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GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY
DEVELOPMENT PROGRAM SEMI-ANNUAL PROGRESS REPORT
APRIL-SEPTEMBER 1979

MASTER

Samuel G. Varnado

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of
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May 1980

Sandia National Laboratories

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GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
SEMI-ANNUAL PROGRESS REPORT
April-September 1979

Samuel G. Varnado

Editor

Drilling Technology Division 4741
Sandia Laboratories
Albuquerque, NM 87185

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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 drilling hardware, 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 3000 MWe by 1985 and 20 000 MWe by the year 2000.¹ It has been estimated that, to meet these goals, 8000 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 assist in meeting the power-on-line goals of the NGEP and to improve the economic feasibility of geothermal 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 (FY) 1977.

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 (1977 dollars) 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 (1977 dollars) 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. Various consultants and a Well Technology Advisory Panel assist the Sandia Program Manager in defining areas for R&D and for assessing program progress. The

Well Technology Advisory Panel is comprised of drilling experts from industry, universities, and other national laboratories. During this reporting period, the panel meeting was held during 26-28 June 1979. 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 management and technical staff are designated for external R&D projects within each work element.

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.

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. A program expansion into the concepts for and design of an advanced drilling and completion system, a system different from conventional rotary techniques, has been initiated. 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.

SECTION 2

MANAGEMENT

2.0 Introduction

Sandia Laboratories is the designated 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 period April 1979 through September 1979 are reviewed in this report.

2.1 Program Planning

Initiation of new projects is based on program needs as determined by Sandia. To define the long-range program, Sandia utilizes the systems analysis approach in conjunction with the recommendations of the Well Technology Advisory Panel and issues milestones and needs to DOE as a path to the stated goals. These needs/milestones are issued annually in the form of Work Program Statements that define the work necessary to be accomplished in the next fiscal year. Management and planning for resources are based on these documents.

A week-long planning session was held in Albuquerque during 7-11 May 1979 to review the recommendations of the workshop on Advanced Geothermal Drilling and Completion Systems held in January 1979 at New Orleans. Network planning methods were used to prepare detailed, long-range plans for the implementation of the recommendations of the workshop and for the development of advanced drilling and completions systems.

These planning networks will be used to generate Requests for Proposals (RFP) for advanced systems development.

2.2 Test Coordination

Field tests performed or scheduled during this reporting period included two tests of the continuous chain drill bit at the Nevada Test Site (NTS) and a test of the polycrystalline diamond compact (PDC) Strata-pax™ bits in the Baca Field, New Mexico. The latter test is scheduled for mid-October 1979. Sandia provided planning, coordination, and data analysis for these tests.

2.3 Systems Analysis

The well cost-sensitivity model² was improved further during this reporting period and was used to estimate potential cost reductions that may be derived from new technology. Systems analysis activities included the following:

1. Modification of the well model to account for reaming and explicit corrosion control costs,
2. Addition of several features to the simulation program to aid in cost data collection and file access,
3. Preparation of well cost profiles for The Geysers, Baca and Cove Fort-Sulphurdale locations and cost/benefit analysis of the use of Stratapax™ drill bits at the three sites,
4. Initiation of work to permit rerunning of used bits in the well cost model so the Stratapax™ bit analysis could be finalized,
5. Preparation of generic well profiles at various geothermal sites and collection of baseline performance data,
6. Initiation of analytical work on the economics of drilling motors and high-speed bits, and
7. Completion of a draft of a programmer's manual for the drilling simulation program.

The BDM Corporation is providing support services to Sandia in the area of cost-of-power estimates for the program. Existing computer codes will be used. Candidates for electric costs are the Mitre Corporation's GELCOM, Lawrence Berkeley Laboratory's GEOTHM with Mitre economics, and Pacific Northwest Laboratory's (PNL) GEOCOST with updated cost information. The GEOTHM code is running at BDM, and the GEOCOST program has been received. Sandia is investigating the GEOCOST methodology with updated costs. Also, the GEOCITY program was obtained from PNL and delivered to BDM for consideration as Sandia's main vehicle to analyze the implications of drilling costs on direct heat applications. Mitre's WELCST program was received and implemented on Sandia's computing system. It will be used as a comparison to Sandia's well cost estimates.

A report on a well cost-sensitivity model was presented to the annual meeting of the Geothermal Research Council (GRC) in Reno, Nevada, 24-27 September 1979.³ The report presented the results of an analysis of diamond compact drill bits when applied to drilling in three geothermal areas: The Geysers, California; Cove Fort-Sulphurdale, Utah; and the Baca location, New Mexico. The parameters of rate of penetration, bit cost, and bit life were examined to determine the performance required to achieve cost reductions. The analysis indicated that substantial savings may be realized when long bit runs are possible. Technology which will reduce the cost and time of frequent drilling contingencies and/or reduce bit cost will make high-performance bits more attractive. The wells analyzed were all actual wells which have been drilled. The simulated depth versus time curves agreed closely with the actual plots. The actual plots for The

Geysers and Cove Fort wells are shown in Figures 1 and 2, together with drilling and cost information. The conclusion from these analyses is that a broadly based R&D program is required to reduce the cost of drilling geothermal wells.

2.4 Contracting

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

DRILLING HARDWARE

Terra Tek, Inc. -- geothermal drill bit (Nov 78-May 79, Jul 79-May 80)
Terra Tek, Inc. -- improved downhole drilling motor (Nov 78-Oct 79)

DRILLING FLUIDS

University of Oklahoma -- temperature limits of drilling fluids (Aug 78-Dec 79)
Texas Tech University -- basic understanding of chemical and elevated temperature effects on clay-based drilling fluids (Jul 79-Jul 81)

COMPLETION TECHNOLOGY

Completion Technology Co. -- completion technology consultation (Dec 78-Sep 79)
Daedalean Associates -- cavitating-jet descaling (Feb 79-Aug 80)
Terra Tek, Inc. -- geothermal formation damage (Jul 79-Sep 79)
Enertech Engineering and Research Co. -- temperature history and lost circulation experience in geothermal wells (Aug 79-Apr 80)

ADVANCED DRILLING SYSTEMS

University of Missouri -- water-jet drilling (Feb 79-Feb 80)
Hydronautics, Inc. -- Cavijet™ method of rock cutting (Jan 79-Sep 79)
Hydronautics, Inc. -- feasibility and design study of a downhole pressure-pulsing device (Aug 79-Jul 80)

SUPPORTING STUDIES

Enertech Engineering and Research Co. -- wellbore thermal simulator (Jun 78-Jul 79)
Foster-Miller Associates, Inc. -- characterization of erosion drilling systems (Aug 79-Jul 80)
Scientific Applications, Inc. -- rig rate algorithm (Jul 79-Nov 79)

OTHER SIGNIFICANT CONTRACTS

Maurer Eng. -- consulting services (continuing)
Livesay Consultants -- consulting services (continuing)

Figure 1. Depth versus Time Plot for the Geysers, CA, Well--1978

Figure 2. Depth versus Time Plot for the Cove Fort-Sulphurdale, UT, Well--1978

Tech. Reps., Inc. -- program management support services (continuing)
BDM -- programming services (continuing)

ORIGINAL DOE CONTRACTS STILL IN PROGRESS

NL/Baroid -- Properties of Drilling Muds, High-Temperature and
Pressure Instrumentation (Apr 78-Mar 80)
General Electric Co. (Corporate Research and Development) -- poly-
crystalline diamond compact bit development (Jun 76-Nov 79)

A detailed description of the activities included in these contacts is given in Section 5 of this report.

2.5 Meetings, Visits, and Presentations

A complete listing of significant meetings, visits, and presentations is compiled in Appendix B. Through discussions, association, and informational disclosures, a more thorough understanding and appreciation of the problems encountered in geothermal drilling and completion is gained, and progress in solving problems is communicated for possible commercialization and use.

2.6 Reports

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 report has been published, giving a summary of the program from October 1978 through March 1979 (see Reference 2). The current report is the second semi-annual report for the Geothermal Drilling and Completion Technology Development Program. Beginning with the 1980 fiscal year, quarterly reports and an annual report, replacing the two semi-annuals, will be published. The annual report will be published at the close of the fiscal year and will summarize activities in the first 3 quarters and report progress in the fourth.

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 3

PROGRAM STATUS

3.0 Introduction

During this reporting period, the Geothermal Drilling and Completion Technology Development Program has continued to concentrate on the goal of a 25% reduction in drilling costs. While the program emphasis has been directed at the improvement of present rotary drilling techniques and associated hardware, several new programs were initiated that are concerned with advanced drilling technology and the long-range goal of 50% reduction in drilling costs. This section presents a brief overview of the existing program. A detailed description of each project is presented in later sections.

3.1 Internal R&D

Research conducted internally by Sandia emphasized a variety of topics this reporting period. Of particular significance were two field tests of the continuous chain bit and the development of test facilities for studies in bit hydraulics, drill stem corrosion, rock mechanics, and aqueous-foam drilling fluids.

Drilling costs can be reduced significantly by reducing the requirement for tripping out and tripping in to replace worn drill bits. Sandia's project to design, fabricate, and test a prototype downhole replaceable drill bit is directed toward this cost reduction goal. The approach to this objective is the development of a bit concept that utilizes a continuous chain of cutting surfaces. The final design will provide for 15 changes of the cutting surfaces before removal of the drill bit from downhole. Early in this reporting period, laboratory tests of the chain bit were completed at the Drilling Research Laboratory (DRL). These tests identified minor modifications required to reduce the buildup of cuttings inside the male spline cavity that prevented cycling of the cutting surfaces. Following modification, four holes of 1.2 metres (4 feet) each were drilled, and the bit was cycled 10 times after the drilling with no problems. The laboratory tests also established the adequacy of the drilling capability of the chain bit. One set of diamond links, after drilling 8.53 metres (28 feet) into Sierra white granite, showed no damage and only normal wear of the diamonds. Following the DRL tests, field tests were conducted at the Nevada Test Site (NTS). The chain bit drilled a total of 76 metres (250 feet) with six cutting surfaces, and the chain was successfully cycled approximately 85 times downhole. The average drilling results for six chain link sets were (1) footage drilled, 12.7 metres (41.6 feet);

(2) weight on bit, 28 kN (6400 lb); and (3) rate of penetration, 1.2 m/h (4.0 ft/h). Near the end of this reporting period, additional field tests were initiated at NTS following modification of the bit to correct minor problems encountered in the earlier field tests. However, these additional field tests were terminated when premature failure of the cutting surfaces was encountered. Subsequent tear down of the bit revealed that the failure was caused by internal hydraulic leakage resulting in a lack of mud flow across the diamond cutting surfaces. Modifications are being made to correct this problem, and another field test at NTS will be scheduled in 6 to 8 months.

Significant increases in rate of penetration and bit life with resulting decreases in drilling costs can be obtained by optimizing bit hydraulics. The objective of Sandia's bit hydraulics studies project is to achieve the required optimization through analytical and experimental investigations devised to determine optimal number, size, and placement of nozzles used for cooling and cleaning purposes. The complexity of the three-dimensional viscous flow field along the bit face limits the practical information which can be obtained from analytical studies. Hence, a bit hydraulics test facility has been designed and is being built to visualize the flow field along the bit face. During this reporting period, the test stand design was reviewed in detail. The final design changes increased the capability and flexibility of the facility. Among the changes were (1) strengthening components to meet safety factors that resulted in a capability for full-scale flow rates, (2) modifying the dye injection tube to eliminate any flow interference and to permit higher dye flow rates, and (3) incorporating a slip-ring assembly to accommodate data transmission for a cutter heat-transfer study. Fabrication and acquisition of the required components and instrumentation were in an advanced stage at the close of the reporting period.

The often hostile downhole environment in geothermal drilling subjects conventional equipment to serious corrosion related failures that add to drilling costs. A particular devastating failure is the downhole fracture of the drill stem, leading to expensive fishing operations. The objective of Sandia's drill stem corrosion project is to study the metallurgical composition of conventional drill stem and to make compositional changes in the drill stem material to maximize its chemical resistance to geothermal H_2S environments without large sacrifices in its mechanical properties or cost. The approach being pursued is the development of a modified duplex, ferritic/martensitic alloy steel containing strong carbide-forming elements such as vanadium. The test equipment for the drill stem corrosion fatigue tests has been designed and fabricated and is ready for final assembly. Some delays were experienced in acquisition of standard drill stem material and in making the modified dual-phase steel for test specimens. The standard drill stem material remained undelivered, but the manufacture of the dual-phase steel was imminent at the end of this reporting period.

