigated. Previous R&D work has been done in this area (liquid-Amoco, air-Mission and Ingersoll Rand). To be used in directional applications, some means of rotating the bit while holding the pipe stationary would be required.

C. Bits for Geothermal Directional Drilling

High speed turbine bits will probably have to be diamond bits. There is some question about whether this should be considered a selection, testing, and proving program of bits that can currently be fabricated, or an R&D problem. In any event, development is needed.

Lower speed roller bits can possibly be upgraded in life by field testing of improved versions more adaptable to high temperature situations. An improvement of current bits with 50 rpm capability to 150 rpm capability would also probably improve bit life at even higher rotating speeds. However, resulting life would probably still be inadequate for use with high speed turbines.

An evaluation of current mud percussion bit performance should be made. Testing of available bits plus other possible improved designs should be undertaken as necessary.

D. Other Needed Items

The three directional drilling systems described above could provide the capability to kick-off and build angle in hard, competent (unfractured) rock. It was mentioned earlier that the preferred strategy is to do no directional work in fractured formations, but to try only to maintain hole angle and direction. In order to accomplish that strategy, technology improvements are also needed in several other areas. These are discussed below.

1. Holding Angle and Direction in Fractured Rock

This problem falls into two operational categories -- motor (turbine) or percussion drilling and rotary drilling. With motor or percussion drilling, improvements are needed; novel approaches should be considered. With rotary drilling, novel methods to maintain hole trajectory need to be considered, e.g., "Drill-Tru."

2. Sidetracking in Open Hole

Current methods and materials for sidetracking in open holes are inadequate for geothermal drilling. Improvements are needed in:

a. Cements for sidetrack plugs
b. Ability to reenter the original hole.

V. Recommendations

A. Bits

A recommended approach to the development of bits for directional drilling is as follows:

1. Collect and evaluate the available drilling data and bit design information. This would include all drilling in geothermal fields or geothermal-type rocks, including fractured, broken formations both in the field and the laboratory. Caution must be exercised to differentiate between bit designs that have been fairly tested and those that have not. The danger is in considering that all diamond bits are the same. (Also, side-tracking diamond bits do not provide for optimum drilling rates in the new hole.) Variation of many important design parameters is possible, even in a bit having the same model designation.

2. Having assessed the current situation, initiate a program of drilling experiments in geothermal rock types using a variety of bit designs. Use the test results to improve the most promising designs, and retest.

3. All types of diamond bits including surface set, ridgeset, impregnated and polycrystalline should be considered.

4. A good cutting structure on both the gage and the face of the bit should be utilized for directional drilling.

Task 1. High Speed Bit Development

Develop a high rotational speed drilling bit that will be suitable for use on a high speed motor. Typical speeds would be 400-800 rpm. Size range required is 6-12 1/4". These bits should probably be of the solid body type, have a significant operating life, and, if possible, incorporate features advantageous to directional drilling. Such features might permit the easy change of drilling angle.

Task 2. Lower Speed Bit Development

Develop a bit that would operate at speeds near 200 rpm. This could be a cone, diamond or hybrid bit. Again, compatability with the directional drilling system is more important than a high rate of penetration.

Task 3. Percussion Bit Development

The requirements for a bit operating on this principle, even when taken aside from the required operating system, are unknown. A study of these requirements should be undertaken and any required development should be initiated.

Task 4. Hybrid-Jet Bit (High ΔP Jet Plus Mechanical Cutters) Development

A combination of mechanical and high pressure fluid jetting could prove useful in directional drilling. The jet cutting action could initiate fractures. A hybrid bit for directional drilling should be developed.

B. Motors/Drills

Task 5. High Speed Turbine

A high speed turbine with a compatible drill bit would be extremely useful to geothermal directional drilling. Research activities should be limited to liquid driven motors. Necessary research topics would include the development of a workable sealed or mud lubricated bearing package capable of operating at a bit pressure drop of 500-1000 psi and temperatures up to 300°C.

Task 6. Low/Moderate Speed Turbine

This turbine would be similar to that in Task 5 but would operate at a lower speed. This could be accomplished in a variety of ways; possibly with a speed reducer or gear box.

Task 7. Percussion Drill

Little is known about directional drilling with percussion drills. Research into designs for use with various fluid types (air, water, foam) is needed. This may depend upon the formations encountered. Extensive development will also be required to provide a directional drilling capability with this tool. Steering control would be critical.

Task 8. Vane Type Motors

Principal research work should be on materials for blades or vanes.

C. Borehole Guidance Instrumentation

Task 9. Sensors

Development is required for successful sensor utilization, and the information provided by these devices is crucial to geothermal directional drilling. There is a minimum of nine desired parameters which should be incorporated into a directional system. These are as follows: 1) hole inclination; 2) hole direction; 3) tool face orientation; 4) hole curvature; 5) motor reaction torque, 6) turbine rpm; 7) weight-on-bit; 8) bit wear; and 9) downhole temperature. These sensors should be as close to the bit as is conveniently possible.

Task 10. Downhole Signal Conditioning and Telemetry

The highest priority in this task is for the development of a wireless system. Crucial to this development will be advances in high temperature electronics, high temperature conductor lines and deployment systems. The Panel feels that a wireless system is preferred to a conductor system because of temperature problems, cable handling problems, and connector problems.

Task 11. Surface Analysis

A computer interface will be required so that the data can be processed in the most effective manner. This processing will require accompanying software development.

D. Other Research Areas

Task 12. Bottomhole Assembly Design to Maintain Trajectory in Fractured Rock

The problem here is to maintain or modify trajectory in a controlled manner. Studies into the interaction of the bottomhole assembly (BHA) with various formation types are needed. High angle drilling is also important. The effects of the chosen drilling system (motors, percussion, jets) on the BHA aspects of directional drilling should be investigated. Placement of stabilizers, reamers, etc., should also be studied.

Task 13. Develop Hard Rock Directional Drilling Analytical Methods

Curvature analysis for trouble-free directional drilling in hard, hot rock should be examined. Geological analysis and trajectory control are also important.

Task 14. Side Tracking in Open Hole Situations

The methods and hardware required to sidetrack and reenter open holes is an area of needed development. Successful exists from the borehole should also be considered.

Task 15. Training of Personnel in Directional Drilling

Current drilling personnel are inadequately trained to implement current technology in directional drilling. The problem will be compounded by the new technology needed in geothermal drilling. Training courses should be made available to the industry.

Task 16. Improved Mud Pumps

High pressure pumps (6000-15000 psi) will be needed to provide power for hydraulic jet drilling. The reliability of existing equipment needs to be improved.

E. Priorities for Recommended Tasks

Task Number	Priority
1	1
2	3
3	4
4	7
5	1
6	3
7	4
8	6
9	2
10	2
11	4
12	2
13	3
14	2
15	5
16	8

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