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Geothermal Drilling and Completion Technology Development Program Semi-Annual Progress Report October 1978--March 1979

Samuel G. Varnado

MASTER

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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
SEMI-ANNUAL PROGRESS REPORT
October 1978--March 1979

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Editor

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ABSTRACT

This report describes the progress, status, and results of ongoing Research and Development (R&D) within the Geothermal Drilling and Completion Technology Development Program. The work reported is sponsored by the Department of Energy/Division of Geothermal Energy, with program management provided by Sandia Laboratories. The program emphasizes the development of geothermal drill bits, drilling fluids, and completion technology. Advanced drilling systems are also under development. The goals of the program are to develop the technology required to reduce well costs by 25% by 1982 and by 50% by 1986.

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SECTION 1

PROGRAM ORGANIZATION

1.0 Introduction

In 1975 the Department of Energy (DOE) instituted a National Geothermal Energy Program (NGEP) and established power-on-line goals of 3,000 MWe by 1985 and 20,000 MWe by the year 2000.¹ To meet these goals it has been estimated that 8,000 new geothermal wells will be required by 1990. Furthermore, it has been estimated that 30% to 70% of the cost of producing electricity from geothermal resources is associated with drilling and completing the geothermal wells.

Traditionally, the cost of drilling and completing geothermal wells has ranged from two to four times that of comparable oil and gas wells. To meet the power-on-line goals of the NGEP and to effect economic compatibility between geothermal and fossil fuel electrical energy generation, the Geothermal Drilling and Completion Technology Development Program was implemented. Sandia Laboratories was selected to manage this program by the DOE/Division of Geothermal Energy (DGE) in the latter part of Fiscal Year 1977 (FY77).

1.1 Program Objective and Goals

The primary objective of the Geothermal Drilling and Completion Technology Development Program is to develop the technology required to reduce the cost of geothermal wells. This objective must be accomplished to allow geothermal energy production at costs competitive with that of conventional energy sources. The following specific goals have been established to support this primary objective: (1) to develop the technology necessary to achieve a 25% reduction in well costs by 1982 through improvements in conventional drilling and completion techniques and equipment and (2) to develop the technology necessary to achieve a 50% reduction in well costs by 1986 through advanced and innovative drilling and completion methods.

1.2 Program Description

Program Management Structure -- Under the auspices of the DOE/DGE, Sandia Laboratories has assumed managerial responsibility for the Geothermal Drilling and Completion Technology Development Program. As program manager, Sandia has structured the program as shown in Figure 1.

Figure 1. Geothermal Drilling and Completion Technology Development Program Structure

Various consultants and a Drilling and Completion Advisory Panel assist the Sandia Program Manager in defining areas for R&D and for assessing program progress. Panel meetings are held on a semiannual basis. The panel reviews the progress of the program and identifies various paths which will be needed in the future to realize the stated goals of the program. The Drilling and Completion Advisory Panel comprises drilling experts from industry, universities, and other national laboratories. Members of the panel are listed in Appendix A.

The program has been divided into three major areas of responsibility: (1) management, (2) internal research and development, and (3) external research and development. Each major area has been further

identified by work elements consistent with the management and R&D aspects of the program. Technical consultants from the Sandia technical staff are designated for external R&D projects within each work element. Figure 2 shows the breakdown of each major area by work element.

Figure 2. Geothermal Drilling and Completion Technology Development Program Work Elements

Program Approach -- The basic approach to achieving the programmatic goals is to identify areas where technology development can lead to significant cost reductions and then to implement the necessary development through external R&D contracts awarded on a competitive basis and through internal R&D activities. This approach is defined by a four-step procedure as follows:

1. A systems study to define various areas of present geothermal well costs and the areas which are most amenable to cost reduction through improved technology,
2. a systems analysis to quantify the sensitivity of well cost to technology improvement, and an independent assessment of potential for cost reduction by an industry-based technology advisory panel,
3. the implementation of research, development, and testing activities necessary to provide the cost reduction benefit, and
4. commercialization of developed technology through industrial participation in research, development, and testing.

Step 1 of the described method has been applied to several existing geothermal wells in various reservoir types. The study showed that for these particular wells the associated costs fall into four major categories: (1) rig costs-rotating, (2) rig costs-nonrotating, (3) trouble costs, e.g., fishing, and (4) completion and other costs. While some of

the costs within each group appear to be difficult to reduce through technology improvements, other costs may lend themselves to significant reductions. Through the procedural methodology indicated above, technology development activities which could lead to cost reductions in present geothermal well drilling and completion have been identified and have provided a basis for the current research and development activities. These activities include improved, high-temperature, high-performance drill bits; high-temperature drilling fluids; high-temperature, high-pressure downhole motors; advanced drilling and completion systems; and supporting research. These activities are outlined in the program plan (see Reference 1).

Research and Development Emphasis -- Research and development for the improvement of present geothermal rotary drilling techniques was initiated in FY75 by DOE/DGE. Some of the projects have continued into the present and have been transferred to Sandia management. In the near term, a program expansion into the concepts for and design of an advanced drilling and completion system (a system different from conventional rotary techniques) is planned. The present emphasis on conventional rotary technology improvement is directed at the stated 25% cost reduction goal, while the advanced drilling and completion systems research is directed at the 50% cost reduction goal. A continuing program of analysis will identify further those areas where application of research and development is necessary.

SECTION 2

PROGRAM STATUS

This reporting period has seen the Geothermal Drilling and Completion Program concentrate on the 25% reduction goal. The program emphasis has been directed at the improvement of present rotary drilling techniques and associated hardware. This section presents a brief overview of the existing program. A detailed description of each project is presented in later sections.

Recent laboratory testing of an improved geothermal roller-cone bit, polycrystalline diamond compact (PDC) bits, and the continuous chain drill has provided optimism that bit development can significantly contribute to programmatic goals. A geothermal roller-cone bit was fabricated using a conventional design, except that materials having higher hot hardness were substituted in certain bit wear areas. Laboratory and field testing and subsequent wear analysis indicate an improvement in downhole bit life of approximately 30% over that of the conventional roller-cone bits. Investigations into high-temperature seals and lubricants for sealed roller-cone bits are in progress, and laboratory tests have been conducted. To date, metal sealing devices and high-temperature elastomeric seals show the most promise. Candidate seals and lubricants for additional field testing will be identified during follow-on laboratory testing.

PDC bits have emerged as a highly viable option in the improvement of present rotary technology. Applications of PDC's to new bit designs, to high-speed bits for use with downhole motors, and to the Sandia chain drill are a few of the areas being investigated. Single-cutter tests and laboratory and field tests of new bit designs have been conducted. Preliminary results of the testing have shown that longer downhole bit life can be expected, but high torque at low rpm is experienced. Further investigations into this phenomenon are being pursued through computer models of the cutter/rock interaction and through bit hydraulics studies.

The Sandia chain drill has been tested in the laboratory and is scheduled for field testing in the latter part of FY79. The cycling mechanism has been improved, and it is expected that the field tests will prove the downhole life of the drill system. Activity is continuing in this area to fully develop the new technology and effect its commercialization.

Facilities have been constructed for testing and evaluating bearing and seal packages for use with high-temperature downhole motors. A bearing and seal test package has been designed and fabricated, and testing will commence in the latter part of FY79. Newly developed seals

have been submitted by industry to be tested. Candidate lubricants have been identified, and initial screening of 23 candidates has been completed. Evaluation of the test results is in progress and further screening tests are planned.

Other areas receiving attention during this period were fluid technology and completion technology. Fluid technology development was directed at understanding the nature of drilling fluids used in geothermal drilling. Conventional drilling fluids do not maintain adequate rheological properties in the environment encountered in geothermal wells. Facilities to test fluid properties at high temperatures and pressures are being fabricated and, in one instance, have been utilized by private industry. A new high-temperature drilling mud has been formulated with indications of superior performance over present fluids. Investigations into high-temperature drilling foams were also initiated. Increased research and the subsequent development of drilling fluids is anticipated in the near future and will consider, in addition to the above, inert gas fluids and the lost circulation problem.

Completion technology has received only cursory attention this last year, due in part to the large activity concentrated in the drilling area and the emerging fluid technology interest. However, two projects of note have occurred this period: (1) a successful field test of a new and innovative pipe descaling system and (2) completion of a state-of-the-art study of completion techniques in all geothermal reservoir types. The pipe descaling system, using cavitating jets, was demonstrated at a geothermal well site in FY78. The demonstration showed a superior performance over conventional descaling methods in that comparable pressures were used without the acid presoak presently required. The latter study established the areas in which future intensive research is required. These areas, which include casing design, reinjection, and completion fluids, are now programmed to be initiated in the current fiscal year. Additionally, workover technology and sand control will be investigated as areas where cost reductions can be realized.

Advanced drilling systems and a wellbore thermal simulator were two additional areas pursued this reporting period. The advanced drilling system project investigated the effects of jet pressure, polymer additives, and cavitation bubbles on water-jet performance for hard-rock drilling. A hybrid bit using jets to slice rock and roller cones to break up the rock and size the hole was developed. Test results indicate that this method has the potential to effect hard-rock drilling with lower pressure than before. A continuation of this work to develop water-jet underreamers is presently in progress.

A computer model has been developed to predict transient wellbore temperatures during drilling, circulation, injection and production in geothermal wells. The program has been entered into the Sandia computing system, and preliminary calibration testing is in progress. Further work in this area will enable the program to handle two-phase and compressible flow.

SECTION 3

MANAGEMENT

3.0 Introduction

As stated earlier, program management has been delegated to Sandia Laboratories by DOE/DGE. Sandia has assigned a program manager to direct and oversee the DOE/DGE Geothermal Drilling and Completion Technology Program. Assigned personnel under the program manager are responsible for monitoring the technical aspects of the program, managing those incumbent contractual activities, and conducting in-house R&D. The managerial staff, through the direction of the program manager, is also responsible for maintaining the program work elements established. The activities occurring within these program work elements during the past reporting period are reviewed in the following paragraphs.

3.1 Program Planning

Program planning consisted of two functions: assimilation of ongoing projects during the transition from DOE to Sandia contracting, and initiation of new projects based on program needs as determined by Sandia with guidance from the Advisory Panel. Figure 3 is a diagram of the management activities utilized in implementing a new project.

