SUMMARY

The U.S. Department of Energy sponsored program in geothermal drilling and completion research and development (R&D) is managed by Sandia National Laboratories. The program objective is to conduct long-range R&D aimed at developing advanced geothermal drilling and completion systems to expand resource utilization. The program is organized into four broad categories: 1) rock penetration mechanics, 2) drilling fluids, 3) borehole mechanics, and 4) diagnostics technology.

Although much effort has been concentrated on bit development under rock penetration mechanics, current work focuses on understanding the limitations of drag bits as they apply to high-speed hard rock drilling systems. Other technologies being pursued include cavitating jets and percussion systems as well as more exotic rock penetration techniques.

Fluid technology R&D addresses the high temperature, high corrosion and abnormal pressure problems found in geothermal areas. A high-temperature clay-based mud has been developed. Current emphasis includes: 1) developing on-site inert gas (nitrogen) generators, and 2) studying and testing high-temperature stable aqueous foams.

The R&D in borehole mechanics addresses the problems of lost circulation and lining and cementing the well, as well as problems of production maintenance such as perforating and scale removal. A unique high-temperature lost circulation/cementing test facility is under construction which will provide data on advanced materials and techniques for controlling lost circulation and cementing casing.

Well logging and downhole instrumentation R&D activities are organized under the diagnostics technology program element. The major thrust is in developing high-temperature electronic components, transducers and concomitant materials. A wellbore inertial navigator is also being developed.

This paper presents the accomplishments of the program, and the status of current projects and plans for future activities.
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THE USA PROGRAM IN GEOTHERMAL DRILLING AND COMPLETION RESEARCH AND DEVELOPMENT

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1. INTRODUCTION

A large portion of the cost of developing geothermal energy is attributable to the high costs of drilling and completing geothermal wells. Geothermal wells generally are two to four times more expensive than those completed for petroleum development. Much of this increased cost comes from factors that are unique to geothermal drilling—including the high temperatures that are inherent in the geothermal resource, the hard fractured nature of the rocks which are commonly found in geothermal reservoirs, and the nature of many geothermal fluids that cause problems of corrosion and scaling.

Sandia National Laboratories manages the U. S. Department of Energy's (DOE) Geothermal Technology Development Program which is aimed at solving these problems through development of new technologies for geothermal drilling and completion. The objective of the program is to conduct long-range research and development (R&D) activities aimed at developing advanced systems to expand the geothermal resource. During the current government budget year the program is funded at a level of approximately $2 million. This supports 20 researchers within Sandia Laboratories and allows contracted support from approximately 20 organizations outside of Sandia.

An essential aspect of the Geothermal Technology Development Program is the participation of an advisory panel, the members of which are drawn from universities and the geothermal industry in the United States. The panel contributes to the program by suggesting general areas for technology development as well as by evaluating the technical details of particular development projects.

This paper discusses many of the projects that are included in the Geothermal Technology Development Program. It separately considers each of the four major areas in the program, summarizing the current emphasis and related recent accomplishments that could be useful to worldwide geothermal drilling and completion.

2. ROCK PENETRATION MECHANICS

The work in the rock penetration area is centered around studies of the phenomena involved in the cutting or breaking of rock. The long-term goal is development of an advanced, high-speed drilling system for hot, hard and fractured formations.

2.1 Drag Bits.

The roller-cone bits that are commonly used for petroleum drilling in hard-rock areas are limited in high-temperature applications because of failures of bearings and seals. Similarly, roller-cone bits are not appropriate for high rotary speeds due to frictional heating and wear on their moving parts. Furthermore, the crushing of rock (on which hard-rock roller-cone bits depend) is inefficient for applications requiring high penetration rates. A drag-type bit with no moving parts that cuts by shearing the rock is better suited for high speed, hot,
I. **Hard-rock Drilling.**