Experiments in the use of polycrystalline diamond compact cutters with drilling bits indicate significant increases in rates of penetration with the attendant potential for reduction in drilling costs. The objective of Sandia's rock mechanics project is to optimize the design of PDC geothermal bits by study of the stress buildup and chip formation processes of rock-cutting tools utilizing PDC cutters. TOODY, a two-dimensional, finite

difference model, is being used in calculations of the drag-tool/rock interaction problem. The model being used for rock failure was expanded to include shear failure as well as tensile failure mechanisms. However, a test calculation showed that the predominant failure mechanism was still tensile failure. Stress and velocity histories on the bit and rock surface were also generated for use in friction heating studies of PDC drag tools.

Substantial reductions in drilling costs can be obtained by improving reamer performance. Cost savings will result from extended reamer life, reduced reaming time, and maintenance of hole gage to prevent bit damage during tripping. The objective of Sandia's reamer project is to achieve improved reamer performance by modifying existing conventional reamers and to verify improvements by field testing. The design approach includes the use of stud-mounted PDC cutters and the incorporation of a real-time, surface readout gage-wear indicator. The development of a PDC reamer proceeded during this reporting period with the modification of a standard Smith Model 62, bottomhole, three-point roller reamer for installation of the PDC cutters. Mounting hardware for the cutters was designed, and fabrication of the modified reamer was initiated. Work is continuing on a signal generator system to indicate bit and reamer wear.

Aqueous foam is a promising geothermal drilling fluid for the under-pressured, hard rock formations frequently encountered in drilling operations. Foam drilling fluids will not harm producing formations, will allow high drilling rates, and will utilize low annular velocities that should reduce the erosion problems of air drilling. The objective of Sandia's aqueous-foam project is to identify and develop foam drilling fluids capable of operating in temperature environments to 310°C (590°F) and having chemical and foaming stability and anticorrosive and antioxidant properties. Aqueous solutions of candidate surfactants are being exposed to high temperatures; foams with controlled density are being generated using nitrogen gas; and the foams are being evaluated with respect to temperature resistance, uniformity of cell structure, drainage time, and pH change. During this reporting period, 56 candidate surfactants were exposed to an ambient-to-260°C (500°F)-to-ambient temperature cycle, and 12 were selected for further evaluation in various chemical environments and at higher temperatures. An autoclave was placed on order at the close of the reporting period to permit additional evaluations at various pressures as well as high temperatures.

3.2 External R&D

Drilling Hardware -- Drill bits with improved penetration rate and life are required to reduce well drilling costs. Projects are presently underway with the objective of improving the performance of sealed and unsealed roller-cone bits and drag bits in the high-temperature geothermal environment. Current technical approaches to this performance objective include substituting high-temperature steels in unsealed bits, design and development of high-temperature seals and lubricants for sealed bits, and the design and demonstration of drag bits using polycrystalline diamond compacts (PDCs) for cutting edges.

In field tests of an improved, unsealed roller-cone bit utilizing high-temperature steels, the bit drilled 70% more hole to gage than a conventional control bit and drilled 30% longer than the control bit before incurring the same bit and hole-gage losses. Analysis of the field test data indicated that the use of the improved bits would save a minimum of 4% of the total cost of a Geyser's well.

Experiments with high-temperature seal designs, materials, and lubricants for sealed bearing bits have identified promising seal/lubricant systems for geothermal use. An oil, designated PLX-014, has demonstrated a load-bearing capability at 316°C (600°F) roughly twice that of the standard rock-bit lubricant at room temperature. A grease version of PLX-014 tested at 317°C (603°F) showed an average load-carrying capability somewhat less than the oil but which still exceeded standard lubricant load capabilities by 50%. Both the oil and grease versions of PLX-014 proved compatible with elastomeric seals fabricated from Viton and Teflon-coated Viton materials. Seal lives in the 100-hour range were demonstrated in seal tests at a temperature of 150°C (302°F) following pretest soaking of the seals at a temperature of 250°C (482°F). A test of a spring-loaded face seal with a Viton side-seal system at 200°C (392°F) ran for 76 hours with very little leakage observed. An all-metal face seal using a metal-bellows side seal was designed and is being fabricated for testing in the next reporting period.

Redesign and fabrication of full-scale drag bits using PDC cutters were completed this reporting period. The design modifications were made to correct the PDC-mounting-stud failures encountered in field tests of the bit late in 1978. Preparations for field test of the modified bit in the Baca Field, New Mexico, are progressing.

Drilling Fluids -- Improved drilling fluids are required to reduce the cost of drilling geothermal wells. The corrosive conditions, high temperatures, and fractured formations typical of geothermal resource areas impose severe operating requirements on drilling fluids. Under these conditions, the physical and chemical behavior of drilling fluids are not currently well understood; thus, basic investigations are required to develop an understanding of the behavior of drilling fluids in the geothermal environment in order to formulate more cost effective fluids. Projects have been initiated with the objectives of determining the high-temperature/high-pressure rheological properties of drilling muds and of gaining a fundamental understanding of the morphology of clay particles under the influences of high temperature and various chemical compounds. Two laboratories at which the required experiments are conducted are in operation, and one is under construction.

The current high-temperature/high-pressure rheological facility has the capability of testing muds to temperatures of 288°C (550°F) and pressures of 20.7 MPa (3000 psi) under flowing conditions. Tests of various mud mixtures in this dynamic high-temperature/high-pressure flow loop tester were underway at the close of the reporting period. Numerous equipment failures delayed the testing program and resulted in an extension of the project period to permit the completion of scheduled mud tests.

Completion of the facility under construction will extend these capabilities to 371°C (700°F) and 138 MPa (20 000 psi). The design of this testing instrument with increased capabilities over the flow loop tester continued during the reporting period. Design activities were directed toward the pressure vessel and its internal cooling system, the high-pressure argon supply system, and the corrosion sensor probe. A microcomputer development system (MDS) and a terminal were purchased, and development of software for controlling the system operation and data storage was initiated. The building to house the instrument was also in the design phase, and a tentative location for the new facility was selected.

The laboratory for the study of the morphology of clay particles has X-ray diffraction and electron microscopy facilities for examination of mud property changes resulting from the effects of chemical compounds and of temperatures to 538°C (1000°F). This project was initiated during the reporting period. Both X-ray diffraction and electron microscopy were used to study the conversion mechanisms of attapulgite to smectite at temperatures to 371°C (700°F) and in the presence of NaCl, CaCl₂, and KCl compounds. The tests showed that conversion was complete at 316°C (600°F) for each compound used and that CaCl₂ promoted the conversion more than the chlorides of potassium and sodium. The experiments with attapulgite are continuing and will be expanded to include sepiolite, saponite, and bentonite.

Completion Technology -- Overall geothermal well costs can be reduced significantly by improvements in completion technology. Improperly completed wells can substantially reduce energy production and require additional well drilling or frequent workover. Projects are presently underway with the objectives of acquiring information on wellbore temperatures, lost circulation control methods, drilling-fluid/formation interactions, injectivity of spent brine, and casing/liner design and cementing technology. A project is also in progress to develop a cavitation technique for downhole well cleaning and scale removal. The approach to improved completions is to develop design criteria, completion techniques, and/or hardware to extend well life and improve production. Efforts were expanded during the reporting period to acquire information on completion technology. Field data on reinjection wells were analyzed, cement-inflatable packers were evaluated, and a study of casing/liner design and cementing technology was completed and nearing publication at the close of the reporting period. Design of a downhole geothermal well cleaning and scale-removal system continued. The system will use cavitating jets and a coiled tubing unit. Work concentrated on the nozzle design and pressure limits of the tubing. Casing scaled by field usage was being obtained to use in the evaluation of the effectiveness of the nozzles and cleaning heads that are under design. Two new projects were initiated. The first began an investigation of drilling-fluid formation damage, and the second started a data collection effort concerned with temperature histories required for well casing design and with lost circulation problems and solutions. Initial data from the formation damage laboratory tests were expected early in the next reporting period. The temperature history and lost circulation efforts were just getting underway at the close of this reporting period.

Advanced Drilling Systems -- Advanced and innovative drilling systems are required to meet the 1986 well cost reduction goal of 50%. Investigations of high-pressure water-jet erosion drilling systems, cavitating jets,

and a pressure-pulse device for use with cavitating jets are underway, and development of a 200-hour-life bearing and seal package for downhole motors is progressing. The objectives of these projects are to develop and demonstrate hardware incorporating these design techniques so that increased rates of penetration and longer downhole drilling periods may be achieved. The approach to these objectives includes laboratory testing of full-scale devices.

Work during this reporting period in the area of advanced drilling systems produced significant data defining the potential of high-pressure water-jet drilling for use in geothermal applications. Extensive data were generated in the experiments to establish a standard for testing rock resistance to cavitation attack. Samples of granite, marble, sandstone, and dolomite were subjected to cavitation attack. The mean and cumulative depth of erosion over a 7-hour period were recorded. The data will be used in conjunction with information that will be generated in a new test series using a larger Lichtarowicz cell, in a further attempt to correlate rock response to cavitation/water-jet action. Experiments continued on the design of an erosion drilling under-reamer for use in geothermal injection wells. Nozzle cutting distances and the use of long-chain polymers were investigated. Design of the prototype reamer is continuing. Field tests of a hybrid water-jet/roller-cone bit were conducted and were nearing completion at the close of the reporting period. The tests demonstrated that the optimum penetration rate in dolomite was achieved with a 1.8-mm (0.07-inch) nozzle at 96.5 MPa (14 000 psi). Also, penetration rate improvements as a function of the water-jet direction ranged from 200% with an axial direction to 700% at a bit-gage direction. These improvements were recorded once a threshold pressure of 82.7 MPa (12 000 psi) had been reached. Laboratory tests were completed to establish the design parameters for a cavitating-type jet nozzle using drilling mud as an erosion medium. A report on the Cavijet™ cavitating-jet experiments was nearing publication at the close of the reporting period. A project to investigate the feasibility of a downhole pressure-pulsing device for use with cavitating jets was initiated late in the reporting period. Preliminary design studies are proceeding with a review of past research and literature on shear and oscillating flows.

The bearing/seal package design and testing program for downhole motors continued to emphasize testing of candidate seal configurations and fabrication of the full-scale test facility. Non-elastomeric packages using graphite seals were run for periods up to 40.9 hours before failure. The pressure drop across the seals was 10.3 MPa (1500 psi), and the speed of rotation of the sealed shaft was 412 rpm. Additional testing of this type of seal material in varying seal configurations was underway at the close of the reporting period. Construction of the full-scale bearing/seal package test facility was completed and debugging and operational checks made. The facility will permit testing of candidate bearing/seal packages with full-scale motors at simulated downhole conditions of 300°C (572°F) and 34.5 MPa (5000 psi). Design parameters include a differential pressure across the bearing/seal package of 0 to 13.8 MPa (0 to 2000 psi), a flow rate of 0.006 to 0.013 m³/s (100 to 200 gpm), a rotational speed of 100 to 1000 rpm, and a dynamic load to 267 000 kN (60 000 lb). The first test to check the function of the total system was completed, and system

performance evaluation was in process at the close of the reporting period. Four additional functional tests are planned early in the next reporting period.

Supporting Studies — The proper design of improved and new well-drilling and completion equipment and materials requires a firm understanding of the special requirements and criteria necessary to operate in the geothermal environment. The objective of supporting studies is to acquire and provide the necessary information. Currently, projects are underway to predict transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells and to assess the performance potential and economics of erosion drilling systems.

The approach in the case of wellbore temperature is to develop a computer model to account for the complexities of heat transfer in a well. The development of the Wellbore Thermal Simulator computer code was completed, and sensitivity studies and correlation with field data were conducted during this reporting period. Consideration is being given to the development of an advanced wellbore code to keep the simulator as fully user-oriented as possible.

The assessment of erosion drilling systems is being approached with a comprehensive program to gather, analyze, and present data on past efforts involving this technology. A systems study was initiated near the end of the reporting period.

3.3 Program Accomplishments

Significant program accomplishments during FY79 including technical achievements, facility improvements, commercialization of new technology, and program direction are highlighted in the following paragraphs.