During the transition from DOE to Sandia management, Sandia entered the flow path at the step "Monitor Work" on a number of contracts and continued from this point.

To define the long-range program, Sandia has utilized the systems analysis approach in conjunction with the recommendations of the Drilling and Completion Advisory Panel and has issued milestones and needs to DOE as a path to the stated goals. These needs/milestones are issued annually in the form of Laboratory Planning Documents (LPAD) that define the work necessary to be accomplished in the next fiscal year. Management and planning for resources are based on these documents. During this reporting period, a long-range program plan (see Reference 1) was published to guide future program activities.

3.2 Test Coordination

One function of management was to coordinate the field tests necessary to fully evaluate new technology. The field tests performed or scheduled included (1) cavitation-jet descaling of power-plant plumbing for the San Diego Gas & Electric Geothermal test facility at Brawley, California, in January 1978, (2) testing of the unsealed geothermal

Figure 3. Flow Path for New Project Planning and Implementation

roller-cone drill bit at Union Geothermal's CMHC No. 6 well at Geysers, California, during August 1978, (3) conducting well injectivity tests in the Imperial Valley of California, (4) scheduling a field test for the PDC drill bits in the Baca location of the Jemez Mountains in New Mexico for early FY79, and (5) scheduling the field test of the continuous chain drill bit at the Nevada Test Site (NTS) for June 1979.

3.3 System Analysis

The design of a well cost sensitivity model was completed during this reporting period. This model will be used to verify benefits derivable from cost reductions brought about by new technology. The effectiveness of the program will be enhanced during the next reporting period by the inclusion of an improved model and a drilling motor model.

The well cost network model is depicted in Figure 4 and represents the operational procedures encountered in drilling geothermal wells. The model can be manipulated to represent various modes of drilling operation by selecting the appropriate inputs. The outputs of the model which may be selected are listed in Table 1.

Figure 4. Well Cost Network Model

TABLE 1

Well-Cost Model Output Parameters

System Parameters
 Cost/foot
 Cost/hour
 Avg. Rate of
 Penetration (ROP)

Item Cost
 Rig
 Logging
 Casing
 Cementing
 Bits
 Etc.

Operation Time and Costs
 Drilling
 Tripping
 Surveying
 Logging
 Casing
 Cementing
 Bits
 Etc.

Plots Available
 Time vs Depth
 Depth vs Cost

To determine the benefits accruing from technological improvements, the well cost model compares the impact of these improvements with actual data from completed wells. Field data are being collected and filed as inputs to the model. The improvements in the various input parameters--

bit life, downhole time, etc.--through new technology are then substituted for several of the observed input parameters, and these hypothetical outputs are compared to the established output parameters of the actual well. The estimated savings, expressed as a percent reduction in overall costs, determines the expected benefit of the new technology.

In addition to the well cost sensitivity model, systems analyses have been used repeatedly to define areas within well drilling and completion which have the potential for cost reductions. At the outset of this program, an analysis showed that the potential for achieving the stated goal of a 25% cost reduction lay mainly in improving conventional rotary drilling techniques and associated hardware. Consequently, the major emphasis of the program to date has concentrated in this area. Further analysis has also shown that in order to achieve the stated goal of a 50% cost reduction the potential lies in the development of advanced drilling and completion systems. The present program has now been tailored to initiate development of the required systems.

3.4 Contracting

Following is a brief synopsis of significant contracts ending, implemented, or continuing during the reporting period.

1. DRILL BITS & MOTORS

Terra Tek -- Geothermal Roller Cone Bit (May 78 - Oct 78,
Nov 78 - May 79)
Terra Tek -- Improved Downhole Drilling Motor (Apr 78 - Oct 78,
Nov 78 - Oct 79)

2. DRILLING FLUIDS

Univ. of Okla. -- Temperature Limits of Drilling Fluids (Aug 76 -
May 78, Aug 78 - June 79)
Maurer Eng. -- Improved Drilling Fluid Technology (July 77 - June
78)
Maurer Eng. -- State-of-the-Art Study, Foam Drilling Fluids (Apr
78 - Sept 78)

3. COMPLETION TECHNOLOGY

Completion Technology Co. -- Completion State-of-the-Art Study
(July 77 - Nov 78, Dec 78 - Sept 79)
Brinadd Co. -- High-Temperature and Pressure Effects on Comple-
tion Fluids (Sept 78 - Dec 78)
Daedalean Associates - Cavitating Jet Descaling (Feb 76 - Mar 78,
Feb 79 - Aug 80)

4. ADVANCED DRILLING SYSTEMS

Univ. of Missouri -- Water Jet Drilling (June 75 - May 78, Feb 79
- Feb 80)
Hydronautics, Inc. -- Cavijet™ Method of Rock Cutting (Jan 78 -
Dec 78, Jan 79 - Sept 79)

5. SUPPORTING STUDIES

Enertech -- Wellbore Thermal Simulator (June 78 - July 79)

6. OTHER SIGNIFICANT CONTRACTS

Maurer Eng. -- Consulting Services (Continuing)
Livesay Consulting -- Consulting Services (Continuing)
Tech. Reps., Inc. - Program Management Support Services
(Continuing)
BDM - Programming Services (Continuing)

7. ORIGINAL DOE CONTRACTS STILL IN PROGRESS

NL/Baroid -- Properties of Drilling Muds, High-Temperature and
Pressure Instrumentation (Apr 78 - Mar 80)
GE(CRD) -- Polycrystalline Diamond Compacts Bit Development (June
75 - May 79)

A detailed description of the activities included in these contracts is given in a later section of this report.

3.5 Meetings, Visits, and Presentations

A complete listing of significant meetings, visits, and presentations is compiled in Appendix B. The various meetings, visits, and presentations attended during the last year were instrumental in the formulation of a program plan. Through discussions, association, and informational disclosures, a more thorough understanding and appreciation of the problems encountered in geothermal drilling and completion was gained.

Significant among the meetings were those of the Geothermal Drilling and Completion Advisory Panel. The needs of industry were investigated and identified, and guidelines were established.

3.6 Reports

The reporting system necessary to document the work conducted under this program was fully implemented during the past year. Subcontractors submit monthly progress and financial reports to Sandia. Sandia compiles these reports along with internal inputs and publishes a monthly progress report.

Additionally, a semi-annual and annual report will be published giving a summary of the program status to date. This report constitutes the first major summary of Sandia's participation as program manager for the Geothermal Drilling & Completion Program.

Other additional reports are published as necessary. These reports are generated as a result of contract completions, accomplishment of significant contractual work, and studies. Appendix C is a compilation of reports published during this reporting period.

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SECTION 4

INTERNAL RESEARCH AND DEVELOPMENT

4.0 Introduction

The internal R&D program concentrated its efforts this reporting period toward the development of a downhole changeable bit. Toward the latter part of the period, however, the depth and scope of internal R&D increased to include investigative studies on PDC bit hydraulics, drill string corrosion, rock mechanics, and aqueous foam drilling fluids. Additionally, development of a downhole reamer utilizing PDC cutters was initiated. This section will detail the work and results accomplished to date in the internal R&D portion of the Geothermal Drilling and Completion Technology Development Program.

4.1 Continuous Chain Bit

Concept and Design -- The bit concept utilizes a continuous chain of cutting surfaces. The individual links of the chain provide cutting surfaces impregnated with diamonds, and PDC cutters are utilized in the nose of the bit. As the cutting surfaces become worn and no longer useful, a cycling mechanism advances a new series of links into the cutting position. The cycling sequence involves the proper application of mud pressure and the use of a coil spring to provide the cycling force. The final design will have the possibility of 15 changes of the cutting surfaces before removal of the drill bit from downhole. Figure 5 is an artist's illustration of the Prototype II Mod 2 chain drill.

Test Results -- Early in the test program, two link set designs were tested. Both of these designs, by Christensen and NL Hycalog, were tested with a Prototype I bit at the Drilling Research Laboratory in November 1977 and April 1978, respectively. Based on the results of the testing, the Christensen design was selected for use with the chain bit.

Christensen link sets 1 through 3 were tested, and as a result, link set No. 4 was designed. The results of testing link set No. 4 are indicated in Figure 6. As shown in this chart, link set No. 4 showed a marked improvement in weight-on-bit (WOB) versus penetration rate over a conventional Christensen MD 24 bit.

Link sets 6 and 7 were improved versions of link set No. 4 and were tested with the first model (Mod 0) of the Prototype II drill. Bit hydraulics difficulties encountered during this testing resulted in unfavorable data (see Figure 6). These problems prompted a modification of the cycling mechanism. This Mod 1 design was tested in January 1979

Figure 5. Prototype II Mod 2 Continuous Chain Drill

Figure 6. Test Results, Continuous Chain Drill

with link sets 8 through 10. Internal problems with the cycling mechanism were corrected by a modification, resulting in the Mod 2 drill. Link set No. 10 results are shown in Figure 6, and although they do not duplicate the results of link set No. 4, the configuration of this link set and the Mod 2 cycling mechanism design are considered to be very workable. When the Mod 2 system was tested late in the reporting period, some difficulties still remained with the cycling mechanism, so modification was initiated to produce the Mod 3. The Mod 3 drill and link set No. 10 design will become the configuration for the field test scheduled at the Nevada Test Site (NTS) for June 1979.

The major problems found during the testing of the chain drill and link sets consisted of inadequate hydraulics, increasing sliding friction of the chain over the bit head, fluid leakage past the seals, erosion of bit head and links, inconsistent fluid flow rates and pressures, and rock chips fouling the splined area. The Prototype I hydraulic cycling mechanism proved unsuitable. Prototype II Mod 0 incorporated (1) a coil spring to provide the force necessary to cycle new cutting surfaces into position and (2) enlarged fluid passages in the bit body and link sets. The Mod 1 drill added adiprene seals to all drilling links, added dry film lubricant to the splined area, increased the force of the coil cycling spring, and applied an electroless nickel coating to the spline tube assembly to prevent corrosion. Mod 2 provides for wiper seals on the female spline to contain the dry lubricant and to clean the male spline of all debris.

All of the changes thus far incorporated into the Prototype II Mods 0 through 2 will be present in the Mod 3 for the scheduled field test. Subsequent to the field test, a final report will be prepared, and plans for commercialization will be developed.