For several years a significant portion of the program has centered around polycrystalline diamond compact (PDC) cutters and drag bits that utilize these cutters. Efforts have included development of diffusion bonding techniques to provide a reliable high-temperature, strong attachment of cutter blanks to studs in a bit body. This method results in stronger bonds than does the standard brazing technique. To accelerate PDC bit development, Sandia has worked with several manufacturers on bit design. A cutter placement computer program was also developed. Extensive laboratory tests of PDC bits cutting several rock types under differing drilling conditions have been carried out at both high and low rotary speeds to characterize their performance. (Figure 1). Following laboratory testing, promising PDC bits have been taken to three geothermal areas—the Valles Caldera area in New Mexico; the Geysers area in northern California; and the Imperial Valley area in southern California—to test their performance in geothermal field conditions.

The conclusions based on these tests are that in softer rock formations, such as in the Imperial Valley, PDC bits have higher rates of penetration (2-3 times) and longer bit lifetimes (2-4 times). However, in testing in the harder rock formations PDC bit performance has been disappointing. PDC bits as they are now designed and utilized are appropriate for drilling only in geothermal areas with softer rock.

To determine the reason for poor hard-rock performance, recent work in this area has focused on individual cutters and their interface with the rock. It has included extensive computer modeling and analysis of the mechanical response of both the cutter and the rock engaged by a PDC cutter. (Figure 2). In addition, two laboratory test programs are investigating the interaction of a single cutter and the rock formation. One at General Electric Company, the inventors of Stratapax® PDC cutters, is directed toward studying cutter wear; and the other, being done at Sandia, is aimed at characterizing rock cutting and chip formation. This understanding should lead to improved designs for geothermal PDC bits and could lead to completely different rock cutting modes, such as percussive penetration of rock.

### 2.2 Cavitation Systems

For several years the Geothermal Technology Development Program has sponsored work at Hydronautics, Inc. in the development of cavitating nozzles for use in drilling systems. Cavijet® nozzles have recently been field tested in bi-cone and tri-cone bits which have exhibited a marked increase in rate of penetration. Based on these tests, it is estimated that use of Cavijet® nozzles in roller-cone bits can increase the average rate of penetration by 30-50% or more.

The nozzles utilized were specifically designed to excite harmonic variations in pressure which in turn cause a periodic sequence of cavity rings to leave the nozzle and impinge on the rock surface. (Figure 3). Collapse of the cavities in these cavitating rings causes very high localized pressures which can damage the rock. Also, expansion of the rings over the surface of the rock results in fluctuating pressures imposed at the bit formation interface. It is thought that this pressure fluctuation tends to vibrate and lift the chips, enhancing bottom-hole cleaning and overall rate of penetration. Currently, it is not known whether the increased rate of penetration comes from erosive cutting done by the drilling fluid or whether the cavitation improves the bottom-hole cleaning ability of the drilling fluid.

Current work in the cavitation area is focused on better understanding of the cavitation phenomenon and the nozzle parameters that control it so that the beneficial effects of the pulsed cavitation can...
be designed into nozzles. In addition, Hydra- 
nautics is studying the impact of the cavitation ring on the bottom of the hole to determine which of the effects is actually causing the increased rates of penetration. Whichever it is, cavitating nozzles may prove to be an important part of an advanced, high-speed drilling system.

2.3 Drill String Dynamics

A possible cause of bit failure is repeated impact on the bottom of the hole. Accordingly, a major project in rock penetration involves the study of the dynamic behavior of the bottom-hole assembly on a drill string. This project, essentially the development of a finite element numerical computer model for the behavior of the bottom-hole assembly, has just begun at JAR, Inc. It is centered around modeling a PDC bit at its interface with the rock formation and will aid in understanding the dynamic behavior of that bit in a drilling environment. It is envisioned that the numerical code will be useful in analyzing the performance and behavior of advanced drilling systems, even those that might not use rotating drill pipe for power delivery.