- Developed and commercialized an improved, unsealed geothermal roller-cone bit

The unsealed geothermal drill-bit development program was successfully completed in FY79. The program identified new materials to be used in critical areas of conventional roller-cone bits. These materials demonstrated improved hardness and toughness at high temperatures and extended the life of the bits in hard geothermal formations. Two generations of bits were developed and laboratory tested prior to FY79. In the past year, the third-generation design, the MK-III bit, completed laboratory and field testing. Six MK-III bits were evaluated in a geothermal well at The Geysers along with seven conventional bits. The material improvements allowed the MK-III bits to drill 30% longer before incurring the same gage wear as the conventional bits. Bearing wear was also reduced significantly. By decreasing the number of bits needed to drill a well and reducing rig time costs, the MK-III bits were able to save a minimum of 4% of the total cost of the well. This new technology has been commercialized by a leading bit manufacturer.

- Identified promising seals and lubricants for use in sealed geothermal roller-cone bits

Fabrication of test equipment for evaluating seals and lubricants under simulated downhole conditions was completed, as was screening of commercially available materials. A new bit grease manufactured by private industry was developed and tested. An EPDM O-ring seal with this grease exhibited a lifetime in excess of 100 hours. The lubricant is being marketed as "Geobond" grease by Pacer Lubricants, Inc., of Houston, Texas. In addition, new seal designs using metal-to-metal contact were fabricated for testing in FY80.

- Designed, fabricated, and tested a new geothermal drag bit

Laboratory tests of single and triple PDC cutters were conducted under simulated downhole conditions. Results of these tests were used in designing two new bits. One bit was tested unsuccessfully, but stress analyses have recently been used to identify the cause of the failure. New bits of improved design will be tested in FY80.

- Developed the capability for modeling drag-cutter/rock interaction

A computer model for calculating the stress induced in drag-type cutters and for modeling the tool/rock interaction was developed and applied to the use of steel cutters in sandstone. The model is a finite difference code called TOODY, which has been used extensively in describing shock wave propagation. The code will next be used for calculating stresses induced in PDC cutters used in hard rock.

- Conducted a successful field test of the downhole replaceable chain drill

The chain drill, in which the cutting surfaces can be replaced without removing the bit from the hole, was successfully field tested while drilling granite at NTS. A subsequent field test resulted in premature wear of the cutting surfaces. Correction of this problem is underway, and, following additional field proof tests, commercialization of this new technology is anticipated.

- Completed fabrication of a geothermal drilling-fluid test loop

Fabrication of a flow loop capable of measuring the rheological properties of drilling muds at simulated downhole conditions of 20.7 MPa (3000 psi) and 288°C (550°F) was completed. The loop is being used to test commercially available geothermal muds. Several industrial firms are presently using the loop.

- Identified morphological characteristics of drilling muds

The changes that occur in the structure of bentonite particles as a function of temperature were investigated. Upon heating, the particles change structure, causing gellation. On the other hand, sepiolite particles undergo a transition with temperature which reduces their tendency to gel. Investigations of the effects of chemicals on these morphological characteristics were initiated.

- Identified surfactants for use in generating foam drilling fluids

Preliminary screening tests of commercially available, high-temperature surfactants were conducted to identify those which could be used to generate a high-temperature, noncorrosive foam for use in geothermal drilling. Several sulfonate compounds have survived testing at 260°C (500°F) at a foam density of 45 kg/m³ (0.45 lb/gal). Further tests will be conducted under more stringent conditions.

- Identified field/portable techniques for generating inert-gas drilling fluids

Corrosion is an extremely severe problem in geothermal drilling. The use of inert gas as the drilling fluid has the potential for significantly reducing this problem. Techniques for generating copious quantities of N₂ at the drilling site are needed. A portable cryogenic system for N₂ generation has been designed and fabricated by a private company. This system will be field tested in FY80. Another technique for generating N₂ involves the combustion of diesel exhaust gas with additional diesel fuel in the presence of a catalyst. A laboratory study was initiated to determine the composition of the product gas, the lifetime of the catalyst, and the potential for scaling the system up to field size.

- Developed a conceptual design for a high-temperature, open-hole packer

Elastomeric failure at high temperatures limits the use of conventional open-hole packers in geothermal wells. A new design was prepared which utilizes a reinforced elastomeric element and the principle of mechanically supporting the elastomer to produce minimum stress on the element.

- Demonstrated a new technique for removing scale from pipe

A descaling system utilizing high-pressure cavitating jets for removing scale from pipes in geothermal power plants was developed and demonstrated. Silica scale was removed from pipes at the East Mesa facility at nozzle pressures of 55 MPa (8000 psi). Application of this technique to removing scale from the wellbore while the well is on production was investigated. A preliminary test of the system in a flowing

well at the East Mesa site was successful in defining the parameters needed for designing the new system. Operational characteristics of the system were shown to be compatible with a flowing well.

- Formulated design requirements and a concept for a high-pressure water-jet under-reamer

A design concept was formulated for using a high-pressure water-jet system for under-reaming a geothermal wellbore. Laboratory tests of the rock-cutting ability of several nozzle designs under conditions of high wellbore pressure were conducted. These tests demonstrated the sensitivity of rock-cutting ability to standoff distance when the borehole is filled with water at high pressure. In addition, the depth of cut was shown to be strongly dependent on the confining pressure in the rock.

- Identified geothermal casing failure modes

A report was published documenting the reasons for geothermal well casing failure. Case histories of well failures in Cerro Prieto and the Imperial Valley were documented. Recommendations were formulated for technology development which would reduce the probability of casing failure.

- Developed and commercialized a computer model for predicting wellbore temperatures

A computer model for predicting the temperatures of borehole fluids and downhole equipment under real-time flowing conditions was formulated, documented, and verified. The model analyzes single-phase flow during drilling, production, or injection. The undisturbed geothermal temperature gradient must be specified. Validation of the model involved comparison of computer predictions with actual field measurements of temperature in oil, gas, and geothermal wells. The model is now commercially available for use by the industry.

- Completed development of a well cost-sensitivity model

Development of an operations-based model for analyzing the effects of improved technology on well costs was completed. The model has been used to predict the percentage reduction in well cost obtainable with improved penetration rates. Other technological improvements are currently being evaluated.

- Designed a facility for conducting studies of drill bit hydraulics

A small facility has been designed for flow visualization studies and studies of the heat transfer between drill bit cutters and a flowing fluid. Parts for the facility have been fabricated, and assembly is expected in FY80.

- Identified new seal designs and lubricants for use in downhole motors

A facility for testing a downhole motor bearing and seal package under simulated downhole conditions has been completed. This facility has been used to screen seal designs and lubricants. A canted, radial lip seal using a new high-temperature lubricant supplied by private industry achieved a lifetime of 45 hours in laboratory testing. New redundant-seal designs were formulated which have the potential for achieving a lifetime of 200 hours.

- Demonstrated improved drilling performance with high-pressure cavitating jets

An experimental program completed in FY79 established the feasibility of utilizing cavitating jets to drill deep holes for geothermal and petroleum extraction. The effects of elevated borehole pressure and the use of drilling mud on jet performance were assessed. Results indicate that cavities can be formed under high ambient pressures. Once formed, these cavities have a rock-damage potential which increases as the third power of borehole pressure, and rock-cutting rates increase approximately as the third power of nozzle-pressure drop. Thus, significant rock-cutting rates can be achieved with cavitating jets at much lower nozzle pressures than those required with noncavitating jets. It was further shown that the use of drilling mud imposes no adverse effects upon jet performance. These results lead to the conclusion that cavitating jets may be used in conjunction with mechanical bits to drill deep holes at increased penetration rates with existing rigs and hydraulic equipment.

- Generated plans for the development of advanced drilling systems

A workshop comprising 50 participants from private industry, universities, and government was held to provide recommendations to DOE on the development of an advanced geothermal drilling and completion system. Systems recommended for development include high-speed motors and bits, percussion systems, and high-pressure water-jet drilling systems. Detailed planning activities were conducted to formulate the approach to the development of these systems.

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SECTION 4

INTERNAL RESEARCH AND DEVELOPMENT

4.0 Introduction

The internal R&D program continued to concentrate effort this reporting period on the development of a downhole changeable bit. Two field tests of the bit were conducted. Work on the bit hydraulics studies, drill stem corrosion, and PDC reamer was characterized by extensive efforts in the design and fabrication of test facilities and acquisition of test equipment and specimens. Development of aqueous foams for use in geothermal applications continued with the initial screening of 56 surfactants and the selection of 12 for further investigation. Studies of the tool/rock interaction problem using PDC cutters were continued using the TOODY model. This section details the work accomplished and the results achieved in the internal R&D portion of the Geothermal Drilling and Completion Technology Development Program during this reporting period.

4.1 Continuous Chain Bit

Project Objective -- The objective of this project is to design, fabricate, and test a prototype downhole replaceable drill bit. The bit concept utilizes a continuous chain of cutting surfaces. 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 capability of supplying 15 changes of the cutting surfaces before removal of the drill bit from downhole.

Status and Results -- A Prototype II, Mod 2 chain drill bit was tested at DRL in April 1979. The bit was first cycled to establish pressure signatures for various load and flow rates. Then the bit drilled 40 cm (14 inches) into Sierra white granite, and the chain was successfully cycled through 10 link-set changes.

The first set of diamond links was cycled into place, and drilling was continued to 1.2 metres (4 feet) in each of seven holes, for a total depth of 8.5 metres (28 feet), before any additional chain cycles were attempted. The performance of the link set was considered excellent compared to previously tested, commercial, diamond bits. Visual inspection of the links showed no damage, only normal wear of the diamonds. However, an attempted chain cycle at this point failed to fully pull the next link set into position.

The chain was misaligned with respect to the nose of the bit by 3.2 mm (0.125 inch) after the cycling attempt. This problem had not been encountered previously. The bit was disassembled, and it was found that a combination of high friction and cuttings buildup caused the misalignment. Rock cuttings had entered a pressure port and collected inside the male spline cavity. This caused friction when the spline was operated, preventing the body from opening fully. The leaking pressure port was sealed off and fluid rerouted to the chain cavity. The spline seal was modified to reduce friction, and lubricant was added to both the spline and chain track. Minor modifications were made to reduce the buildup of cuttings.

The bit was reassembled, and testing was continued. The chain bit was first cycled 10 times. Then four holes of 4 feet each were drilled, and the bit was cycled 10 more times with no problems. A postmortem analysis of the bit revealed no deposits of rock cuttings in the spline cavity. The modification appeared to have been successful.

The drilling penetration rate, torque, and bit weight parameters met the expectations based on earlier tests of the cutting surface design. Figure 3 is a plot of these parameters for one link set and 8.53 metres (28 feet) of drilling. The diamond wear was minimal after drilling 8.53 metres (28 feet). It was concluded that the head drilling capability was more than adequate. It was also concluded that minor, low-risk modifications could significantly reduce the particulate buildup and friction problems. These modifications were made to both bits.

Following the tests at DRL, preparations were made for field tests at the Nevada Test Site (NTS). Newly fabricated and reworked parts for two chain drills were assembled to the latest design configuration, designated Prototype II, Mod 3. A chain was made up of 50 chain links, 35 of which (7 cutting surfaces) were new. All 50 links had new fluid seals molded of adiprene rubber, except for 5 links that had special tungsten-carbide inserts in place of seals. The two chain drills were tested in accordance with a formalized acceptance test plan that utilized the Sandia cycling test fixture and triplex mud pump. Unit No. 1 required some minor reworking to adjust the aligning pawl, but both units successfully passed all tests.

The continuous chain drill was tested at NTS 5-20 June 1979. A test hole was prepared with 14-cm, 22.3-kg/m (5-1/2-in., 15-lb/ft) casing set at 123 metres (404 feet) in granite formation. The formation varied in hardness, with several stringers or pockets of soft granular granite experienced. The test procedure is given in Appendix D.

The chain bit drilled a total of 76 metres (250 feet) with six cutting surfaces. The chain was successfully cycled approximately 85 times down-hole. Two Christensen MD24 diamond bits were also tested for comparative data. The performance of the chain drill system was considered to be good, with one cutting surface drilling 24 metres (78 feet). The drilling results are summarized in Table 1.

The bit cycled reliably; however, problems were encountered because of the mud system being used. Repeatedly, the chain-bit nozzles became partially plugged with debris such as rubber, Teflon, and rocks. This in

Figure 3. Drilling Parameters for Continuous Chain Link Bit, Mod 2, Tested at Drilling Research Laboratory

Table 1

Average Drilling Results per Bit

<u>Drill Bits Tested</u>	<u>Footage Drilled metres (feet)</u>	<u>Weight on Bits kN (lb)</u>	<u>Rate of Penetration m/h (ft/h)</u>
2 Christensen MD24	8.7 (28.4)	41 (9 150)	1.0 (3.3)
6 Chain Link Sets	12.7 (41.6)	28 (6 400)	1.2 (4.0)

turn caused problems which, in the most severe cases, required the chain bit to be removed from the hole and cleaned. Plugging can be prevented by use of downhole and surface in-line filters and screens. This was not a bit failure but rather an inadequacy in surface equipment.