4.2 Bit Hydraulics Studies

Project Objective -- The objective of this project, initiated at Sandia early in FY79, is to optimize the design of bit hydraulics for geothermal drill bits.

Project Status -- The design of a laboratory test facility for performing flow streamline visualization studies has been completed. Fabrication of the facility will commence in April 1979 and be completed August 1979.

A program plan for the initial investigations in bit hydraulics research has been formulated. The test facility will first be used to evaluate the present nozzle configuration of a 12 cm (4-3/4 inch) diameter PDC drill bit. The hydraulics design of this bit has received no previous study, and optimization of nozzle configuration is considered essential to assure success of the design.

An outline of the approach to be taken in this optimization is as follows:

1. Study of bottomhole flow field,
2. Study of scavenging ability,
3. Establishment of hydraulics design criteria,

4. Redesign of nozzle configuration, and
5. Verification of new design.

The bottomhole flow field will be studied by using flow visualization techniques to map fluid streamlines. The effects of mud weight, viscosity, and flow rate on the flow patterns will be assessed, as will the effects of nozzle diameters. The use of air or foam as the drilling fluid will be studied. This study will provide an indication of the ability of the flowing fluid to clean and cool the PDC cutters by identifying regions of stagnant flow and possible inefficient nozzle placement.

The scavenging ability of the flow can be assessed by measuring the bottomhole pressure distribution and relative chip removal ability as functions of the hydraulic parameters. The relative importance of these parameters will serve as a guide in establishing hydraulic design criteria.

These criteria will include guidelines for the number, diameters, and placement of nozzles. Based on these criteria, the need for redesign of the present nozzle configuration will be determined. If this need is proven, a new configuration will be designed and built. The new design will then be tested as described above to verify the design criteria and the new design itself.

4.3 Drill Stem Corrosion

Project Objective -- The project objective is to study the metallurgical composition of drill stem presently available and to make compositional changes in the drill stem material to maximize its chemical resistance to geothermal H_2S environments without large sacrifices to its mechanical properties or cost.

Project Status -- Test facilities have been designed to perform corrosion tests on new compositional drill stem material in an H_2S geothermal environment. Fabrication of the test facilities, including safety approval, will be completed in May 1979.

Compositions for the experimental drill stem alloy materials have been selected. The experimental alloy, a low alloy steel, will have strength properties equal to those of the conventional drill stem steel, grade E, but the ductility and resistance to H_2S will be significantly improved. The experimental steel is based on the duplex phase Fe-Si steels. The final structure will be a mixture of ferrite and martensite and will have two compositions:*

Composition A: 1.9 ± 0.2 Si, 0.085 ± 0.015 C, balance Fe

Composition B: Composition A plus 0.08 ± 0.02 Vanadium

Sandia's Melting Laboratory will provide 500 pounds of experimental specimens (1/2 Comp. A and 1/2 Comp. B). The specimens, to be completed in June 1979, will be machined into test samples, with testing to commence in September 1979.

*Compositions are in weight percent.

Conventional drill stems to be tested for a comparative analysis with the experimental steels have been ordered, and testing of these specimens should start about June 1979.

4.4 Rock Mechanics for Polycrystalline Diamond Compact (PDC) Cutters

Project Objective -- The project objective is to study stress buildup and the chip formation processes of rock cutting tools utilizing PDC cutters in order to optimize the design of PDC geothermal bits.

Project Status -- A two-dimensional, finite difference model, designated TOODY, is being utilized to investigate the problem. Previous studies have used arbitrary boundary conditions, due in part to not understanding how stresses develop between tool and rock. TOODY will be used to model the tool/rock interaction during chip formation so that stresses in both tool and rock can be calculated.

A review of rock mechanics literature and previous studies of PDC tools and bits has suggested four areas for rock mechanics support of a PDC bit development program. These are (1) tool wear analysis, (2) tool stress and failure calculations, (3) chip formation mechanisms, and (4) system studies. The systems studies would include the combined effects of PDC cutters and other rock breakage mechanisms, e.g., water jets.

During the last few months of this reporting period the TOODY model has been modified to allow calculations of the tool stress. Future work will investigate the effect of rake angle, depth-of-cut, and confining pressure of drilling mud on the tool/rock interaction.

4.5 PDC Reamers

Project Objective -- The project objectives are to modify existing, conventional reamers to allow placement of manmade diamond cutters on the periphery; to field-test the modified reamer for substantiation of expected life increase of the reamer; and to determine improvements in the ability of the reamer to size the wellbore.

Project Status -- This project was initiated in the last quarter of the reporting period, and to date the emplacement design of the PDC cutters has been under study. An additional feature of this project will be to design and develop a down-hole gauge indicator to be used in conjunction with the reamer. Indications of hole gauge will be transferred to the surface for real-time use. At present, two configurations are being investigated: (1) an entrained, detectable gas within the returning drilling mud and (2) a dye release system. Field tests of both the reamer and hole gauge indicator are planned for late FY79.

4.6 Aqueous Foam Drilling Fluids

Project Objective -- Identify and develop aqueous foams for use in geothermal applications. The foams must be capable of operating in elevated temperature environments to 310°C (590°F) and should exhibit chemical and foaming stability and anticorrosive and antioxidant properties.

Project Status -- This project is the most recent of those initiated at Sandia Laboratories during the reporting period. An initial report has been issued which delineates the technical approach to development of the foam. The initial thrust will be to provide screening of the existing surfactants under elevated temperature conditions. Laboratory apparatus for conducting the screening tests is being fabricated.

SECTION 5

EXTERNAL RESEARCH AND DEVELOPMENT

5.0 Introduction

The main thrust of the Geothermal Drilling and Completion Program this reporting period has been to improve conventional rotary drilling techniques and associated hardware. Exploratory research in drilling fluids and completion technology was undertaken, as were some projects in advanced drilling techniques.

Following are summaries of the projects that were in progress during the reporting period. Division is by program work element within the external R&D structure. Information contained herein includes the project, contractor, principal investigator, project objective, and status and results of the project during the performance period.

5.1 Bits and Motors

5.1.1 Geothermal Roller-Cone Bits

Contractor: Terra Tek, Inc.

Principal Investigator: R. R. Hendrickson

Project Objective -- The objective of this project is to design and develop improved tricone roller bits for geothermal applications. The project has two thrusts: (1) to substitute high-temperature steels in unsealed bits and (2) to develop high-temperature seals and lubricants for sealed bearing bits.

Status and Results -- The program was begun in May 1975 with funding from what is now DOE/DGE. Sandia picked up the funding from the point of the DOE contract through the remainder of FY78. A new contract was issued for continuation of this project in FY79. The contract will run from 1 November 1978 through 31 May 1979.

Test facilities have been fabricated, and research bits incorporating steels with higher hardness at high temperature have demonstrated less wear in the simulated downhole drilling environment compared to production bits. Now, third-generation bits have been fabricated and field testing has been completed. These bits (Figure 7) have utilized the new materials indicated in Table 2. Wear analysis is complete and the results are shown in Figure 8. These bits were tested in two wells in the Geysers.

Figure 7. Geothermal Tricone Bit

TABLE 2

Bit Component Materials

Experimental MK III Bits

Timken CBS-600 Steel Lugs
M50 Steel Rollers and
Balls
M2 Steel Thrust Button
Carboloy 90-Guage Row
Inserts

Type OCR-763

Carboloy 248 Bushing
Reed "Tube Metal" Hardfacing

Type OCR-764

M50 Steel Bushing
Cabot No. 1 Mod.
Stellite Hardfacing

Control Bit--Reed Y73-JA

8620 Steel Lugs
S2 Solar Steel
Rollers and Balls
M2 Steel Thrust
Button
Carboloy 231 Inserts
430 Steel Bushing
Cabot No. 1 Mod.
Stellite Hardfacing

Figure 8. Wear Analysis of the Geothermal Tricone Bit

The following conclusions and observations on bearing wear were drawn from these drilling tests and resultant analysis.

Lugs--The use of CBS-600 steel (Timken, Inc.) reduced wear in the ball and roller races by a factor of about 2-1/2 and also reduced wear in the pilot-pin area of the lugs, particularly on the experimental bits utilizing M50 pilot bushings in the cones. Microhardness traces on sections of CBS-600 lugs indicated that surface temperatures exceeded 400°C (752°F) on the roller and ball races and 600°C (1112°F) under the Stellite on the end of the pilot pin. Deformation of the pilot pins was noted on the experimental bits but to a lesser extent than on the Y73JA's. Lug wear, although greatly improved, needs to be reduced further.

Cones--The cones of the experimental bits were standard Reed Y73JA cones of AISI 4820 steel, with either tungsten carbide or M50 pilot bushings in place of the standard AISI 430 stainless steel bushings used on conventional bits. Timken CBS-600 should be used for cones to reduce wear in the roller and ball races. The M50 pilot bushing system was slightly better than the tungsten carbide system; the overall wear in the pilot bearing system ("friction pin area") is excessive and should be reducible by a factor of three.

Rollers and Balls--The M50 rollers reduced wear by a factor of 3 over the conventional Solar Steel rollers; the amount of wear [on the order of 0.08 mm (0.003 inch)] is considered acceptable. The excessive ball wear was due to the design of the ball retainer plug; a definitive test of the M50 balls is still required. Good performance is expected, based on the low wear experienced by the M50 rollers.

Metallurgical analysis of the MK III lugs and bearings is in progress and the data are expected to be available during May 1979.

A preliminary analysis of the field test data from the Geysers tests, shown in Figure 9 and 10, indicates that the MK III bit could drill 30% longer than a conventional bit before incurring the same gauge loss. This results from improvements in the hot hardness of bearing and gauge row insert materials.

Laboratory equipment for testing seals and lubricants under simulated downhole conditions of temperature and pressure has been fabricated. This equipment is being used to screen existing seals and lubricants for use in sealed bearing geothermal bits. Seal studies for lubricated, conventional drill bits identified five types of seals that exhibit some potential for use in a geothermal environment. These seals are identified below:

1. Coil compression spring face seal,
2. Free-floating belleville seal,
3. Fluorocarbon proprietary blend elastomer seals,
4. O-rings with TFE coating and Viton core, and
5. O-rings containing proprietary compounds of Kalrez.