3. FLUID TECHNOLOGY

The fluid technology program elements include the development of drilling fluids that are especially applicable to geothermal drilling and the study of the hydraulics involved in cutting rock and cleaning the bottom of a borehole.

Many geothermal reservoirs are underpressured, meaning that the pore pressures at some depth in the formation are less than the pressure exerted by a column of water in a borehole drilled to that depth. Conventional drilling fluids can invade formations and cause formation damage plus lead to significant loss of drilling fluids. These problems are commonly avoided by air or mist drilling the under-pressured portions of geothermal wells.

3.1 Inert Drilling Fluids

The corrosion of drill pipe and casing during air drilling can be one of the most significant problems in many geothermal areas. For example, the cost of additives to control corrosion during the air drilling portion of a geothermal well can amount to 10% or more of the total well cost in the Valles Caldera area of New Mexico. In November 1980, a test was conducted using nitrogen as a drilling fluid for one of the wells at the Valles Caldera. From this test, (Figure 4) it was determined that the use of nitrogen could reduce drill pipe corrosion by more than an order of magnitude. Engelhard Industries has investigated the feasibility of catalytically converting diesel exhaust to a stream of oxygen-free, or inert, gas that could be used in drilling fluid. Tests showed that oxygen levels of less than 10 ppm could be achieved.

Based on Engelhard results, a design was completed by Foster-Miller Associates, for a full-scale portable system that would provide acceptable drilling gas from the exhaust gases of the diesel engines on a drill rig. The initial cost of the system has been estimated to be $900,000 and the cost for the inert gas, including amortization of capital, is estimated to be $1.50 to $2.00 per thousand standard cubic feet. At the time of this writing, the status of commercial development of the purification unit is uncertain.

3.2 Aqueous Foam Drilling Fluids

Aqueous foam drilling fluids have densities between air and muds with sufficient lifting capacity to lift cuttings with relatively low velocities in the wellbore. Thus, they offer the potential for
avoiding both lost circulation and erosion problems. In addition, aqueous foam drilling fluids can be made with nitrogen or another inert gas to avoid corrosion problems.

The first phase of the aqueous foam work involved screening numerous commercially available surfactants to identify those suitable for high-temperature application in the chemical environments common to geothermal reservoirs. This work identified several promising surfactants from the nearly 150 that were screened. The procedure involved first exposing the surfactant to high temperatures then making a foam and checking its stability in various chemical environments at room temperature. After this preliminary screening, more realistic simulation was performed in a high-pressure, high-temperature chamber in which the surfactant and the gas were mixed and the stability of the resulting foam was evaluated at high pressure and temperature. This led to a better understanding of the effects of temperature and pressure on foam stability (Figure 5) and to identification of the most promising surfactants. So far surfactants from the alpha olefin sulfonate family have performed best.

Current work in the development of aqueous foam focuses on the dynamic characteristics and behavior of foam. In particular, two different flow test loops are being utilized to study the heat transfer characteristics and the rheology of flowing foam. Both tests will evaluate the surfactant, the foam generator, the foam shear rates, and the nature of the flow path.

Through this lab testing, a foam formulation will be developed for geothermal drilling applications, and it is envisioned that full-scale field tests of the identified foam system will be carried out.

3.3 Bit Hydraulics

The bit hydraulics research is focused on studying the behavior of fluids around PDC bits since ineffective cleaning of the surfaces of the cutter elements may limit the rates of penetration of the bits. In addition, some of the wear of the cutter elements is due to the high temperatures imposed on the cutters by friction and formation heating.

The work to date has developed a bit hydraulics test stand, which allows study of the flow of the drilling fluids around a bit. (Figure 6). The analysis can be carried out using flow visualization techniques, direct cutter cooling measurements, and measurements of the pressure distribution on the bottom of the hole. All three of these techniques have been used to study the flow patterns set up around different cutter-nozzle arrangements.