The most serious problem associated with the chain-bit performance was the loss of a tapered pin in the bit body when severe drill stem vibration was experienced. This caused the drill to lock up in the hole and required the bit to be tripped. The problem was rectified by staking and welding all screws and cover plates.

The field test also indicated the need for a technique for locking the chain to prevent movement when tripping the bit in and out of the borehole. This capability would reduce the number of times the chain must cycle down-hole and also simplify the operation of the chain-drill system.

Additional field tests were conducted at NTS during the week of 17 September 1979 after the reworking of two chain bits and the modification of the chain links. The components were adjusted in order to prevent recurrence of the problems encountered in the June field tests. The reworked parts were assembled in the two chain drills and cycle tested at Sandia prior to shipment to NTS. A problem in chain link alignment occurred and was corrected.

The first day of testing was spent checking out drilling equipment and rig instrumentation. A special mud filtering system built by Terra Tek was installed between the mud pump and the swivel. This equipment was used in addition to the shale shaker and the desander in the regular mud system. Debris filtering and solids control were excellent. No bit plugging was experienced during the test.

The 229-metre (751-foot) hole was reamed to bottom with a 12.1-cm (4.77-inch) diameter diamond reaming shell and a 0.9-metre (3-foot) core taken. The unconfined compressive strength of the core was 228 MPa (33 000 psi), an increase from the 103 MPa (15 000 psi) recorded in the earlier field test. A Hycalog diamond bit (UH-1) designed for hard rock drilling was run. The UH-1 drilled 16 metres (53 feet) before the bit was pulled when the bit load reached 6804 kg (15 000 pounds), and penetration rate was less than 0.6 m/h (2 ft/h). The hole was again reamed to a 12.1-cm (4.77-inch) diameter and another 0.9-metre (3-foot) core taken. Again, the unconfined compressive strength was 228 MPa (33 000 psi).

Chain bit No. 1 was successfully cycled 10 times at the surface using the Sandia cycle tester. The bit was then run in the hole to a depth of 250 metres (807 feet). Next a decision was made to cycle the chain bit 10 times through all the links to obtain bottomhole pressure signatures for each link set. After cycling 10 times, link set No. 12 (a worn link set) was in drilling position. Using this link set, the hole was deepened 15.2 cm (6 inches) to form the contour of the chain drill in the hole bottom. Link set No. 17, a new link set, was then cycled into drilling position. Drilling was started using this link set, but a 1.2-m/h (4-ft/h) rate could not be obtained with increasing bit load. After drilling for 1 hour, the bit was cycled when the drilling rate dropped to 0.6 m/h (2 ft/h) with a 6804-kg (15 000-lb) bit load. The total depth drilled was only 0.67 metre (2.2 feet). Next, link set No. 19 was cycled into drilling position. This link set only drilled 0.37 metre (1.2 feet) in 24 minutes with a maximum bit weight of 6350 kg (14 000 pounds). The chain drill was pulled when rough drilling was experienced.

Inspection of the drill showed no damage to the bit body, but both chain link sets (Nos. 17 and 19) indicated excessive diamond wear and damage to the Stratapax™ in the bit pivot area. The center of bit rotation, as identified by the wear in the pivot area, had not occurred at the proper location on the center link. At the time, this was believed to be the reason for the poor drilling performance.

Chain bit No. 2 was modified in the field to properly position the bit pivot point relative to the center link. The cycling of the bit chain was tested on the surface before the bit was run in the hole. A shock sub used with bit No. 1 was left out of the string on this test.

On reaching bottom, the No. 2 bit was cycled five times, bringing link set No. 20 into the drilling position. After drilling 0.61 metre (2 feet), the bit was cycled to bring link set No. 21 into drilling position. After drilling about 0.9 metre (3 feet), the chain bit was pulled out of the hole.

Examination of the cutting surfaces of link sets Nos. 20 and 21 showed flattening of diamonds similar to that of link sets Nos. 17 and 19. However, the Stratapax™ were not damaged. The bit body showed evidence of severe downhole vibration, because screws that had been staked and welded had loosened and fallen out.

The drilling tests were terminated when it was determined that field repairs could not be made. The drill bits and equipment were shipped back to Sandia.

The premature failure of the four cutting surfaces was caused by internal hydraulic leakage in the bit. This caused a lack of mud flow across the diamond cutting surface and, therefore, a reduction in bit life. Modifications are presently being incorporated into the bit design to correct this problem. Another field test at NTS in 6 to 8 months is anticipated.

A diamond-set optimization study for chain links was completed this reporting period by Christensen Technical Center in Salt Lake City, Utah.

In order to make this study, Christensen modified their computer program to determine the diamond performance for each 0.02 radian (1°) of arc of the hemispherical bit head. The results of the study showed that, by removing 5% of the diamonds, the bit performance could be improved. It was jointly agreed that more work should be done to determine the effect of the diamond pattern shifting due to mechanical tolerance built up in each chain-bit assembly.

4.2 Bit Hydraulics Studies

Project Objective -- The objective of this project is to optimize the design of bit hydraulics for geothermal drill bits. Analytical and experimental investigations will be conducted to determine optimal number, size, and placement of nozzles which direct fluids used for cooling and cleaning purposes. A bit hydraulics laboratory will be built to visualize the flow field along the bit face.

Project Status -- The design of the bit hydraulics test stand has been completed and fabrication of all components initiated. Commercially available items required for the test stand have also been ordered. A sketch of the test stand is shown in Figure 4.

Prior to release for fabrication, the test stand design was reviewed in detail. Among the design changes resulting from the review were (1) structural modifications to increase the strength of certain components in order to meet pressure safety requirements (safety factor 4.0); (2) changes in the dye injection tube design to allow the end of the tube inserted in the nozzles to rotate with the bit, thus eliminating any flow interference; (3) increase in dye injection tube diameter to permit higher dye flow rates; and (4) increase in the length of the drill pipe to accommodate a slip-ring assembly. As a result of the design changes, the bit hydraulics laboratory will be more flexible and will allow a more complete investigation of bit hydraulics performance.

Instrumentation planned for analyzing the hydraulics of a Stratapax™ bit includes convective heat transfer gages, which will provide data sufficient for computation of heat transfer coefficients and of flow shear stresses on the Stratapax™ cutter faces. Pressure transducers of the bonded strain gage type will be used to measure the pressure gradients along the bottom of the simulated borehole. The transducers ordered are miniature in size and can be flush-mounted, allowing direct measurement of jet impact pressures.

A light-beam oscillographic recorder has been ordered for the pressure measurement recording system. This recorder will be used to measure bottomhole pressures and cutter heat-transfer coefficients. The selected recorder utilizes a cathode ray tube in conjunction with a fiber-optic assembly to convert electrical signals to graphic data. Therefore, it does not suffer from the mechanical limitations of conventional light-beam galvanometers.

Pertinent specifications of the recorder include a 16-channel capability, frequency response to 5 kHz, maximum sensitivity of 1 mV/in.,

Figure 4. Bit Hydraulics Test Stand. Its capabilities include (1) 6.89 MPa (1000 psi) maximum system pressure, (2) 1000 rpm maximum bit rotational speed, (3) 24 channels for bit instrumentation, and (4) conventional or reverse circulation modes.

maximum trace amplitude of 7.2 inches/channel, and trace identification capability.

Parts ordered for the bit hydraulics test stand have started to arrive. All parts designed specifically for the test stand should be completed and shipped by the end of October 1979.

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 in order to maximize its chemical resistance to geothermal H₂S environments without large sacrifices in its mechanical properties or cost.

Basic Metallurgical Considerations -- An important conclusion from a review of alloy composition and microstructural effects is that certain trade-offs must be made in the design of steels for specific uses. In the case of steel for drill stem applications, the steel must attain a certain strength level (tensile requirements are shown in Table 2) and fatigue resistance and also must retain a good toughness. When used in certain drilling applications, specifically geothermal drilling, the steel should also show a suitable resistance to certain kinds of corrosion and corrosion fatigue. Resistance to hydrogen sulfide, a compound which can often cause sudden and catastrophic drill stem failures, is of particular importance. The mechanical and chemical requirements must also be balanced with economic requirements which limit the use of expensive high-alloy steels.

Table 2

Tensile Requirements for Drill Stem

<u>Grade</u>	<u>Yield Strength</u>				<u>Tensile Strength</u>	
	<u>MPa</u>	<u>(ksi)</u>	<u>MPa</u>	<u>(ksi)</u>	<u>MPa</u>	<u>(ksi)</u>
	Min.		Max.		Min.	
D	380	(55)	--	---	656	(95)
E	518	(75)	--	---	690	(100)
X-95	656	(95)	863	(125)	725	(105)
G-105	725	(105)	932	(135)	794	(115)
S-135	932	(135)	1 139	(165)	1 001	(145)

Note: The steel should have a minimum elongation (e) which exceeds

$$e = 625\,000\,A^{0.2}/U^{0.9}$$

where A is the cross-sectional area of the tensile test specimen (in square inches) and U is the minimum tensile strength (in psi).

The general variations in important parameters controlling strength, toughness, and hydrogen embrittlement are briefly summarized below. The variations will be related to obtaining a steel most suitable for drilling in geothermal environments. High strength can be obtained by

1. Solid solution strengthening (e.g., carbon in iron),
2. Precipitation strengthening (e.g., alloy carbide formation),
3. Solid-state phase transformation (e.g., martensite in steels),
4. Refinement of grain size and substructure,
5. Hot and cold working (including thermomechanical processes), and
6. Dispersion strengthening (e.g., oxide particles in nickel alloys).

Toughness and ductility are generally increased by

1. Refining grain size and substructure,
2. Controlling the shape and distribution of precipitates and inclusions,
3. Eliminating (or modifying) the formation of brittle phases, and
4. Employing ductile phases as crack arrestors.

Resistance to hydrogen embrittlement can be enhanced (in ferritic/martensitic steels) by

1. Using solutes which suppress local hydrogen reactions at crack tips or at specific precipitates (e.g., silicon in steel) and decreasing solutes, such as manganese and carbon, which increase these local reactions,
2. Refining grain size and substructure,
3. Reducing planar slip by increasing the stability of coherent precipitates (e.g., silicon stabilizes carbides),
4. Adding solutes which trap hydrogen (e.g., titanium in steel), and
5. Reducing inclusion interfacial area (e.g., reduce total sulfur content and form rare earth sulfides).

The above lists, when combined, indicate that certain courses may be followed in trying to improve the properties of drill stem steels for use in geothermal environments. Concerning the steel composition, manganese and carbon should be reduced and silicon increased as much as possible, compatible with the strength and toughness requirements. Tramp elements such as sulfur and phosphorus should be reduced to as low a level as possible. Further, certain sulfide inclusions, specifically manganese sulfide, should be eliminated; sulfur control and sulfide shape stabilization

can be accomplished by rare earth additions. The grain size and substructure should be reduced to as fine a scale as possible. Carbides should be stabilized thermally and mechanically by use of selected carbide formers, such as vanadium. Ductile phases should be employed as crack arrestors. Secondary phases can also be employed to control hydrogen diffusion or to change the potential at the crack tip as it penetrates this second phase. Many of the above considerations for producing a hydrogen-resistant steel with sufficient mechanical properties can be included in a class of steels known as duplex-phase steels.

The steels which are commonly used for drill stem are usually quenched and tempered or normalized and tempered. These heat treatments can be summarized by referring to Figure 5, which is the iron-rich corner of the iron-carbon phase diagram. When a steel is quenched and tempered, the steel is heated above the A_1 line and quickly cooled (quenched) to room temperature or below, thereby causing the austenite (face-centered cubic crystal structure) to transform to martensite (body-centered tetragonal crystal structure). The as-quenched martensite is a hard, brittle alloy until it is heated and held for some period of time at a temperature below A_1 . At this "tempering" temperature, precipitation of carbon out of the martensite occurs along with residual stress relief. These events combine to yield a material somewhat less hard and less strong but with a significant increase in toughness. A schematic of the quench and temper process is shown in Figure 5. A material that is normalized is air-cooled rather than quickly quenched. It can also form a martensitic structure (or a closely related bainitic structure) or a ferrite and carbide mixture, depending on the hardenability, which is a function of the alloy content of the steel. Tempering of a normalized steel will produce a structure which is generally some combination of tempered martensite, ferrite, and spheroidized carbides.