Figure 9. Field Test Data of the Geothermal Tricone MK III Bit

Figure 10. Field Test Data of the Geothermal Tricone MK III Bit

All of the seals indicated above have been tested with the exception of the Kalrez O-rings, which are expected to undergo preliminary testing during April/May 1979. Of the seals tested, the spring-loaded face seal and the fluorocarbon elastomeric seals have shown promise for long life at 200°C (392°F).

The fluorocarbon seals have been tested for 21-23 hours before failure (leakage). These seals will be returned to the manufacturer for failure analysis. Further testing at increased temperatures is contemplated with these seals. Fluorocarbon, Inc., the manufacturer of the seals, has expressed an interest in developing a second-generation seal design based on the results of the previous tests.

The spring-loaded face seal completed several tests, including one of 41 hours at 200°C (392°F). A goal for this seal will be to develop an all-metal version with a 100-hour life at 350°C (662°F). Shown in Figure 11 is the present configuration of this seal. Figure 12 shows the seal broken down into its component parts.

Facilities have been designed and fabricated to test high-temperature lubricants; high-temperature, high-pressure seals; and new designs in bearing/seal packages.

Figure 11. Geothermal Tricone Roller Bit with Spring-Loaded Face Seal

Figure 12. First Prototype Spring-Loaded Face Seal. Shown left to right are the CBS-600 face disc, adapter ring, Kalrez O-ring, seal ring, 18 springs, and spring housing.

An illustration of the high-temperature lubricant tester is shown in Figure 13, and the design specifications are listed in Table 3.

The high-temperature lubricant tester operates by rotating a steel test ring partially immersed in the lubricant against a steel test block. The test block is thrust against the test ring with a normal load of 68 kg (150 lb). A transducer monitors the tangential force so that the coefficient of friction can be calculated. The ring is rotated at 72 ± 1 rpm. At the completion of each test, the width of the wear scar on the test block is measured. The width of the wear scar indicates the wear prevention capability of the test lubricants: a narrow scar indicates lower wear and a better lubricant, and a wide scar indicates higher wear and a poorer lubricant.

Forty different lubricants have been tested during this reporting period. The most successful high-temperature lubricant to date is an experimental oil from Pacer Lubricants, Inc., known as PLX-014. The load bearing ability at 290°C (554°F) is approximately twice that of conventional bit grease at room temperature. The oil is a synthetic hydrocarbon with a proprietary additive system. Graphite particles are suspended in the PLX-014, but these tend to settle out rapidly in storage. The manufacturer is currently working to develop an improved bit grease based on PLX-014. Key features will include improved suspension of graphite, addition of a thickener to attain No. 2 weight, and the same oil and additives as PLX-014. Nearly all future lubricant testing will be centered around PLX-014 oil and its derivatives.

Figure 13. High-Temperature Lubricant Tester

TABLE 3

High-Temperature Lubricant Tester Specifications

Chamber Pressure	1.38 MPa (200 psi)
Lubricant Temperature	Ambient to 427°C (800°F)
Test Ring Rpm	72 $\pm$ 1
Test Block Loading	68 kg (150 lb)

5.1.2 Geothermal PDC Drill Bit Development

Contractor:

General Electric Company,
Corporate Research and
Development

Principal Investigator:

L. E. Hibbs, Jr.

Project Objective -- The overall objective of this project is to develop and demonstrate the performance of a new type of drill-bit design that will provide increased penetration rates and/or longer bit life utilizing high-pressure, sintered polycrystalline diamond compacts for the cutting edges. The scope of this contract includes instrumented rock cutting experiments, diamond compact wear and failure mode analyses, rock removal modeling studies, bit design and construction, full-scale laboratory testing, and field testing.

Status and Results -- Experiments at atmospheric conditions on the cutting of rock with individual PDC cutters have established a predictive capability for the performance of full-scale bits. Demonstrations at atmospheric conditions with full-scale bits have proven this predictive capability. Smith Tool Co. and Christensen Diamond Products built prototype, full-scale bits for downhole simulated testing in May 1978. Figure 14 shows the PDC cutter and stud assembly, Figure 15 shows the Smith bit, and Figure 16 shows the Christensen bit. Field testing of these bits was scheduled for the fall of 1978, with a second generation [21.6 cm (8-1/2-inch) diameter bits] to be tested in early 1979. The first field test of a Smith Bit, designated S-1, occurred in November 1978 and resulted in a catastrophic failure of the bit. Subsequent investigation indicated that

Figure 14. PDC Cutter and Stud Assembly

(a) SIDE VIEW

(b) TOP VIEW

Figure 15. Smith (S-1) PDC Geothermal Drill Bit

(a) SIDE VIEW

(b) TOP VIEW

Figure 16. Christensen (C-1) PDC Geothermal Drill Bit

the pocketed stud used in this bit was damaged during bit fabrication. Stress raisers were set up which caused fracturing and severing of the studs when drilling was attempted. The test was aborted after several attempts to obtain data. A new version of the S-1 Bit, the S-1 (modified), has been redesigned and will be fabricated so that field testing of this bit can be re-initiated. Efforts are continuing to identify a hole suitable for use, but the field test of the C-1 Bit and the S-1 (modified) are at this time not scheduled. It is hoped that field testing will take place for both bits in the late fall of 1979 or early spring of 1980.

5.1.3 Improvement of Downhole Drilling Motor Bearings and Seals

Contractor: Terra Tek, Inc.
Principal Investigator: A. D. Black

Project Objectives -- The application of downhole motors to geothermal drilling has been limited because of short bearing and seal life in the high-temperature geothermal environment. The specific objective of this project is the development of a 200-hour-life bearing and seal package adaptable to most types of downhole motors. The package should operate with a 6.9 MPa (1,000 psi) pressure drop across the bit at a 125°C (257°F) circulation temperature.

Status and Results -- The project began in 1976 with funding from what is now DOE/DGE. Sandia picked up funding from the point of the DOE contract through the remainder of FY79. Completion of the entire program as planned will require funding through mid-FY80.

Based on some preliminary testing and a survey of downhole motor manufacturers, candidate lubricants have been identified and undergone preliminary screening tests at 204°C (400°F). Table 4 lists the candidate lubricants and the results of the initial screening. A certain number of candidate lubricants will be selected to undergo a further screening test at a higher temperature--from approximately 232°C (450°F) to 260°C (500°F). The results of this second screening will allow selection of two or three of the best lubricants for testing in the bearing/seal package. The lubricants undergoing initial and subsequent screenings were and will be tested in the same test facilities as described in the section on Geothermal Roller-Cone Bit (5.1.1).

The downhole-motor seal tester is shown in Figure 17, with the design specifications listed in Table 5. The seal tester is maintained at 121°C (250°F) while conducting the tests. The seals have a differential pressure applied across them from the high-pressure port to the test equipment outer seals. The shaft is normally rotated between 200-500 rpm. Seal failure has been defined as that point in time when 0.0038 m³ (1 gal) of lubricant has leaked past the seal while under test.

Candidate bearing seals have been identified, and through this reporting period 26 tests have been run on the bearing seal tester. The candidate seals are listed in Table 6.

Baseline tests were run using Utex 701 seals since they are widely used in the petroleum industry for surface and downhole rotary applications and will provide the necessary comparison data. The standard test

TABLE 4

Results of Screening Tests at 204°C (400°F)
Candidate High-Temperature Lubricants

<u>Candidate Lubricant</u>	<u>Lubricant No.</u>	<u>Avg. Wear Scar Per Test (inch)</u>
Amoco	31052	0.326
Amoco	M-125	0.164
Amoco	1157	0.125
Amoco	Amdex No. 1 EP	0.242
Amoco	Rykon No. 2	0.140
Amoco	Rykon No. 2 EP	0.150
API	BUC 5A2	0.114, 0.130
Dow-Corning	710	0.561, 0.576
Dow-Corning	M-77	0.269
Jet-Lube	Kopper Kote	0.136, 0.136, 0.197
Mavom	B5K	0.142, 0.162
Mobil	600W	0.137, 0.148
Optimol-Olwerke	Optimoly White T	0.307, 0.376
Pacer	PLX-010	0.092, 0.094
Pacer	PLX-011	0.075, 0.083, 0.102
Pacer	PLX-013	0.077, 0.080
Pacer	PLX-014	0.057, 0.064, 0.070
Pacer	PLX-015	0.098, 0.108
Schmierstoffe	Gleitmo 500	0.104, 0.132, 0.147
Tenneco	Anderol 456	0.167, 0.185
Texaco	EP85-90	0.259, 0.260
Warch	10:1	0.116, 0.158, 0.165
Wooley Booger	Teflon Grease	0.173, 0.204

conditions (Table 7) and test procedures are described for baseline and new-development seal testing. Deviations from standard test conditions were present in some tests and can be found in Reference 3.

The seals are individually dipped in the pressurizing fluid before installation. The heaters are turned on after the seals are installed in the tester, and the temperature of the vessel is increased to 121°C (250°F). The heating process requires about 2 hours. Once the vessel is heated, the fluid is pressurized to 6.9 MPa (1,000 psi) on both sides of the test seals. The valves that control the cooling water to the vessel seals are opened. Immediately prior to rotation of the main shaft, $3.8 \times 10^{-5} \text{ m}^3/\text{s}$ (32 gal/h) of cooling water is directed beneath the shaft sleeve in the area of the lower seal. Water to cool the test seal is turned on just enough to register on the flowmeter [6.3×10^{-6} to $8.4 \times 10^{-6} \text{ m}^3/\text{s}$ (6 to 8 gal/h)] and then rotation is begun. The differential pressure is applied across both seal packs, and as this is done, the flow of cooling water in the area of the test seal is increased to $1.9 \times 10^{-5} \text{ m}^3/\text{s}$.