3.4 High-Temperature Fluids

Early effort in this program was directed toward development of water-based drilling fluids that could withstand the geothermal temperatures. This led to the development of a formulation of a high-temperature-capable mud (based on sepiolite and bentonite) that was successfully field tested by Sandia in a geothermal well, and then adopted by industry and marketed as a commercial product. In addition, Texas Tech University conducted an extensive study of the behavior of clays exposed to high temperatures and salt environments. Because of this work in clay morphology, high-temperature behavior of drilling materials such as bentonite, sepiolite and attapulgite is fairly well understood.

Current research in drilling fluids is directed toward studying clays that either can be converted to cements while in the borehole or are similar enough to cement that they need not be fully displaced when cementing casing.
4. BOREHOLE MECHANICS

The work in the borehole mechanics area is, in general, directed at combating borehole stability problems that are common to geothermal drilling and completion and at maintaining high production over the life of a geothermal well.

4.1 Lost Circulation Testing

Research is being initiated in the testing and development of lost circulation materials. Lost circulation is one of the most serious of drilling and completion problems in geothermal reservoirs. The fractured and frequently underpressured nature of the geothermal formations cause nearly constant concern about lost circulation in both drilling and cementing operations. Sandia's soon-to-be-completed lost circulation test facility will make possible full-wellbore-diameter tests of the ability of various lost circulation materials to plug lost circulation zones in simulated fractured formations and in simulated permeability-loss formations. (Figure 7). This facility will allow testing of the materials at high temperature and pressure in the borehole and with simulated formation pressure.

In order to screen materials for use in the lost circulation test facility, numerous lost circulation materials have been tested in a high-temperature, small-scale apparatus to identify those that seem to have the greatest potential for solving lost circulation in a geothermal environment. One material that shows promise is ground automobile battery casing.

Recent testing involved a simulated downhole test of a two-component rigid urethane foam for sealing lost circulation zones. The two components of the foam can be delivered separately, mixed downhole and squeezed into the formation. The components would set up to a rigid foam with about an eightfold volume expansion. The foam would seal the lost circulation zone and could be drilled through and cemented over.

4.2 Cement Displacement Tests

The same facility that will be used to study lost circulation and to test lost circulation materials will be used to study the mechanisms of cement displacement by drilling mud. The thermal cycling as the geothermal well is taken on and off line can create serious problems with casing that is not supported by a good cement bond. When completed, the facility will allow cementing and cement displacement under downhole conditions of temperature and pressure. It is planned that the clay-to-cement materials discussed above will be tested in this test facility.

4.3 Jet Descaling

In 1980, Daedalean Associates completed development of a unit that used high-pressure jets of water to descale and clean the inside of wellbore casing (Figure 8). Potential advantages for a jet descaler are that it will allow cleaning of the well while flowing and without mechanical damage to the well casing or liner.

In late 1980, the unit was tested in the Niland area of the Imperial Valley. In this test, the descaling unit easily cleaned more than 100 feet of a barium sulfate scale. However, problems developed with the surface equipment that supported the unit, and the test had to be terminated before more well footage could be cleaned. At this writing, a follow-up test of the descaling unit has been planned. This test will utilize a more reliable surface system and attempt to test the concept of an entire descaling system rather than testing only the prototype descaling head.
5. DIAGNOSTICS TECHNOLOGY

The diagnostics technology area involves projects directed toward gathering downhole information. Much of the work in this program element has been in the development of high-temperature electronic components and systems.

5.1 Geothermal Borehole Televiewer

Development of a high-temperature system was the major thrust of the work on the borehole televiewer. A commercially available televiewer that had no high-temperature capability was adapted for geothermal applications. This involved replacing certain components that had limitations, updating the entire electronics package and repackaging the components into a tool that had operating capability to 275°C. In addition, the supporting signal processing was expanded to increase the utility of the tool in investigating fractures in geothermal wells. After these extensive modifications were completed the tool was used to inspect wells at the Fenton Hill Hot Dry Rock site in New Mexico and to give before and after looks at the Valles Caldera well that was used for the DOE geothermal stimulation experiment.