The problem of using low-alloy steels in hydrogen-sulfide-containing atmospheres has been approached for the most part by attempting to modify conventional quenched and tempered steel. Steel manufacturers and oil companies have concentrated much of their work on AISI 4130 alloy steel and have moderately raised the level of resistance to sulfide stress cracking. The AISI 4130 alloy steel nominally contains 0.50 weight percent manganese, 1.0 weight percent chromium, 0.20 weight percent molybdenum, and 0.30 weight percent carbon. Careful attention to compositional control, including strict limitations on inclusion level, and an increase in chromium and/or niobium have allowed an increase in the resistance to hydrogen embrittlement to be achieved. An alternate approach is based on manganese-molybdenum modified steels in which the molybdenum level is raised above the levels conventionally used for drill stem to a total of 0.75 to 1.0 weight percent. This approach offers lower alloy costs and good compositional control during the steel-making process; well-controlled heats of this steel have led to a level of resistance to hydrogen sulfide which is even higher than that found for the modified AISI 4130 steels at the same strength levels.

The approaches described above have the advantage of working with a commonly used steel, a steel of which the steel-making and -treating processes are well known. Because they are so familiar, their introduction as

(a)

(b)

Figure 5. Quench and Temper Heat Treatment of an Iron-Carbon Alloy: (a) Phase Diagram; (b) Heat Treatment Schematic

alternate drill stem material may be more readily accepted when compared with newer, less familiar steels suggested for the same uses. The modified 4130 steels still utilize the same heat treatment, namely quench and temper, which yields a familiar, tempered, martensite structure. Unfortunately, the changes in composition discussed in the previous section, changes which should lead to an improved hydrogen resistance, are difficult to impose on a quenched and tempered steel which will still maintain good strength and toughness properties. Recent research in the area of unique heat treatments of iron alloys has produced steels which incorporate a strong martensitic phase as the load-carrying constituent in a ductile ferrite matrix. These steels have been called duplex, ferritic/martensitic steels, or, more commonly, duplex steels. This heat treatment involves quenching the steel from the austenitic phase (temperature above A_3) to room temperature to form untempered martensite. Then, rather than tempering, the material is heated above A_1 (but below A_3) into the austenite and ferrite two-phase region. It is held at this temperature until an equilibrium mixture of ferrite and austenite is formed. The alloy is then quenched to room temperature, causing the austenite to transform to martensite within a ferrite matrix. The heat treat schematic is shown in Figure 6 for an iron-carbon-silicon alloy (note the effect of silicon on the phase diagram by comparing Figures 5a and 6a). These duplex-phase steels offer, in general, very good combinations of strength and ductility. One particular steel contains 2.0 weight percent silicon and 0.1 weight percent carbon (nominal composition) and has a combination of strength and ductility properties superior to plain carbon or controlled, rolled, high-strength, low-alloy steels (such as Van 80). The combination of strength and ductility properties is also superior to the steels normally used as drill stem steels, such as Grade E. More important, from this review of the chemical adjustments desired for improvement of hydrogen embrittlement resistance, this steel would seem to be ideal. Both the carbon and manganese levels are lower, and the silicon content is significantly higher. Yet this is accomplished without decreasing the alloy's strength, and indeed, an increase in toughness can be achieved. This type of steel thus has many desirable compositional and structural features suiting it for use in drill stem.

Further adjustments can be made to the basic chemistry and heat treatment described above to include other changes in microstructure which should improve the resistance to hydrogen. For instance, cyclic heat treatments and/or controlled working (hot and warm) can cause both the ferrite and martensite grain size to be refined. Additions of strong carbide-forming elements such as vanadium may allow the tempering of the two-phase structure into a tempered ferrite and martensite with a distribution of stable alloy carbides. It has also been suggested that duplex steels can contain very fine layers of austenite retained between the martensite laths. Such a retained austenite structure may prove beneficial in providing a diffusion barrier to hydrogen in steel. If this duplex-phase steel, with appropriate modifications, is made with attention to limiting total sulfur and phosphorus and controlling the remaining sulfur with rare earths, almost all of the suggestions offered for a hydrogen-resistant steel with good strength and toughness can be included in one steel. The cost of this steel should be comparable to the cost of conventional, good quality, hydrogen-sulfide-resistant drill stem. Although the heat treatment needed to produce the duplex-phase structure is more costly

(a)

(b)

Figure 6. Duplex Ferritic/Martensitic Heat Treatment of an Iron-Carbon-Silicon Alloy: (a) Phase Diagram; (b) Heat Treatment Schematic

than that for the conventional quenched and tempered structure, this increase should be offset to some extent by the reduced cost of alloying additions. Research to characterize the chemical and mechanical properties of such a modified, duplex, ferritic/martensitic steel is the objective of this project.

Project Status -- The project was unavoidably delayed by two problems during the reporting period. The first problem was concerned with the delivery of the conventional drill stem from various drill stem manufacturers. The pipe is being supplied through the Loffland Brothers Drilling Co's. supply yard, but, prior to release, the pipe must be inspected by a representative from the steel mills for reimbursement and accounting procedures. Because the inspection had not been performed, the pipe had not arrived at Sandia at the end of the reporting period. Preparations have been made to flatten and machine the pipe into suitable test samples as soon as it is delivered.

The second problem involved the making of the modified dual-phase steel. The vacuum system of Sandia's induction melting facility broke down prior to the melting of the steel for this project. The system had been repaired by the close of the reporting period, and melt of the required steel was scheduled for mid-October 1979.

The test equipment has been designed and fabricated and can be placed in operation as soon as test specimens are available. The corrosion/fatigue experiments will be conducted on an MTS Model 810.12, closed loop, servohydraulic test system. A specimen environmental chamber that is compatible with MTS testing frames will be used for the brine-H₂S testing.

The modified dual-phase steel, which is being designed at Sandia to yield an alloy with improved resistance to geothermal drilling fluids, is similar in composition and heat treatment to the steels originally developed and patented for DOE by the Gareth Thomas group at the University of California, Berkeley. Revisions in both the composition and the heat treatment will be made during the Sandia research program in an attempt to regulate the properties to meet those required for drill stem. The Berkeley group was contacted concerning this program and assisted in planning the variations to produce a dual-phase steel suitable for drilling applications. Professor Thomas is interested in encouraging development and use of dual-phase steels. After learning that a Sandia research program had designed a dual-phase steel for corrosion/fatigue testing in geothermal-like environments, he expressed the desire to cooperate in this research. He visited Sandia on 9 May 1979 to explore possible areas of cooperation as well as to present a seminar on his research activities in the area of alloy design. Professor Thomas proposed that the dual-phase alloy to be made by Sandia's melting lab and tested for corrosion/fatigue resistance and stress corrosion behavior could be further characterized at Berkeley. This characterization will include mechanical testing as well as transmission electron microscopy to identify important substructural features. The main bulk of this characterization will be performed as part of a master's degree thesis by a student under the direction of Professor Thomas. No Sandia/DOE funds are required for the support of the Berkeley work.

As part of a general study of corrosion of low-alloy steels, several steel samples of varying compositions (Table 3) were obtained from Professor Thomas. The samples, which can be heat treated to duplex-phase microstructures, were machined into cylinders approximately 7.94 mm (0.31 inch) in diameter by 6.35 mm (0.25 inch) thick. These cylinders were mounted on copper rods of the same diameter with a conductive epoxy. Next, a nonconductive epoxy was potted around the outside of the sample cylinder, extending for a centimetre or so up the copper rod. The nonconductive epoxy electrically insulates the sample and provides mechanical strength for the joint between the copper and the steel sample.

The samples were 7.9-mm (0.31-inch) steel discs. Each sample was subjected to general corrosion tests using the following procedures. The bottom of the epoxy was ground away to expose the sample's face that was surrounded by the nonconductive epoxy. The uncovered face was then exposed, as the anode, to a corrosive medium. Information on the general corrosion behavior was determined as a function of potential. The general corrosion behavior of the steels versus minor changes in composition was thus determined.

Small additions (less than about 2 weight percent) of most alloying elements to steels do not greatly affect the corrosion rate of low-alloy steels. In fact, this is shown to be the case in the first set of experiments in which potentiostatic measurements were made on steel samples immersed in a 0.01 N H_2SO_4 solution (see Table 4). The measured corrosion rates varied from 0.56×10^{-4} to 1.32×10^{-4} amps/cm², which are on the same order as those commonly measured for other low-alloy steels. Since the samples were mechanically polished immediately before testing, the formation of a protective film or oxide was not allowed. Elements such as Cr, Al, and Si in sufficient quantity can promote the formation of a protective layer if given enough time to form continuously on the surface. Such layers can cause a substantial decrease in the corrosion rate. Potentiostatic tests will be repeated on several samples to determine if the presence of Cr, Al, or Si will allow the formation of a surface layer that will decrease the corrosion rate.

Table 4

Corrosion Rates for Steel Alloys in a
0.01 N H₂SO₄ Solution

<u>Alloy Designation</u>	<u>Corrosion Rate (amps/cm²)</u>
1	0.69 x 10 ⁻⁴
2	0.89 x 10 ⁻⁴
3	1.2 x 10 ⁻⁴
4	1.0 x 10 ⁻⁴
5	0.72 x 10 ⁻⁴
6	0.56 x 10 ⁻⁴
7	0.56 x 10 ⁻⁴
8	0.99 x 10 ⁻⁴
9	1.0 x 10 ⁻⁴
10	1.32 x 10 ⁻⁴

4.4 Rock Mechanics for Polycrystalline Diamond Compact (PDC) Cutters

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

Project Status -- During this reporting period, TOODY, a two-dimensional, finite-difference model, continued to be used in calculations of the drag-tool/rock interaction problem. It was discovered that the zoning originally used for the problem (see Figure 7) was producing erroneous results, so different zoning options were investigated. The problem now appears to be satisfactorily zoned (see Figure 8), although further work is necessary to permit proper treatment of the material layers (geometry) for the PDC tools. TOODY stress contours with the present zoning show the same character as those obtained in earlier finite element calculations of the problem. Details of the results differ, however, since the TOODY calculations treat the interaction of tool and rock, while the finite element calculations assumed a load distribution on the cutting edge of the tool.

In the TOODY calculations, the rock has been treated as a purely elastic body. While not allowing for stress relief as the rock fails, these calculations show how stresses develop and distribute in the tool. Regions of highest shear stress were found to occur at the cutting edge and at the corners where the tool attaches to the bit body. Figure 9 shows a contour plot of maximum shear stress for a calculation in which both tool and "rock" were modeled as steel bodies. Magnitudes associated with the various contour lines could not be clearly identified from the plot; however, further examination of the TOODY output showed the shear stresses increasing as indicated in the figure. Some refinements to the contour plotting program appeared to be needed so that calculated results could be more easily displayed and interpreted.

Figure 7. Original TOODY Zoning for Drag-Tool/Rock Interaction Problem.

Figure 8. Present TODDY Zoning for Drag-Tool/Rock Interaction Problem

Figure 9. Contour Plot of Maximum Shear Stress in Tool and Rock

Calculations of the tool/rock interaction problem were continued with (1) finer zoning (better resolution) in tool and rock, (2) a larger region of rock included in the calculation, (3) material models which more appropriately treat rock response (brittle failure), and (4) zoning and material definition to properly treat diamond and tungsten-carbide layers in the PDC drag tool.

A simple, force-balance model has also been developed for estimating tool loads on PDC drag cutters. This model, Figure 10, is similar to those developed by Nishimatsu⁴ for pick-type (positive rake) cutters and by Paul and Sikarskie⁵ for wedge-type indenting tools. The present model, however, uses no empirical constants, so previous cutting experiments are not necessary in order to make predictions of tool performance in a given rock. Parameters which must be specified are tool rake angle, depth of cut, coefficient of tool/rock friction, rock cohesive strength and internal friction angle (Coulomb-Mohr failure criterion is used), and fluid pressure. Calculations have been made with the model for shale cutting experiments reported by Cheatham.* Calculated tool forces were found to agree reasonably well with the measured forces, as shown in Figure 11.