Figure 17. Downhole Motor Seal Tester

TABLE 5

Downhole Motor Seal Tester Design Specifications

Pressure	Ambient to 3.45 MPa (5000 psi)
Differential Pressure	
Access Seal	0 to 3.45 MPa (5000 psi)
Temperature	Ambient to 316°C (600°F)
Rotary Speed	100 to 1700 rpm
Shaft Diameter	12.7 cm (5.0 inch)
Lubricant Medium	Water, drilling mud with abrasives

TABLE 6

Candidate Seals

Seals	Type
Utex 701	BUNA-N, Chevron
Utex 42D	BUNA-N, Graphite, Chevron
Utex 125K-RD181	Viton Seal Ring, Backup Seal Ring
Utex GRAFOIL®-BeCu	Chevron, High-Temperature
Utex Graphite-Metal Matrix	Chevron, Graphite Impregnated Wire Mesh
Johns-Manville UNEEPAC® Seal	Neoprene Mesh with Flocked Asbestos
Utex Radial Lip Seal	Ceramic Core, Fluorocarbon-Treated Aramid Fabric Impregnated with Graphite
Utex Canted Radial Lip Seal	Same as Radial Lip Seal with AlBr Backup Rings

(18 gal/h). To simulate the condition of adding drill pipe to the drill string, which entails shutting off the flow of drilling mud and stopping rotation, the differential pressure across the test seals is reduced to zero, the rotation is stopped, and the flow of cooling water to the test seals is reduced. The seal tester main shaft remains in a nonrotating condition for 10 minutes. At the end of this time the startup procedure is repeated. The start/stop procedure is repeated every 4 hours throughout the life of the seals.

The results of the seal testing to date are shown in Table 8.

Seal failure analysis has been conducted for the first series of tests 001-018, and the results of this analysis are presented here. The Type 701 seals exhibited two modes of failure: (1) The seal grabs the shaft and buckles, allowing the lubricant to escape (this is the predominant mode), and (2) fatigue failure through the "V" and along the circumference develops from the pressurizing and depressurizing of the seal. The 420 seal fails in the same two modes as the 701. The 125K-RD181 seal

TABLE 7

Standard Test Conditions

Seal I.d.:	12.7 cm (5.0 in.)	No. of Pressure Rings:	3
Seal O.d.:	15.3 cm (6.0 in.)	Pressurized Fluid:	Texaco EP8590 Gear Oil
Temperature:	121°C (250°F)	Rpm:	412
		Shaft Surface:	Hard Chrome
Fwd. Pressure:	17.2 MPa (2500 psi)	Shaft Surface Finish:	12±2 mm, RMS
Diff. Pressure:	10.3 MPa (1500 psi)	Cooling Water Flowrate:	$1.9 \times 10^{-5} \text{ m}^3/\text{s}$ (18 gal/h)
Back Pressure:	6.9 MPa (1000 psi)		

TABLE 8

Seal Testing Results

Test No.	Seal Type	Test Duration (h)	Rpm
001	701	52.7	211
002	701	28.5	211
003	42D	20.4	211
004	42D	13.1	211
005	42D	5.5	211
006	42D	24.2	211
007	42D	3.1	412
008	701	18.2	412
009	701	3.5	412
010	701	10.3	412
011	ABORT		
012	ABORT		
013	RD181	11.3	412
014	RD181	8.6	412
015	701	5.5	412
016	Grafoil	17.5	412
017	Grafoil	9.9	412
018	701	1.2	412
019	Graphite-metal	4.5	412
020	Graphite-metal	13.0	412
021	Grafoil	3.5	412
022	UNEEPAC®	3.5	412
023	UNEEPAC®	26.8	412
024	Grafoil	45.0	412
025	Grafoil	2.0	412
026	Graphite-metal	1.5	

fails by wearing along the seal-shaft interface and simply leaking the lubricant. The Grafoil®-BeCu seal fails by the grafoil separating from the BeCu. The grafoil is so soft that it breaks away from the BeCu chevron rings, gets pulverized by the turning shaft, and is carried away by the subsequent leaking of the lubricant. Further analysis indicates that the elastomer seals will not function at temperatures in excess of 163°C (325°F) for the required 150-200 hours. Future testing of seals will concentrate on the grafoil, graphite and other nonelastomeric seals. Other areas of investigation will include seal-shaft geometry, redundant seals, and shaft surface finish.

Maurer Engineering, under contract to Terra Tek, designed and manufactured a new bearing/seal package. This package, which is designed to be easily adapted to existing drilling motors, contains a sealed lubrication system which allows the thrust bearings and radial bearings to operate in oil or grease. This overcomes one of the major limitations of existing downhole motors where the bearings operate directly in the abrasive drilling mud. Figure 18 shows the new replaceable bearing/seal package on a typical downhole motor.

Major improvements in this bearing assembly include:

1. Roller Thrust Bearings -- The large roller thrust bearings used in this assembly have much higher thrust capabilities and longer life than the ball or rubber thrust bearings used in existing motors.
2. Roller Radial Bearings -- Large roller radial bearings are used to absorb the high bending loads imparted to the downhole motor in directional holes. This increases seal life and reduces dynamic stresses in the motor shafts.
3. Lubrication System -- A floating piston pressurizes a lubricant reservoir allowing the bearings to operate in oil or grease instead of abrasive drilling mud. This increases bearing life 10- to 100-fold.
4. Seals -- The bearing/seal assembly is designed so that it can accommodate different types of seals, including (a) face seals, (b) packing seals, and (c) radial lip seals. The seals being tested in the seal tester can be immediately adapted to this assembly.

To test and evaluate the performance of the bearing/seal package, a bearing/seal package test facility has been designed by Terra Tek. A cross-sectional and plan view of the facility is shown in Figure 19. The test facility allows controlled and repeatable tests on the bearing/seal package at a simulated pressure of 34.5 MPa (5000 psi), a temperature of 300°C (572°F), a rotational speed of 1000 rpm, and with mud circulation

Figure 18. Replaceable Bearing/Seal Package on a Typical Downhole Motor

Figure 19. Bearing/Seal Package Test Facility

and dynamic loads. The test facility was completed this reporting period, and verification and operational testing is being performed to evaluate the facility. Full-scale testing of the bearing/seal package will commence in May 1979.

5.2 Fluid Technology

Drilling fluids for use in a geothermal environment suffer from several adverse effects of that environment. The elevated temperature environment in a geothermal well degrades the rheological properties, increases corrosion rates, and promotes gelation. Secondly, the formations in which geothermal reservoirs are found are normally of a fractured nature, and these formations contribute to a severe lost-circulation problem. To counteract lost circulation, air and mist drilling are often attempted. This has proven successful in some cases, but with the elevated temperatures, increased erosion to the drill string is quite noticeable.

Fluid technology research and development have been initiated in several areas which will address the problems noted above. Figure 20 depicts the program for fluid technology R&D with both the ongoing effort and future plans incorporated.

High-temperature, high-pressure instrumentation for measuring rheological properties of drilling fluids is being developed under the following two contracts.

5.2.1 Determining Temperature Limits of Drilling Fluids

Contractor: University of Oklahoma
Principal Investigator: E. F. Blick

Project Objective -- The objective of this project is the evaluation of the high-temperature properties of available drilling-fluid additives in a dynamic flow loop. This contract provides for the establishment of a mud test laboratory, for the design and fabrication of a 288°C (550°F), 20.7 MPa (3,000 psi) flow loop and for a moderate amount of drilling-fluids testing.

Status and Results -- Sufficient testing has been accomplished using a modified flow loop at Magcobar to demonstrate the existence of a large discrepancy between ambient data as normally taken in mud laboratories and the actual characteristics of the fluid under dynamic, simulated downhole conditions. A new flow loop has been fabricated at the University of Oklahoma, and testing of muds has begun. The program is continuing under Sandia contract 13-0346, from August 1978 to June 1979.

The flow-loop tester has been moved several times to accommodate facility of operation. Prior to these moves, the flow-loop tester underwent several verification tests and accomplished one test of a commercial fluid. The preliminary results of this test have indicated that the flow-loop tester has performance superior to that presently available in the private sector. Further testing of fluids has been repeatedly delayed due to malfunction of the tester, particularly with erosion of the valves and valve seats. Action is being taken to correct the problem and new valves with high-hardness stellite seats are being installed.

Figure 20. Fluid Technology Research and Development Program

5.2.2 Development of High-Temperature/High-Pressure Drilling Mud Instrumentation

Contractor: N. L. Baroid
 Principal Investigator: K. L. Walter

Project Objective -- This project will result in the fabrication of a drilling-mud testing instrument capable of measuring fluid properties under dynamic flow conditions of up to 371°C (700°F) and 138 MPa (20,000 psi). This is an extension of the 288°C (550°F) capability provided by the University of Oklahoma project.

Status and Results -- Test facilities have been designed, and preliminary drawings of the facility and the major equipment are shown in Figures 21 and 22. The design of the test apparatus and instrumentation calls for pressurization of the fluid under test by argon gas, with heat generation by internal heaters. Under dynamic conditions the fluid being tested will be subjected to the desired temperature and pressure, and the rheological, corrosivity, and density properties will be measured. The final test facility will be completed in October 1979, with the first testing of fluids in February 1980.

Figure 21. Geothermal Drilling Fluid Test System (GDFTS)

Figure 22. Geothermal Drilling Fluid Test System Vessel

A major problem associated with this project has occurred in the last few months of this reporting period. The test facility originally was to have been housed in the present Baroid test labs; however, the new research lab under construction for Baroid is better situated to accommodate the test facility. A decision to locate the test facility in the new lab would necessitate a delay in fluid testing. A decision as to the ultimate location is anticipated within the next report period.

In addition to instrumentation development, the development of improved drilling fluids has been undertaken. The current projects which close out at the end of this reporting period, are described in the following paragraphs.

5.2.3 Application and Utilization of Improved Geothermal Drilling Fluid Technology

Contractor: Maurer Engineering, Inc.
Principal Investigator: W. J. McDonald

Project Objective -- The objective of this project has been to develop drilling fluids with higher temperature capability than those currently available for geothermal drilling. Areas of endeavor have been (1) investigation of existing muds and the formulation of a superior fluid, (2) critique of fluid programs on existing geothermal wells, (3) development of a fluid program on existing geothermal wells, (4) development of a fluid program planning document, and (5) coordination of technology transfer for all existing DGE drilling-fluid programs.

Status and Results -- Tests of muds prepared and submitted by mud companies have indicated that even the industry's specially prepared muds exhibited high-temperature gelation, high viscosity, high filtration rates, and poor corrosivity characteristics at temperatures above 177°C (350°F).

An improved geothermal drilling fluid (HTM-1) has been developed for drilling into hydrothermal reservoirs. The mud can be prepared with conventional equipment from materials which are commercially available. Selling price of the unweighted mud is about the same as that of unweighted muds sold by major mud suppliers for use at high temperatures. The mud has excellent properties when prepared at room temperature and retains many of these properties even after static exposure at 260°C (500°F).