As it now exists, the tool can be used to inspect casing or to view the open-hole portions of a geothermal wellbore. (Figure 9). However, these capabilities will be expanded by addition of a simple lost circulation search capability. This capability would come from a tool, such as a flow meter or a passive acoustic transducer, that could be used to find lost circulation zones. Once found, the televiewer mode of the tool could be used to inspect these zones. Knowledge of the nature of a lost circulation zone should help in selection of the proper lost circulation material used to plug it.

5.2 Wellbore Inertial Navigator

The work on the wellbore inertial navigator has involved developing and packaging an existing two-axis inertial reference system into a 10.5 cm diameter package that could be put into a wellbore. (Figure 10). The signal processing support for the navigation tool uses Kalman filtering and a reading update scheme that should give an accuracy of one meter per kilometer of depth. As of this writing, a test of the wellbore inertial navigation system in a wellbore is imminent. The prototype tool that has been developed has no high-temperature capability and will be tested in a cool well. Development of a high-temperature version of the inertial navigation system is not planned; the technology contributions from this system are the reduced size package, improved accuracy and advanced signal processing.

5.3 Casing and Cement Bond Inspection Tool

Inspection tools are currently used in petroleum wells. However, certain of their critical components, including silicon controlled rectifier (SCR) switching circuits and the transducers, fail at geothermal temperatures. These components have been replaced by high-temperature-capable components designed specifically for this application. The replacement of the SCR by a modified sprytron tube has been a major portion of this effort. Recently, a sprytron tube has survived 100,000 switching cycles at 275°C. Because of the sensitivity of geothermal wells to good cement bonds as discussed above, this tool and its development are an essential part of the diagnostics technology program element.

6. SUMMARY

The brief discussions above summarize the current activities
and the current emphases in the United States Geothermal Drilling and Completion Technology Development Program. In addition, there have been recent accomplishments in areas that are no longer essential parts of the program. These include: 1) development of improved materials, seals and lubricants for roller-cone bits for high-temperature applications; 2) development of a chain bit which features downhole replaceable cutting surfaces and is especially applicable to deep drilling; 3) completion of the GEOTEMP computer model—a wellbore thermal simulator capable of simulating the environment in a geothermal well; 4) development of a high-temperature perforator system which features a high-temperature detonator that contains only secondary explosive; 5) analysis of geothermal drilling costs and development of representative well models that are used to study geothermal well costs and evaluate the impacts of new technologies; and 6) development of numerous high-temperature electronic components that are the featured subject of a Sandia-sponsored conference on high-temperature electronics in December 1981. Further information on the individual projects can be found in the many references listed below.

The four program elements outlined above reflect the current approach to achieving the program objective—conducting long-range research and development for advanced systems. The recent accomplishments reflect a continuing emphasis on identifying near-term contributions to the geothermal community. This mix of long-range projects with near-term contributions is essential to the viability of the DOE Geothermal Technology Development Program.
7. REFERENCES


National Association of Corrosion Engineers Annual Meeting April 1981


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LEGEND

- RINGS INSTALLED NEAR THE BOTTOM OF THE DRILL STRING
- RINGS INSTALLED NEAR THE TOP OF THE DRILL STRING
- WELL DEPTH VERSUS TIME

PHASE 3
(TREATED AERATED WATER)

PHASE 2
(NITROGEN AND WATER)

PHASE 1
(TREATED AERATED WATER)

TIME IN/OUT (days in November 1980)

CORROSION RATE, mm/y

DEPTH, metres (feet)

6 7 8 9 10 11 12 13 14 15 16

600 (244)
1,000 (305)
1,200 (366)
1,400 (427)
1,600 (488)
1,800 (549)
2,000 (610)
EFFECT OF PRESSURE ON AQUEOUS FOAM CELL SIZE
LIQUID VOLUME FRACTION - 0.045