TOODY calculations of the drag-tool/rock interaction problem were continued using the biaxial tensile fracture model available in the code to treat rock failure. Rock properties chosen for these calculations correspond to sandstone with a density of 2 gm/cm³ (0.07 lb/in.³), a sound speed of ~2 km/s (6562 ft/s), a Poisson ratio of 0.1, and a tensile strength of 10 MPa (100 bars). The sequence of Figures 12 through 15 shows the calculated development of damage (tensile fractures) during the first 100 microseconds of loading. Figure 16 shows the calculated tool cutting-force (horizontal force in this case) history for this problem.

As the tool moves into the rock face during early stages of the problem (up to ~50 μ s), tensile fractures develop beneath the tool (Figure 12) and propagate away from the surface (Figure 13). As shown in Figure 16, however, the tool cutting force increases steadily during this stage of the problem. As loading continues, fractures are seen to develop ahead of the tool (Figure 14) and propagate in roughly spiral fashion toward the rock surface (Figure 15). At the same time as these latter fractures are developing (~60 μ s in the present calculations), the calculated tool force, shown in Figure 16, is decreasing rapidly. This calculated tool-force history agrees qualitatively with force histories obtained in actual rock cutting experiments (Figure 17).

More extensive TOODY calculations of the drag-tool/rock interaction problem are being undertaken. In preparation for analyzing the calculational results and for comparing tool and rock response for the various problems, effort has been devoted to developing convenient procedures for graphically displaying the output. One method that has been developed is illustrated in Figure 18; a dot density plot is used to show, at selected problem times, the distribution or intensity of stress in the tool and the distribution of cracks or failed zones in the rock. A small program was also written to plot tool-force histories, which are maintained during the

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*Presented at ASME Conference, Houston, November 1978.

Assumptions:

1. Chip is in equilibrium
2. Coulomb-Mohr criteria satisfied along chip:

$$\tau_r = \tau_0 + \sigma_r \tan \phi$$

cohesive strength
angle of internal friction

3. Coulomb friction between tool and rock:

$$F_f = \mu F_N$$

4. Chip will form for smallest possible cutting force, i.e., when

$$\frac{dF_c}{d\theta} = 0$$

Figure 10. Schematic of Idealized Chip Formation Problem

Figure 11. Comparison of Calculated and Measured Tool-Force Data for Shale Cutting Experiments

Figure 12. Drag-Tool/Rock Interaction Problem, Early Stage ($20 \mu\text{s}$)

Figure 13. Interaction Problem at $25 \mu\text{s}$. The TOODY simulation shows fractures propagating below the tool for early times.

Figure 14. Interaction Problem at 55 μ s. The simulation shows fractures developing ahead of cutting edge.

Figure 15. Interaction Problem at 70 μ s. Fractures are shown ahead of cutting edge propagating in "spiral" fashion toward the rock surface.

Figure 16. Calculated Cutting-Force History for Drag-Tool/Rock Interaction Problem

Figure 17. Typical Experimental Force-Displacement Curves for Drag Cutting of Rock at Atmospheric Conditions

Figure 18. Stress State in Tool and in Failed (Cracked) Zones in Rock. Dots identify (1) regions in tool where maximum shear stress exceeds 10 MPa (100 bars) and (2) regions in rock where material has failed (cracked).

TOODY calculations. Both cutting- and thrust-force histories can be plotted, and the program can be used to compare results from a number of different calculations, as illustrated in Figures 19 and 20. The results shown in the figures derive from the separate effects studies started during this reporting period with preliminary calculations made to investigate effects of rake angle on tool and rock response. Results of these calculations suggest that, for the present case (i.e., for the rock model and material properties used in the calculations), both the peak and average thrust forces increase with rake angle, while peak cutting force decreases somewhat and average cutting force stays about the same. A Coulomb failure criterion was developed, tested, and coded into TOODY. This allows for failure in shear. A test calculation was performed, but the predominant failure mechanism was still tensile failure. The Coulomb criterion is expected to be important when the in situ hydrostatic pressure and the pressure due to the drilling mud are included in the problem.

The direction of future studies in this area will depend on specific needs of the drilling programs. For example, while studies of the effects of tool geometry (rake angle and supporting stud design) on cutting force and tool stress are of interest for conventional rotary bits, the effects of cutting speed on tool response could be of more importance if emphasis is placed on development of high-speed bits. Presently, the calculations address the effects of rake angle and depth of cut on tool forces, since fairly extensive experimental data exist on these effects for comparison with the calculated results. Future work may also investigate (1) quantitative agreement between calculated tool forces and data obtained in single-point cutter tests, (2) stress state in the tool and efficiency of rock removal for various rake angles, depths of cut, cutting speeds and rock type, and (3) modification of the problem definition to treat the effects of confining and in situ pressure on the rock surface.

Stress and velocity histories on the bit and rock surface were also generated for use in friction-heating studies of PDC drag tools. A fairly complete literature search was conducted to determine the extent of the present knowledge regarding rock friction. An extensive body of literature exists concerning metal-on-metal friction and lubrication and on the resulting friction-generated heat. A substantially lesser amount of work has been performed in the field of rock friction. The two most important aspects of friction as applied to the calculation of drag-tool temperatures are (1) the availability of constitutive relations for frictional force as a function of sliding velocity and normal force and (2) accurate estimation and/or measurement of real contact area between the drag tool and rock. Both of these facets are treated to some degree in the literature.

The investigation to date has not required knowledge of the magnitude of the heat flux imposed at the cutter/rock interface. A classical, analytical model of heat transfer in a short, cylindrical spine or fin has been found to be applicable to the case of the composite cylinder sliding on a semi-infinite rock plane. It is hoped that comparison of temperatures predicted by this model with temperatures measured in sliding friction specimens will verify friction models and thermodynamic relations predicting surface heating. At this time, the friction relation being utilized is of the form

DRAG TOOL FORCE HISTORIES

COMPARISON OF TOOL FORCE HISTORIES FOR TWO RAKE ANGLES
 SOLID LINE = -20°; DOTTED LINE = -40°

Figure 19. Tool Cutting-Force Histories

Figure 20. Tool Thrust-Force Histories

$$\tau = S_0 + c\sigma$$

where

τ = friction force,
 σ = normal force, and
 S_0, c = constants.

This constitutive equation⁶ appears to be independent of sliding velocity in the rock/steel friction measurements. The applicability of this relation to friction of polycrystalline diamond on rock such as granite must be verified.

At present, a two-dimensional model of a Stratapax™ stud with a 20° negative rake angle is being built to be run on a conduction code CINDA. Property data (k, ρ, c_p) are being sought for diamond and carbide. Tentatively, surface normal forces and velocities at the tool/rock interface predicted by TOODY are being used to calculate the heat generated at the interface. An energy partitioning principle predicting the manner in which the heat generated at the interface is proportioned between tool and rock has not yet been formulated and, at present, is the single most important item of study.

4.5 PDC Reamers

Project Objectives -- 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 -- A Smith Model 62 bottomhole, three-point roller reamer was selected as the test bed for field tests of the PDC reamer concept (Figure 21). Placement of the cutters is being made to provide maximum protection of the PDC during tripping-in. The cutter surface is aligned with the axis of the roller cutters to preclude dragging of the PDC on the borehole wall. Modifications of the reamer body were restricted to those that would insure normal reamer operation, field dressing, and reaming capability of the standard roller cutters.

Modification of the roller-reamer body for installation of the steel-stud-mounted compact cutters has been completed. Mounting hardware for the cutters has been designed, and fabrication is progressing. Work is continuing on a signal generator system to provide an indication at the surface when bit and reamer wear are excessive and an undergage hole is being drilled. Field tests are anticipated in the July-August 1980 time frame.

4.6 Aqueous Foam Drilling Fluids

Project Objective -- The objective of the project is to 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.

Figure 21. Smith Model 62 Bottomhole Three-Point Roller Reamer with Modified Cutter Block

Project Status -- Work on the development of aqueous foams for use in geothermal drilling was initiated at the end of the previous reporting period. Aqueous foam is a promising drilling fluid for the underpressured, hard rock formations frequently found in geothermal reservoirs. The primary advantages of foam drilling fluids are as follows: (1) they will not harm producing formations; (2) they allow high drilling rates; and (3) they utilize low annular velocities that should eliminate the erosion problems of air drilling. Successful use of aqueous foam for geothermal drilling will require a surfactant system which will have sufficient chemical stability to withstand the harsh thermal and chemical environment found in geothermal wells. In addition to chemical stability, the surfactant must also be capable of forming stable foams at high temperatures and pressures. Because of the low density of foam, its successful use will require a high-pressure rotary drilling head suitable for geothermal well use. Such a drilling head will allow balanced drilling and control of formation water and steam. Corrosion problems may require the use of nitrogen rather than air to make the foam unless corrosion inhibitors can be found that will work in the high-temperature geothermal environment.

During this reporting period, in order to identify surfactants for use as foaming agents, more than 50 candidate surfactants in deionized water were evaluated before and after exposure to a temperature cycle up to 260°C (500°F). Based on their performance, 12 surfactants were selected for further evaluation. The evaluation was continuing at the close of the reporting period. The surfactant screening procedures and representative test results are presented in the following paragraphs.

Aqueous solutions of the surfactants were exposed to the following temperature cycle: (a) increase from ambient to 260°C (500°F) in 2.0 hours; (b) maintain 260°C (500°F) for 2.0 hours; and (c) decrease from 260°C (500°F) to ambient in 3.0 hours. The solutions were contained in heavy-walled, stainless-steel tubing with Swagelok end caps and were prepared by mixing 50% by weight of the surfactant, as received in deionized water. A few surfactants were aged as either 0.2 or 1.0 weight percent solutions in a Baroid, 500-cc, high-temperature aging cell because of the limited solubility of those surfactants.

Aqueous foams for evaluation were made by metering nitrogen gas and the surfactant solution into a static mixer. This system provided uniform, small-celled foams with controlled density. Density and drainage time to 50% by volume were measured on foams made before and after the exposure of the surfactants to the high-temperature cycle. The solution pH was also measured before and after exposure. The foams were evaluated qualitatively, as well, by observation of their cell structure. Ratings of good, fair, and poor were assigned on the basis of the nonuniformity of their cell structure. The density of all foams was controlled to 45.0 ± 5.0 kg/m³ (2.8 ± 0.3 lb/ft³) with some exceptions. High-foaming surfactants were selected for evaluation on the basis of their chemical structure and/or supplier's recommendations. Amphoteric, anionic, cationic, and nonionic types, all with varying chemical structures, were evaluated.

Amphoteric surfactants evaluated were the betaines, amido betaines, sulfo amido betaines, an imidazoline compound, and a proprietary fluorochemical material. Most anionic surfactants evaluated were sulfonic acid

salts or sulfonates. Alkyl, alkyl aryl, and perfluoro alkyl sulfonates were included. Other anionic types tested were an ethoxylated alkyl sulfate and an amide-linked, carboxylic acid salt. Cationic types evaluated were an imidazoline compound, ethoxylated tertiary amines, and a proprietary fluorochemical material. The nonionic surfactants tested were ethoxylated fatty alcohols, alkyl aryl alcohols, and a polyoxypropylene-polyoxyethylene block copolymer.

The data presented in Tables 5, 6, and 7 concern the effect on various surfactant solutions of exposure to 260°C (500°F). These data are selected from data on more than 50 surfactants. The tables include data on all promising surfactants and representative data on all types tested. The surfactants are identified by chemical type whenever possible and are subdivided into amphoteric, anionic, cationic, nonionic, and proprietary classes.

The density given was obtained on the foam dispensed for the original drainage tests. A few of the more poorly foaming surfactants would not make foams of $45.0 \pm 5.0 \text{ kg/m}^3$ ($2.8 \pm 0.3 \text{ lb/ft}^3$) in the generator. This is noted in the original cell structure column. The density of $45.0 \pm 5.0 \text{ kg/m}^3$ ($2.8 \pm 0.3 \text{ lb/ft}^3$) was chosen as representative of the preformed, stable foams used as drilling fluids.

Foam drainage is defined as the time to 50% weight loss of a preformed foam. It is a measure of density stability of the foam. Foams with long drainage times or good density stability are desirable for drilling-fluid applications. The drainage data are presented as the time in minutes to 50% by weight drainage between the original and exposed samples.