Composition of mud HTM-1 is as follows:

Water	0.16 m ³ (1.0 bbl)
Sepiolite	6.8 kg (15.0 lb)
Bentonite	2.3 kg (5.0 lb)
Brown Coal	9.1 kg (20.0 lb)
Sodium Polyacrylate	0.9 kg (2.0 lb)
Sodium Hydroxide	0.9 kg (2.0 lb)

Figure 23 shows a comparison of the filtrate of the mud HTM-1 at 177°C (350°F) and 3.4 MPa (500 psi) with that of the five commercial muds tested in Phase 1 of this project. Mud HTM-1 has better filtration control after being exposed to 260°C (500°F) for 24 hours than any of the

Figure 23. Filtrate of HTM-1 and Five Test Samples

muds submitted by the major mud suppliers. Two of the muds, B and C, had lower filtrates than mud HTM-1, both initially and after being exposed to (450°F) for 24 hours. A field test of the HTM-1 mud is planned for late FY79 or early FY80.

5.2.4 Foam Drilling Fluid Evaluation

Contractor: Maurer Engineering, Inc.
Principal Investigator: W. J. McDonald

Project Objective -- The objectives of this project have been to determine the extent of the need for and the effects of the availability of a high-temperature foam for geothermal drilling, to test existing foams to determine their limitations, and to formulate recommendations for a future foam-development program, including test methods, test equipment development, and the desirable characteristics of foams to be developed.

Status and Results -- A survey of over 50 industry technical personnel has been conducted to determine the need for foams in geothermal well drilling. The consensus of the survey indicated that foam drilling fluid could be applicable to 80% of geothermal drilling if the present technical problems could be overcome. These problems are listed below.

1. Stability of foams under changing pressure and temperature conditions,
2. Stability of foams under water or brine intrusion,
3. Corrosivity of foams, including pH stability,
4. Foam breaking, cleaning, and disposal problems,
5. Borehole stability in the presence of foams,
6. Sensitivity of foams in inert or stack gas hydrocarbon impurities,
7. Foam generators and other surface hardware,
8. Lifting capability of foams,
9. Heat transfer/insulation and heat capacity of foams, and
10. Testing and screening procedures for foams.

Testing and screening of present foams have been accomplished during the course of this study. The best test of those presently available has proven to be the modified Chevron test; that is, testing before and after high-temperature aging. The results of the testing showed that all foams presently used degrade rapidly when subjected to high temperatures. The acetic acids which form when foams degrade cause them to be very corrosive, with a noted reduction in the pH of the water.

Based on the survey and results of the initial testing of commercially available foams, a foam development program has been recommended. The recommendation consists of development of a dynamic loop foam tester capable of temperatures to 370°C (700°F), development of foams for use in geothermal drilling to temperatures of 370°C (700°F), and design of surface equipment to recover the foam and remove entrapped solids.

As reported previously, development of surfactants for geothermal use has been initiated at Sandia Laboratories and is discussed in the internal R&D section.

5.3 Completion Technology

Improperly completed wells can substantially reduce energy production and require additional well drilling or frequent workover. Completion and reinjection technologies are critical to the overall economics of geothermal development when viewed from the perspective of the total useful life of both production and reinjection wells.

Several broad areas concerning well completion problems associated with geothermal energy development have been identified through a state-of-the-art study. The areas identified for future R&D effort are listed below:

1. Corrosion control and its effects on the life of downhole tubing and plugging of formations, which in turn affects methods of fluid production.
2. Casing programs for improved life and capacity, together with cementing programs for improved placement, performance, and thermal resistance. This also includes drilling and fracturing fluids and their effect on skin damage and stimulation results.
3. Reinjection for fluid disposal and improved reservoir life, including sand control and formation protection.

During this reporting period, the results of these generalized studies identified specific problems which led to recommendations for development activities.

5.3.1 Completion Technology Consultation

Contractor:	Completion Technology Company
Principal Investigator:	R. M. Jorda

Project Objective -- The objective of this project is to provide consulting services and assistance to the geothermal drilling and completion technology development effort. Specific objectives of the project include (1) assistance in the definition and review of current completion technology programs, (2) evaluation of field millipore filter injectivity tests, (3) completion of a state-of-the-art study of casing/liner design and cementing technology relating to geothermal/geopressured environments, (4) assistance on a study of high-temperature properties of casing and casing joints, and (5) evaluation of cement-inflatable packers in hot dry rock (HDR) and fluid-dominated geothermal systems.

Status and Results -- State-of-the-art studies of the completions used in various reservoir types have been performed.

An analysis was completed of the Magma-East Mesa reinjection well in the Imperial Valley. The major problem identified by this analysis is sand fill in the injector caused by repeated back flows of fine unconsolidated sand when the injection well was shut in. The injector was back flowed and the fill removed, causing a decrease in injection pressure and an increase in injectivity by a factor of 7.5; however, some slight impairment is thought to exist. A second analysis shows that the wells at East Mesa have a very high potential injectivity and that overall water quality is quite high.

The literature search on casing and liner studies was completed during this reporting period, and a draft outline of the scope of the studies was prepared. Work was also begun during this period on the casing design report, which is intended to be a basic manual describing common casing problems and offering useful design and selection considerations. Casing failure modes and specifics of casing and liner technology with application to geothermal wells will be included in the report.

A study was performed and documented for Magma Power to estimate the injection test duration required to predict long-term subsurface injection performance for the spent-brine from the 50 MW power plant now under construction at the Niland KGRA, California.

The report concludes that an acceptable long-term estimate can be obtained in 2 to 4 months if specific water quality and well survey data are acquired, but that the water treating and disposal plant stream factor should be at least 90% during the test period in order to obtain reliable data.

The report also contains transient pressure behavior of the reservoir and provides guidance for differentiating between injection surface pressure increases caused by the transient reservoir pressure and pressure increases caused by well impairment. The report is titled Predicting Injector Performance at the Proposed Magma-SDG&E Fifty Megawatt Geothermal Power Plant.

An evaluation of the use of cement-inflatable packers in HDR and fluid-dominated geothermal systems was initiated during this reporting period.

5.3.2 The Effects of High-Temperature and Pressure Aging on Completion Fluids

Contractor: Brinadd Company
Principal Investigator: M. R. Childers

Project Objective -- The objective of this project has been to define the effects of high-temperature and pressure aging on completion fluids for geothermal drilling applications.

Status and Results -- Work under this contract is completed and a final report was issued during this reporting period. The study included a survey of the major oilfield fluids companies. Only one company claimed to have a potential completion fluid. This formulation was tested using aging cells placed in an oven to simulate the downhole geothermal environment. The conclusion of this study was that there are no geothermal completion fluids on the market. The recommendation was made for future development of a geothermal completion fluid to meet the following criteria:

1. Low fluid loss with rapid shutoff
2. Filter cake is easily removed with backflush
3. System is physically and chemically stable to 340°C (650°F).

5.3.3 Cavitating-Jet Descaling of Geothermal Equipment

Contractor: Daedalean Associates
Principal Investigators: Dr. A. A. Hockrein, Jr.
Dr. A. P. Thiruvengadam

Project Objective -- The objective of this project has been to demonstrate the superior performance of cavitating water jets in removing water-deposited scale from equipment used on geothermal sites. During this reporting period the contractor has investigated the cavitation phenomenon, designed and fabricated the cleaning apparatus, and conducted a demonstration at an actual geothermal installation.

Status and Results -- The contractor conducted a demonstration of the cleaning technique at the San Diego Gas and Electric geothermal project at Niland, California, during January 1978. Figure 24 depicts the nozzle configuration used in this demonstration.

The demonstrations showed the superior potential of cavitating jets when compared to the existing cleaning procedure. They removed scale using comparable pressures, but without the acid presoak now required.

The piping between the third and fourth stage brine flash tanks was descaled in the demonstration. The total cleaning parameters are given in Figure 25.

Work on cavitation-jet descaling of surface equipment was essentially completed under Daedalean's original contract during this reporting period. Under a new contract, work is continuing on development of a cavitation descaling technique for cleaning and removing scale from geothermal wellbores without shutting-in the well.

During this period, a design parameter identification test sequence was held at the East Mesa Geothermal Test Facility. It was determined that when the nozzle was positioned so that the cavitating jets impinged at the intersection of the base of the scale crystals and the pipe wall, the threshold for scale removal was 6,000 psi. The configuration is shown in Figure 26(a). When the nozzle configuration was changed to impinge at an angle perpendicular to the wall, Figure 26(b), the threshold pressure for scale removal was 10,000 psi. Several different nozzle designs were also evaluated during these tests. It appears from this initial test sequence that the fan spray type of nozzle, Figure 27(a), is the least effective of all the configurations. The best scale removal performance is obtained with a nozzle that produces a conical spray pattern, Figure 27(b).

Figure 24. Nozzle Configuration for Descaling Demonstration

Figure 25. Flash Tank Piping Between 3rd and 4th Stage Flash Tanks
Cleaning Demonstration Data Parameters

(a)

(b)

Figure 26. Nozzle/Scale Impingement

a. FAN SPRAY

b. CONICAL SPRAY

Figure 27. Nozzle Configurations Utilized During Test

5.3.4 Min-Stress Packer Development

Contractor: L'Garde, Inc.
Principal Investigator: A. R. Hirasuna

Project Objective -- The objective of this project is to generate geothermal packer performance specifications, update the min-stress packer concept to reflect requirements of specifications, define candidates for the elastomer reinforcing substrate and design a laboratory simulation test for the packer concept.

Status and Results -- During this reporting period, the packer concept was updated to conform with the performance specification generated for the program. Significant changes were required to adopt the design for open-hole use and for the potential thermal expansion/contraction of the inflation fluid which may be encountered in the downhole environment. The concept will require significant advance in the state-of-the-art in several areas such as the inflatable seal and O-ring seal.

Definition of the elastomer candidates was also completed and documented during this period. The base polymers recommended are propylene TFE (AFLAS) and Ethylene Propylene Diene Terpolymer (EPDM). Reinforcing substrate material candidates were also defined. Inconel 718, Kevlar 29 (an Aramid fiber), and AB-312 (a ceramic fiber) are recommended. The candidate coupling agents recommended for the next phase are the family of chemlok adhesive systems, Asahi Glass adhesive systems, resorcinol formaldehyde, and a system developed by L'Garde for Air Force EPDM systems.

The 3D SIM laboratory simulation test design was finalized. Detailed drawings of the pressure vessel were completed and checked. The various parts and components for the overall simulator were identified and sized for cost estimating.

5.4 Advanced Drilling Systems

Improvements in conventional rotary technology, while necessary to accomplish the near-term goal of a 25% reduction in cost, are not capable of achieving the goal of a 50% reduction. The goal of a 50% reduction in geothermal well cost by 1986 can potentially be met by the development of advanced or innovative drilling systems. This will require extensive R&D to develop systems not presently available.

An advanced drilling workshop was held in January 1979 to identify advanced drilling systems that have the potential for reducing the cost of drilling and completing geothermal wells. Approximately 50 participants from industry were invited. Three systems were identified: (1) water jet drilling used in conjunction with roller-cone bits, (2) downhole motors with high-speed bits, and (3) percussion drilling techniques. R&D tasks required to implement these systems were identified by the workshop participants, and these tasks will be utilized to formulate an R&D program for one or more of these advanced drilling systems.

To promote and develop these advanced systems, preliminary investigations have been initiated which will study the effects of water jet erosion and cavitation effects on well drilling. Following is a discussion of these studies.

5.4.1 Design of a Water-Jet Drill for the Development of Geothermal Resources

Contractor: University of Missouri-Rolla
Principal Investigator: D. A. Summers

Project Objective -- Investigations have been made to determine the effects of jet pressure and fluid additives on water-jet performance and to demonstrate the applicability of a design concept using water jets as an effective hard-rock drilling method.

Status and Results -- This project has demonstrated the ability of water jets to drill hard rock using much lower pressures than had previously been required. It was determined that polymer additives have a second-order effect on jet drilling. In comparing the effects of water-jet drilling with those of cavitation-jet drilling, it was found that, at low pressures, water jets with abrasive additives are superior, but above certain pressure levels, the reverse is true. During experimentation it was found that although water jets can produce a more rapid rate of penetration, hole size was inadequate. This led to development of a hybrid bit using water jets to slice the rock and roller cones to break up the rock and size the hole.

In the initial investigations of water jet drilling two types of rock were used: Berea sandstone and granite. The sandstone is granular and erosion is accomplished by continual particle removal. Since the single-jet nozzle first used was oriented at angles to the direction of penetration, the jet had to remove the rock particles outward from the center to the hole radius. As the hole advanced radially, the removal ability of the jet was diminished. Subsequently, a new nozzle design, Figure 28, was tested and ultimately patented. This design diverts a portion of the jet stream ahead of the nozzle to remove the central core of rock, providing preliminary clearance for the nozzle head and inclined jet. The removal of the central core leaves less rock for the inclined jet to remove and has had the effect of enlarging hole diameter and advancing penetration rate. Penetration rates of about 7.11 m/min (280 in./min) have been achieved in this testing configuration.

Crystalline rock, e.g., granite, differs in structure from sandstone in that it has a large intergrowth of crystals. The failure mode of this rock is by transcrystalline fracture, and these fractures can extend into the central core. Thus the nozzle used in this testing was without a center jet, and all energy of the jet stream was concentrated into one inclined jet. Advance rates in granite to 1.02 m/min (40 in./min) have been observed at jet cutting pressures between 102.7-109.6 MPa (15-16,000 psi).

A phenomenon observed when simulating downhole conditions was the shrinking of the hole. A triaxial chamber was used to simulate hole depths to 1,829 metres (6,000 feet). The results of this testing are shown in Figure 29. This figure also shows the effects of adding polymers to the jet stream. Although some increase in hole size at depth is indicated, the relatively small increase in advantage was not sufficient to warrant further examination of polymer additives during the course of this project. At first the decrease in hole size was thought to be due to the

Figure 28. Nozzle Design Used for Advanced Rate Studies

Figure 29. Chemical Additives, Confining Pressure, and Borehole Pressure Effects on Hole Diameter in Berea Sandstone, 10,000 psi Jet Pressure, Type 2 Nozzle

pressure drop across the nozzle due to the hydrostatic pressure of the wellbore fluid. However, it was found during subsequent testing and verification that the rock medium itself reduced the cutability of the rock. Jet drilling is accomplished by high-pressure water jets impacting the rock and entering into small cracks, microfissures, etc; crack propagation and erosion is then accomplished by local hydraulic fracture. The depth of the hole causes an increased pressure on the in-situ rock being eroded and compresses or closes these small cracks and microfissures, reducing the penetration for hydraulic fracture.

Hole shrinkage as experienced above presented a real problem in obtaining successful water jet drilling in geothermal reservoirs. The high pressures required for cutting hard rock at high rates are not currently obtainable on existing rigs. One advantage of water-jet drilling observed during testing was that large kerfs were cut radially in the wall of the hole while drilling. The ridges of rock left were found to be relatively weak in shear and tension, and very little crushing action was necessary to remove them. This result suggested that a combined water-jet mechanical bit for drilling holes of the size desired might be possible. Ultimately, a hybrid drill bit of this concept was developed. Photographs of this type bit are shown in Figure 30. The general principle of this hybrid bit was to create a cavity ahead of the bit and have the lateral jets cut kerfs and cool the roller-cone bit. The roller-cone bit could then easily crush the rock ridges produced by kerfing. Results of lab testing with the hybrid bit showed an improvement on the order of 25% over conventional roller-cone bits.

Field test equipment was developed during the course of this project to test the water-jet drills. The equipment was packaged aboard a 12.2-metre (40-foot) trailer and included a 250-kW generator, two large water tanks, and a drilling frame. In field testing the water jet, a 2.5-cm (1-inch) diameter hole was drilled at rates up to 0.91 m/min (3.0 ft/min) in limestone and dolomite with a compressive strength to 206 MPa (30,000 psi). Subsequently, the test rig was modified to accept an 8.9-cm (3.5-inch) bit which could be operated with or without high-pressure water jets. During testing of the hybrid bit, it was found that considerable pressure drops occurred between pump and nozzle, and to achieve a 68.5 MPa (10,000 psi) pressure at the nozzle, it was necessary to generate 150.7 MPa (22,000 psi) at the pump. This nozzle pressure was sufficient to produce a cavity ahead of the roller cone, but on occasion, harder rock intrusions of dolomite or chert were encountered, and the water jet was no longer able to maintain a hole ahead of the roller-cone bit. This effectively put all the load on the nozzle, and thus the bit was worn away rapidly. A fix to this problem was accomplished by adapting a 2.5-cm (1-inch) diamond coring bit to fit around the edge of the nozzle to cut clearance for the nozzle body when it encountered a particularly difficult strata of rock to penetrate.

This project has shown that water-jet drilling can effectively cut rocks of varying hardness, but the pressures required are sometimes greater than can satisfactorily be generated with conventional rig equipment. A test comparison program was developed during this project to find a method or methods which allow water-jet penetration rates comparable to those previously described but at pressures low enough to be accommodated by existing field equipment.

Figure 30. View of Jet Head and Roller-Drill Bit: a) Silhouette of Jet Stream and b) Hybrid Roller-Cone Bit

The test procedures developed to identify the methods necessary were to modify the water-jet drilling equipment to produce a cavitating jet stream and to inject abrasive material into the jet stream. A precedent has been set with A. Conn's work* on cavitation at Hydronautics and Gulf Oil's field work with abrasive water jets. Figure 31 shows the results of testing the three different modes of water jet drilling.

Figure 31. Relative Erosion Capacity of Jets as a Function of Pressure at 15-cm Standoff

These results indicate that at 100 MPa (14,500 psi) the plain, unaltered water jet becomes a better material remover than the abrasive jet. Below 56 MPa (8,200 psi) the abrasive jet produces the greatest effect. The cavitating jet stream above the 56 MPa (8,200 psi) threshold is far superior to either the plain or abrasive jet and is a verification of Conn's work indicating that cavitating jets have an equal or greater capability to remove rock at significantly less pressure and that the pressure necessary is within the realm of present equipment.

Since the cavitation method of rock erosion appears to have the greatest potential, further understanding of this phenomenon was undertaken as a thesis topic. Standards for cavitation testing were researched, and it was found that an ASTM method existed, but under test it proved inadequate for rock. As a result of further thesis research on cavitation standards,

*See following section of this report

a test procedure for cavitation damage has been submitted as a standard to ASTM. Since this procedure has been developed around the use of metal samples, further research is needed to develop a standard for rocks.

During the last month of this reporting period, a new contract has been placed with the University of Missouri-Rolla to design, fabricate, and demonstrate a first prototype of an erosion drilling underreamer for use in geothermal injection wells. Additionally, the contract calls for completion of a field-test program for the hybrid water-jet/roller-cone bit and continuation of investigations into development of the proposed cavitation test method for rocks.

5.4.2 Drilling Mud Effects Using Cavitating Jets

Contractor: Hydronautics, Inc.
Principal Investigator: A. F. Conn

Project Objective -- The project objective is to determine the effects of drilling mud as an erosion medium using cavitating jets for rock cutting and nozzle design. The results of testing will be used to design a full-scale, jet assisted rock bit for laboratory testing.

Status and Results -- Standard bit drilling tests have been conducted to establish baseline data for comparison with jet augmented bits. Augmented bit tests have been conducted to investigate the effects of nozzle design and the use of mud as the drilling fluid.

Pressure-cell tests on Berea sandstone have been initiated in a recently modified test facility to determine threshold bit pressures for the onset of cavitation under ambient and pressurized-borehole conditions. The cavitation number, σ , defined as the ratio of ambient pressure to nozzle pressure drop, is a parameter which can be used in scaling laboratory results to full-scale tests. Table 9 shows the preliminary results of the initial parameter testing. The fluid medium in these tests has been water, but testing utilizing drilling mud has been initiated.

Preliminary results of the previous cavitating-jet testing has shown that a rate of penetration comparable to that of present water-jet erosion drilling can be accomplished by using much lower pressures. This effect has been recently verified by D. Summers of the University of Missouri-Rolla, as previously reported.

5.5 Supporting Studies

As a result of high temperatures experienced in geothermal wells, special design criteria are needed for drilling, completion, and injection or production systems. To ensure proper design of the various components of downhole equipment, a firm understanding of the temperatures and the many variables which influence these temperatures in and surrounding the well is necessary. Experience has demonstrated the need for a computer model to account for the complexities of heat transfer in a well.