All foams tested were qualitatively evaluated for cell structure and given ratings of "good--small uniform cells," "fair--nonuniform cell structure," and "poor--nonuniform cells with large voids." The test indicates that degradation products from the surfactant are acting as anti-foamers or defoamers in the solution. These results imply that higher temperatures or longer times would create solutions incapable of making foams. This would be disastrous for foam drilling-fluid applications. Some foams made with surfactants exposed to 160°C (320°F) retained or even improved their drainage time; however, they would not make "fine--uniform-celled foams." Many surfactant solutions would not make foams after exposure to 260°C (500°F). This is noted with a "No Foam" rating in the aged cell structure column.

The last column in the tables gives the change in pH of the aqueous solution before and after exposure to 260°C (500°F). Without knowing the degradation mechanisms of the surfactant evaluated, the reason for a change in pH is difficult to determine. For this series of tests, pH was treated as a relative value indicative only of some change in the solution. All data presented are the average of three determinations.

The aging data presented in Table 5 on amphoteric surfactants show that these materials, as a class, performed poorly. Only one, a coco betaine, had good cell structure after aging, accompanied by a 28% decrease in drainage time. A cetyl betaine gave a small decrease in drainage time; however, the poor foam-cell structure after aging indicates problems will

Table 5

Effect of 260°C (500°F) on Selected Amphoteric Surfactant Solutions

<u>Chemical Type</u>	<u>Density (kg/m³)</u>	<u>Time (Min) to 50% Drainage</u>		<u>Δ% Drainage</u>	<u>Cell Structure</u>		<u>Δ pH</u>
		<u>Original</u>	<u>Aged</u>		<u>Orig.</u>	<u>Aged</u>	
Cetyl betaine	46.4	5.63	5.40	-4.10	Good	Poor	+1.45
Coco betaine	45.6	6.83	4.90	-28.3	Good	Good	+1.82
Coco amido betaine	47.0	5.66	3.48	-38.5	Good	Poor	+1.62
Coco betaine	44.6	6.79	No foam	--	Good	No foam	+1.83
Sulfo coco amido betaine	45.3	5.33	No foam	--	Good	No foam	+0.67
Potassium coco amino acid salt	44.5	4.85	No foam	--	Good	No foam	-1.89
Coco imidazoline betaine	45.7	6.82	No foam	--	Good	No foam	-1.72
Proprietary fluorochemical	4.44	9.83	No Foam	--	Good	No foam	-1.27

Table 6

Effect of 260°C (500°F) on Selected Anionic Surfactant Solutions

Chemical Type	Density (kg/m ³)	Time (Min) to 50% Drainage		$\Delta\%$ Drainage	Cell Structure		Δ pH
		Original	Aged		Orig.	Aged	
Sodium alkyl ester sulfonate	41.4	7.28	24.2	+232.0	Good	Fair	-2.65
Sodium alpha olefin sulfonate	43.8	7.84	7.38	-12.0	Good	Good	-2.73
Triethanol amine alkyl aryl sulfonate	45.1	8.74	6.95	-20.4	Good	Fair	-0.28
Sodium alkyl aryl polyether sulfonate	46.1	5.12	4.94	-3.51	Good	Good	+0.78
Sodium alkyl amide carboxy acid salt	46.4	5.86	4.72	-19.4	Good	Fair	+1.41
Sodium alkyl amide sulfonate	43.1	4.97	4.54	-8.60	Good	Good	-0.32
Sodium alkyl sulfonate	44.7	5.62	4.21	-25.0	Good	Poor	-1.21
Potassium perfluoro alkyl sulfonate*	92.8	2.58	3.85	+49.2	High density	Fair	-0.76
Ethoxylated ammonium alkyl sulfate	44.5	5.88	1.55	-73.7	Good	Poor	-3.88

*Aged and tested as 0.2%/wt solution

Table 7

Effect of 260°C (500°F) on Selected Cationic, Nonionic, and Proprietary Surfactant Solutions

Chemical Type	Density (kg/m ³)	Time (Min) to 50% Drainage		Δ% Drainage	Cell Structure		Δ pH
		Original	Aged		Orig.	Aged	
CATIONIC							
Ethoxylated coco amini	43.1	3.17	3.90	+23.0	Good	Poor	-0.96
Proprietary fluorochemical	46.7	8.06	No foam	--	Good	No foam	-2.07
Coco hydroxyethyl inidazoline	54.7	4.73	No foam	--	High density	No foam	No data
NONIONIC							
Alkyl aryl ethoxylated alcohol	47.2	3.87	4.32	+11.6	Good	Good	-1.70
Polyoxyethylene- polyoxypropylene block copolymer	57.4	4.94	4.13	-16.4	High density	Fair	-2.65
Ethoxylated fatty alcohol	44.7	3.42	4.11	+20.2	Good	Good	-0.02
PROPRIETARY							
None given	43.8	8.63	7.16	-17.0	Good	Good	+0.23
None given	45.3	6.92	3.46	-50.0	Good	Poor	+0.30

arise after longer exposure times. Most of the amphoteric surfactants produced no foam at all after exposure to 260°C (500°F). It is interesting to note that one of the surfactants giving no foam is another coco betaine, indicating that there are differences between surfactants sold as the same chemical type by different manufacturers. One surprise in these data was the failure of the fluorochemical surfactant, normally noted for its chemical stability.

The anionic surfactants showed less degradation as a class, as described in Table 6. All anionic surfactants evaluated made foam after our 260°C (500°F) cycle. The best anionic surfactants evaluated were a sodium alkyl aryl polyether sulfonate and a sodium alkyl amide sulfonate. Both showed small changes in drainage time, good cell structure after exposure, and small changes in pH. The first surfactant listed, a sodium alkyl ester sulfonate, showed a large increase in drainage time. In this case, hydrolytic cleavage of the ester linkage will generate a fatty alcohol, which is an excellent foam stabilizer. The presence of the fatty alcohol probably explains the surprising increase in drainage time. Although promising, this result is viewed with caution because the foam-cell structure was rated only fair after exposure to 260°C (500°F). Other anionic surfactants which will be evaluated in future tests are the alpha olefin sulfonate and the triethanol amine alkyl aryl sulfonate. Because of the known hydrolytic instability of the sulfuric esters (sulfates), very few were evaluated. Data on an ethoxylated ammonium alkyl sulfate are given.

Data on cationic, nonionic, and proprietary surfactants are given in Table 7. The cationic surfactants, as a class, performed poorly. One, an ethoxylated amine, had an increase in drainage time; however, it had poor cell structure after aging. Conversely, the nonionics, as a class, performed well. After exposure to 260°C (500°F), two showed an increase in drainage time and made foams with good cell structures. One, an ethoxylated fatty alcohol, gave very little shift in solution pH. Several proprietary foaming agents recommended for foam drilling were evaluated. One system, which is recommended for use as a foaming agent with steam in oil-well stimulation procedures, performed well. This system gave a moderate decrease in drainage, good cell structure, and a small change in solution pH after aging.

These data on the effect of a temperature cycle to 260°C (500°F) on surfactant solutions represent the first step in finding useful surfactants for geothermal foam drilling. Twelve promising surfactants from these tests are now being exposed to acidic, basic, and simulated geothermal brine solutions at 260°C (500°F) and higher temperatures. These tests will establish the chemical stability of surfactant solutions in various chemical environments. The final step in establishing surfactant usefulness will be that of making and evaluating aqueous foams at high temperatures and pressures in an autoclave. The autoclave was placed on order at the close of this reporting period. Successful surfactants from these tests will subsequently be formulated with additives such as corrosion inhibitors, scale inhibitors, antioxidants, and caustic chemicals to develop foaming-agent systems for geothermal drilling.

SECTION 5

EXTERNAL RESEARCH AND DEVELOPMENT

5.0 Introduction

The main thrust of the Geothermal Drilling and Completion Technology Development Program during this reporting period has continued to be improvement of conventional rotary drilling techniques and associated hardware. However, research efforts were increased in the development of drilling fluids and completion technology and 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 Drilling Hardware

During this reporting period, improvement in the performance of unsealed bits through the use of high-temperature steels was proven in field tests. Significant advances were made in the development of high-temperature lubricants and seals for sealed bearing bits. Redesign of the new type drill bit that uses sintered PDCs for cutting edges was completed, and preparations for a second field test were underway.

5.1.1 Geothermal Drill Bit

Contractor:	Terra Tek, Inc.
Principal Investigator:	R. R. Hendrickson

Project Objective -- The objective of this project is to design and develop improved drill bits for geothermal application. 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 project was initiated 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 in November 1978 for continuation of this project in FY79. During the period of this contract, the project work concerned with unsealed bits was completed. A second contract was issued in FY79 that will continue work on seals and lubricants until May 1980.

Unsealed Bits -- Third generation unsealed bits developed under this project (see Reference 2) were field tested in two wells in the Geysers. The data taken during the tests indicate that the MK-III bits were superior in resisting bit-gage loss and in maintaining hole gage as compared with the Reed Y73JA control bits. Figure 22 shows the gage of the MK-III and control bits as a function of a normalized wear life. The best normalizing function was found to be the total hours of drilling accumulated by the bit plus a factor times the total hours of reaming accumulated. Compared with the control bit, five additional hours of life could be expected from the MK-III bit for an average run. For an average 17-hour drilling run (with 3 hours of reaming), 5 additional hours translates to a 30% improvement in drilling life.

Figure 23 presents the results of a similar analysis of the bottomhole gage following a drilling run. Bottomhole gage has been defined as the gage of the largest of four bottomhole drill string elements measured after the run. Again, about 5 additional hours of life were recorded before the hole made by the MK-III bit reached the same gage as the hole made by the control bit.

The point at which the hole began to go undergage was determined to be that point where the next bit began reaming. It was found that the MK-III bit drilled an average of 70% longer before the hole began to go undergage, 11.5 hours versus 6.8 hours.

Figure 22. MK-III Bit Field Test: Bit-Gage Loss versus Wear Time

Figure 23. MK-III Bit Field Test: Hole-Gage Loss versus Wear Time

Based on the analysis of the field test data, the conclusions reached were as follows:

1. The MK-III bit could drill 30% longer than the control bit in an average run before incurring the same bit- and hole-gage losses.
2. The MK-III bit drilled 70% more hole to gage than the control bit.
3. The penetration rate of the MK-III bit was similar to that of the control bit.
4. The MK-III bit had a bearing-insert-gage rating improvement of 1 to 1-3/32 over the control bit rating for the same amount of drilling and reaming. Bearings and inserts were rated from 1 to 8, and gage was measured in inches.
5. Drilling and reaming should be limited to 20 to 25 equivalent wear hours per bit to control gage loss. The equivalent wear hours equal the hours of drilling plus 2.5 times the hours of reaming.

Following the tests, it was discovered that the MK-III bits were run with 1.9-cm (0.75-inch) nozzles while the control bits were run wide open with 2.9-cm (1.14-inch) diameter air jets. The air flow rate through the MK-III bearing cooling passages was twice that through the control bit cooling passages. This may have affected bearing performance. Tests run by industry on other bits using varying nozzle sizes, however, have not produced discernable performance differences.

Use of the MK-III bit to drill the entire 610-metre (2000-foot) hard production zone interval in the test well would have saved an estimated 24 hours of tripping and reaming time at a cost savings of \$40,000. If the material technology identified in this project were applied to developing commercial, geothermal hard-rock bits, very significant geothermal well cost savings could be realized.

Sealed Bits -- The seal screening-test program isolated several candidates for additional testing, including several Viton compounds, Kalrez No. 3072, Fluorocarbon, Inc's., radial lip seal, and several L'Garde compounds. A new type of seal test was introduced during the reporting period to further characterize the performance of these compounds. The test simulates the high temperatures experienced by the drill bit during trip-in to a hydrothermal reservoir. In hydrothermal drilling practice, the bit experiences the full formation temperature prior to initiation of circulation of the drilling fluid; the circulating drilling fluid significantly reduces bottomhole temperature. In the laboratory test, the seal is subjected to a 1-hour "soak" at a temperature of at least 250°C (482°F). The soak is followed by cool-down to 150°C (302°F), at which time rotation is initiated at 90 rpm. The seal is then run to failure, or to 75 hours, at 150°C (302°F). Additional seal tests are then run on unused seals of successful seal candidates, using higher initial soak temperatures. These tests will determine the maximum hydrothermal reservoir temperatures which can be drilled with the various candidate seals.