TABLE 9

Preliminary Pressure-Cell Test Results

Rock: Berea sandstone
 Working Fluid: Water
 CaviJet™ Nozzle: 3.2 mm (0.125 inch), plain
 Standoff: 19.1 mm (0.75 inch)

Run No.	Orien- tation*	Nozzle Pressure Δp MPa (psi)	Ambient Pressure P_a MPa (psi)	Cavitation No. σ	Translation Velocity v cm/s (inches/s)	Mean Slot Depth h mm (inch)	Mean Slot Width w mm (inch)
2A	N	10.3 (1500)	4.1 (600)	0.40	15.2 (6.0)	1.78 (0.07)	17.53 (0.69)
2B	N				7.6 (3.0)	6.10 (0.24)	22.35 (0.88)
2C	P				3.8 (1.5)	1.52 (0.06)	12.70 (0.50)
2D	P				3.8 (1.5)	2.29 (0.09)	12.70 (0.50)
2E	P				3.8 (1.5)	1.52 (0.06)	12.70 (0.50)
3A	P				7.6 (3.0)	4.57 (0.18)	22.35 (0.88)
3B	P				15.2 (6.0)	3.30 (0.13)	22.35 (0.88)
3C	N				3.8 (1.5)	2.03 (0.08)	16.00 (0.63)
3D	N				2.5 (1.0)	3.05 (0.12)	17.53 (0.69)
3E	P				1.3 (0.5)	2.79 (0.11)	17.53 (0.69)
3F	P	10.3 (1500)	4.1 (600)	0.40	2.5 (1.0)	2.29 (0.09)	16.00 (0.63)
5A	N	12.4 (1800)	2.1 (300)	0.16	2.5 (1.0)	16.51 (0.65)	19.05 (0.75)
5B	N	11.4 (1650)	2.4 (350)	0.21	2.5 (1.0)	14.48 (0.57)	22.35 (0.88)

*Orientation of jet to bedding planes of the specimen: N is normal to the bedding planes; P is parallel to the bedding planes.

5.5.1 Wellbore Thermal Simulator for Geothermal Wells

Contractor: EnerTech
 Principal Investigator: G. R. Wooley

Project Objective -- The objective of this program is to develop a computer code for predicting transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells. The code will handle single-phase unidirectional or counter-current flow and static shut-in conditions and will incorporate all significant sources of energy, such as friction heating and viscous dissipation during circulation, bit work during drilling, and heat of hydration during cementing.

The code will be checked against data from actual wells, and sensitivity studies will be performed on the importance of the various input parameters.

Status and Results -- During this reporting period a computer model has been developed which computes downhole temperatures in and around a geothermal well. This thermal simulator (GEOTEMP) incorporates features which produce flowing stream options of (1) injection down tubing, (2) production up tubing, (3) forward circulation, and (4) reverse circulation. The thermal simulator is now fully operational for application to geothermal and other wells. There have been three distinct parts of the model development: the flowing stream energy balance, the wellbore description, and the soil energy balance.

The flowing stream energy balance is a fully transient analysis with vertical heat convection and radial heat conduction. Such a fully transient behavior has not previously been available for public use.

The wellbore description is a composite of annular materials, including the steel, cement, and fluids present in a well. A fully transient, radial, heat-conduction model accounts for the wellbore region. Material heat capacities and natural convection in annular fluids are both included. Figure 32 shows a schematic of the wellbore model used for development of the conductances. Up to five strings of pipe may be modeled in the hole.

A key feature in the thermal simulator is the direct coupling of soil and well temperature calculations. An iterative solution between the soil and well regions is not required as in most other thermal simulators.

GEOTEMP has been used to model conditions for three sets of field temperature data. Comparisons of the field measurements to predicted downhole temperatures demonstrate the accuracy of the program. Two sets of data for geothermal wells and one set for a petroleum well are presented. Some comparisons of the model predictions (based on actual input data) with actual measurement are described in the following paragraphs.

Republic Geothermal has supplied two sets of downhole temperature measurements for production and for shut-in conditions. For the first well, three measurements of shut-in temperatures establishing the undisturbed geothermal temperature distribution are plotted in Figure 33.

The solid line in Figure 33 is the temperature distribution adopted in the computer calculations for flowing conditions. Figure 34₃ gives the measured and computed temperatures during production at 1,908 m³ (12,000 barrels) per day. Also shown is the undisturbed temperature profile and a casing completion diagram.

Field data provide only steady-state temperatures recorded in Well No. 1 after 20 hours of production. Figure 35 illustrates the transient behavior of the fluid temperature at four depths. It is evident that GEOTEMP not only provides accurate temperatures for long times, but predicts how temperatures traverse from the undisturbed to the steady-state condition.

While GEOTEMP is currently structured to analyze two-dimensional, one-phase flow situations, future plans call for changes to the model which will incorporate two-phase flow. Sensitivity studies beginning from a base case calculation will also be undertaken to determine which of the model parameters must be most accurately specified.

Figure 32. Computer Model of Wellbore Completion for Production and Injection

Figure 33. Undisturbed Temperature Distribution, Republic Geothermal Well No. 1

Figure 34. Steady-State Production Fluid Temperature Profile, Republic Geothermal Well No. 1

Figure 35. Transient Temperature Behavior at Various Depths, Republic Geothermal Well No. 1

SECTION 6

FUTURE PLANS

The future development plans of the Geothermal Drilling and Completion Technology Program will emphasize the 25% cost reduction goal through 1982; then an increased emphasis in the area of advanced drilling systems will be initiated to meet the 50% cost reduction goal. Fluid technology programs will be expanded to advance the state-of-the-art in inert drilling fluids, mud chemistry, foam development, corrosion control, and lost circulation control. Completion technology programs will continue to develop well workover equipment and improved casing design and well stimulation and reinjection methods. The wellbore thermal simulator model will be expanded to include two-phase flow, and systems analysis will be utilized to examine the benefits accruable from the new technology developed.

In accord with the 25% reduction goal, a continued effort in the development of high-speed downhole motors, high-temperature lubricants, and PDC bits is planned. However, the major stimulus for this goal remains to transfer the new, improved rotary technology to the private sector.

References

1. Joseph Polito and Samuel G. Varnado, A Program in Geothermal Well Technology Directed Toward Achieving DOE/DGE Power-On-Line Goals, SAND78-0766 (Albuquerque: Sandia Laboratories, October 1978).
2. Melvin M. Newson et al., Geothermal Well Technology Drilling and Completions Program Plan, SAND77-1630 (Albuquerque: Sandia Laboratories, March 1978).
3. Alán D. Black et al., Phase III - Part I Final Report, Program for the Improvement of Downhole Drilling Motor Bearings and Seals, TR78-58 (Salt Lake City: Terra Tek, Inc., November 1978).

APPENDIX A

**Members, Advisory Panel on
Geothermal Well Technology**

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APPENDIX B

Significant Meetings, Visits, and Presentations

APPENDIX B

Significant Meetings, Visits, and Presentations

Meetings and Visits

Visit to Security Division of Dresser Industries, Dallas, TX, by S. Varnado and C. Huff, to present briefing on Sandia's development of Stratapax™ attachment and bit technology, 9 September 1978.

Visit by H. Cholet and M. Martin of Institute Francais du Petrole, Paris, France, to discuss Sandia's drilling research efforts, 18 October 1978.

Visit by H. Malloy of Loffland Brothers Drilling Company to discuss some new techniques for producing nitrogen drilling fluids cryogenically and from diesel engine exhaust gases, 19 October 1978.

Workshop on Advanced Geothermal Drilling and Completion Systems, New Orleans, LA, hosted by Sandia Laboratories, for discussion of future programs in the development of an advanced geothermal drilling and completion system, 9-11 January 1979.

Meeting with representatives of Dresser Industries, Loffland Brothers Drilling Company, Union Oil, and Production Operators, Inc., to discuss problems of lost circulation and corrosion in geothermal wells, 6 February 1979.

Meeting with D. Pyle and S. Pye of Union Geothermal, Nevada Test Site, to review drilling practices and hydrofracturing tests with particular interest in foam drilling practices, lost circulation problems, and use of sepiolite clay muds for high-temperature drilling, February 1979.

Visit to the Amoco Research Center, Tulsa, OK, by A. Maish, to discuss Amoco's work in the area of percussion drills, 21 February 1979.

Visit to Loffland Brothers Company, Amoco Production Research Center, and Conoco Research Center by D. Glowka to discuss bit hydraulics research and to solicit comments on the proposed Sandia Laboratories' research program in bit hydraulics, 20-22 February 1979.

Visit by S. Tanaka, Associate Professor, Department of Mineral Development Engineering of The University of Tokyo; K. Yano, Manager of Oil and Gas Field Section, Daiichi Jitsugyo Co.; and K. Katagiri, Senior Technical Advisor, Geothermal Energy Research and Development Co., to discuss mutual areas of interest with the Drilling Technology Division, 19-20 March 1979.

Visit to the Drilling Research Laboratories of Shell Internationale, The Hague, The Netherlands, and to Institute Francais du Petrole, Paris, France, by S. Varnado, to discuss drilling research in the United States and Europe, 23 March 1979 - 9 April 1979.

Presentations

Geothermal Drilling and Completion Program Plan, by S. Varnado, to Geothermal Advisory Committee, Los Angeles, CA, 6 February 1978.

Drilling Research at Sandia Laboratories, by S. Varnado, to Seminar for Smith Tool personnel, Irvine, CA, 12 April 1978.

Overview of Sandia Geothermal Drilling and Completion Program, by S. Varnado, to DGE Inter-Laboratory Coordinating Committee Meeting, Los Angeles, CA, 13 April 1978.

Geothermal Well Technology Program, by S. Varnado, to Workshop on Geothermal Drilling Fluids, Houston, TX, 23 May 1978.

Sandia/DOE Geothermal Drilling Technology Program, SAND78-1138A, by S. Varnado, to Magma/Hydrothermal Drilling and Instrumentation Workshop, Sandia Laboratories, Albuquerque, NM, 31 May - 2 June 1978.

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APPENDIX C

Reports and Publications

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Reports and Publications

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