In order to determine seal/lubricant compatibility, seal-life tests were run utilizing the most successful candidate lubricant to date, Pacer Lubricants, Inc., PLX-014 oil, and one of the more successful elastomeric seals, Utex Industries' Viton Compound No. RD-185. PLX-014 was formulated to be compatible with Viton and most other elastomers. Minor seal leakage began at 23-1/2 hours, and the test was terminated at 39 hours. Two similar tests run on RD-185 utilizing the standard Lubriplate Hi-Temp grease resulted in seal lives, at 200°C (392°F) with sand and cuttings present, of 48 hours and 31-1/2 hours.* Post-test observations of the seals run with the Pacer PLX-014 oil revealed no apparent chemical degradation of the RD-185 material, but wear on the inner diameter of the seals indicated that lubrication of the seal/steel interface could be improved. The overall compatibility of the Pacer oil with the Viton seals is otherwise excellent. Elastomeric seal tests using the series of four Viton compounds from Utex Industries have been completed.

Two of the EPDM/Viton O-rings provided by L'Garde, Inc., were evaluated. Seal lives of 44 and 47 hours were recorded at 200°C (392°F) with sand and cuttings present. Severe surface wear and extrusion were noted; little or no chemical degradation resulting in cracks or durometer shift was observed. L'Garde compounded these O-rings for static seal applications; it may be possible, therefore, to reduce surface wear and extrusion by optimizing the compound for the drill bit seal application.

Early trip-in simulation tests indicated that Parker No. 4025 Viton seals could withstand a 2-hour soak at 250°C (482°F). Two tests were run at 260°C (500°F) soak temperature, with all other test parameters identical to the previous tests (Pacer PLX-014 grease, rotation at 150°C [302°F], Geysers abrasives). The second test experienced mechanical difficulties. However, one seal ran 107 hours without failure, thus indicating that a higher soak temperature might be possible. A trip-in simulation test was run on a Parker No. 4205 Viton oval seal, using a 270°C (518°F), 2-hour soak cycle. The seal failed after 1-1/4 hours of rotation at 150°C (302°F). This confirmed the previous tests, which indicated that the maximum allowable soak temperature for this elastomer is 260°C (500°F).

Utex Industries, Inc., has compounded a new, proprietary, high-temperature elastomer, designated RD-217, to withstand soak temperatures significantly higher than 260°C (500°F). Utex will mold seals for evaluation in the Geothermal Seal Test Facility. These should be available in late October 1979.

The two first-generation, Teflon-coated Viton oval seals were evaluated using the trip-in simulation test. These seals have a plasma-polymerized, 1-mil-thick, Teflon film deposited on a Parker No. 4205 Viton elastomeric oval seal. The seals soaked for 1 hour at 250°C (482°F) and were then allowed to cool to 150°C (302°F), at which time rotation was initiated. The tests were run with Pacer PLX-014 grease and Geysers abrasives. Seal lives of 107 hours and 40 hours were obtained. The failures were caused by abrasive damage at the seal interface. The second test

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*Lubriplate Hi-Temp tested poorly in the lubricant tester and hence cannot be used in rock bits.

may have been cut short by technical difficulties. These seals were sent to Sandia for analysis. At least two more generations of Teflon-coated seals will be coated at Sandia and sent to Terra Tek for evaluation.

Two Reed-type oval seals of Dupont Kalrez Compound No. 3072 were subjected to seal-life tests, one at 200°C (392°F) and the other at 235°C (455°F). Both tests were run with Lubriplate Hi-Temp grease in the presence of Geysers cuttings with sand. The 200°C (392°F) test was halted after 86 hours; the inner diameter of this seal showed some signs of abrasive wear, but very little grease had leaked past the seal. The seal tested at 235°C (455°F) failed after 41-1/2 hours due to extrusion. Dupont Kalrez Compound No. 3072 appears to be an excellent choice as an elastomer for high-temperature seals for roller-cone bits.

Tests on experimental, first-generation, radial-lip seals from Fluorocarbon, Inc., (No. FC-00912) revealed that the seals tended to shrink at temperatures above 200°C (392°F). This was initially attributed to incompatibility with the Pacer PLX-014 oil and grease. Thus, an additional seal test was run with an oil containing a Teflon-swelling agent. This seal exhibited leakage after 2 hours of rotation. Shrinkage was essentially the same as experienced in previous tests using PLX-014 oil and grease. Subsequent discussions with the manufacturer revealed that the shrinkage resulted from the high temperature, 260°C (500°F), and was not caused by the lubricant. Fluorocarbon, Inc., will supply second-generation seals for evaluation in November 1979, incorporating the following design improvements:

1. A stronger expander spring will be used to overcome the stress generated by shrinkage.
2. Inconel-718 will be used for the expander spring in place of 301 stainless steel.
3. The seal will be mounted in a stainless-steel ring and restrained at the outer lip so that all rotation will occur on the inner lip of the seal, where surface velocity is lower.
4. The cross section will be reduced to a 4.75-mm (0.187-inch) square so that the seals will fit the gland of existing 22.2-cm (8.75-inch) rock bits.
5. Fluoroloy-K plastic (proprietary) will again be used for the seal bodies.

Four seal tests were run on two L'Garde, Inc., compounds which utilize the "Aflas" base polymer from Japan; seals were supplied in the 2-329 O-ring size. The compound, designated 291-II-2, exhibited seal lives of 21 hours and 4-1/2 hours when tested at 200°C (392°F) using Lubriplate Hi-Temp grease and Geysers abrasives. The compound 290-2 seals exhibited lives of 10-1/2 hours and 15-1/2 hours under identical test conditions. The common cause of failure on all four tests was the circumferential delamination along the inner diameter of the O-rings; both compounds exhibited good resistance to wear, extrusion, and chemical degradation. These O-rings and copies of the test results have been forwarded to L'Garde for evaluation.

The spring-loaded face seal (Figures 24 and 25) with the elastomeric side-seal system was perfected, and performance was verified in two successful life tests at 200°C (392°F) with sand and cuttings; lives of 17 and 22 hours were observed. Subsequently, the seal phosphor-bronze ring was hard-coated with chrome oxide to improve wear characteristics. Three additional life tests were run using chrome-oxide-coated seal rings, Viton side seals, and carburized, lapped, CBS-600 steel mating rings. All tests were at 200°C (392°F) using Pacer PLX-014 grease. The first test, run without abrasives, was terminated at 76 hours with very little leakage observed. The next test, run with the same seal ring and with Geysers abrasives, experienced spalling of the chrome oxide plasma layer 2 hours into the test. The third test, also with abrasives, was terminated at 23 hours due to slow leakage caused by abrasives working between the O-ring static (side) seal and the mating surface. Overall wear/leakage performance for the chrome oxide/CBS-600 carburized steel sealing system is excellent. The spring-loaded face-seal design should be usable to 260°C (500°F). Previous tests have indicated that elastomers for static seals are available for this temperature, and numerous commercial face-seal applications involve abrasive slurries and seal lives which greatly exceed the modest 100-hour requirement for geothermal drill bits. Based on these tests, excellent performance is expected from the metal-bellows side-seal version of this seal. The first generation of the all-metal face seal (Figure 26) is being fabricated, and initial seal-life tests are scheduled for early October 1979. Plasma Technology, Inc., has applied chromium oxide ceramic coating (PTI No. 25) to the seal rings and lapped the sealing surfaces to within two light bands. These rings have been forwarded to Bel-Flex Products, Inc., where the bellows and outer ring will be added. The coil compression springs are being fabricated from 17-7 PH stainless steel by Associated Spring Corp.

The fixtures needed to test the metal-bellows face seal in the Geothermal Seal Test Facility have been designed. The mating discs will also have a lapped, chromium oxide surface to insure low wear and low leakage. Discs of carburized steel will be evaluated after successful results have been obtained with the chromium oxide disc.

Lubricant screening tests, while eliminating several products from further consideration, have continued to establish the exceptional performance of Pacer PLX-014 oil. Numerous iterations of seal testing, lubricant testing, and lubricant formulation have led to this product, which is compatible with Viton and is also the most successful high-temperature lubricant. The load-bearing ability of the PLX-014 lubricant at 316°C (600°F) is roughly twice that of the standard rock-bit lubricant at room temperature. The results of the lubricant tests on the most promising products are listed in Table 8. The following observations can be made regarding the results:

1. Pacer PLX-014 lubricant provides better lubrication at 316°C (601°F) than at 204°C (399°F).
2. The Wynn's supplement, an oil, provided excellent lubrication. It probably benefited from residuals of the previous test; additional testing is required.

Figure 24. Cross Section of a Spring-Loaded Face Seal
Installed in a Geothermal, Tricone Roller Bit

3. The PLX-014 lubricant test (No. 96) which followed the Wynn's Supreme Supplement test provided the narrowest wear scar to date; the load-bearing ability of this lubricant (187 MPa [27.1 ksi]) is roughly double anything previously recorded at any temperature. Residuals from the Wynn's Supreme Supplement are suspected to have enhanced the PLX-014's performance, thus indicating further improvements are possible. (A false high reading, indicated by a narrow scar, is virtually impossible with a ring-and-block tester of friction and wear.)
4. The suspended 0.7- μ m graphite particles in the PLX-014 showed no tendency to settle out during tests 104 through 107.

In order to determine the contribution of graphite to PLX-014's performance, five tests were run on a version of the oil, designated PLX-014G, that contained no graphite particles or graphite suspension fluid.* The average final-load-bearing capability was 43.4 MPa (6300 psi) as compared to nearly 69 MPa (10 000 psi) for the standard PLX-014. This is consistent with the drill-bit manufacturers' contention that suspended solid lubricants are a necessary part of a successful journal-bearing bit lubricant, although even 43.4 MPa (6300 psi) is superior to the standard bit lubricant.

Figure 25. Exploded View of the 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.

*The graphite suspension is a relatively new additive product consisting of 0.7- μ m graphite particles in a proprietary suspension fluid.

Figure 26. Cross Section of First-Generation All-Metal Face Seal

Table 8

Results of Lubricant Tests at Temperature

<u>Test</u>	<u>Product</u>	<u>Temperature</u> °C (°F)	<u>Scar</u> mm (inch)	<u>Load</u> MPa (ksi)
94	Pacer PLX-014 (first batch)	288 (550)	1.02 (0.040)	99.3 (14.4)
95	Wynn's Supreme Supplement	288 (550)	1.47 (0.058)	67.6 (9.8)
96	Pacer PLX-014 (first batch)	288 (550)	0.508 (0.020)	187.0 (27.1)
103	Pacer PLX-014 (first batch)	204 (399)	1.78 (0.070)	55.9 (8.1)
104	Pacer PLX-014 (second batch)	204 (399)	2.21 (0.087)	45.5 (6.6)
105	Pacer PLX-014 (second batch)	288 (550)	1.73 (0.068)	57.3 (8.3)
106	Pacer PLX-014 (second batch)	316 (601)	1.09 (0.043)	91.8 (13.3)
107	Pacer PLX-014 (second batch)	316 (601)	1.04 (0.041)	95.9 (13.9)

Pacer Lubricants, Inc., compounded a grease version of the PLX-014 oil as well as four modified oil versions. Some of the test results on these products are shown in Table 9.

The following observations can be made regarding the results:

1. PLX-022 Oil -- This is a version of the PLX-014 oil which utilizes an additional antiwear agent not compatible with elastomers. It is intended for use with the metal-bellows, spring-loaded face seal. PLX-022 exhibited a load-carrying capability of 81.4 MPa (11.8 ksi), with an average scar of 1.24 mm (0.049 inch), at 317°C (603°F) in a series of seven tests. The load-bearing capability of PLX-022 oil is about 20% higher than that of PLX-014 oil.
2. PLX-014 Grease -- Seven standard lubricant tests were run on Pacer PLX-014 grease at 317°C (603°F) with excellent repeatability. The average load was 64.1 MPa (9.3 ksi), with an average scar of 1.55 mm (0.061 inch). As expected, the load is somewhat less than that for the pure PLX-014 oil. However, the results for the grease

exceed the requirement by 50%, indicating that PLX-014 grease is ready for field evaluation.

3. PLX-025 Oil -- This version of the PLX-014 oil contained a Teflon-swelling agent to counter the shrinkage experienced by the Fluoroloy seals. However, as reported above, subsequent investigation revealed that temperature alone caused the shrinkage. Hence, the swelling agent is not required. As the test results indicate, PLX-025 has a poor load-carrying capability.

Table 9

Lubricant Load-Carrying Capacity at 316°C (600°F), 0.76 MPa (110 psi)

Product*	Description	Test Runs	Average Wear Scar mm (inch)	Average Final Load MPa (ksi)
PLX-022	Oil for all-metal face seal; not compatible with elastomers	6	1.52 (0.060)	69 (10.1)
PLX-023	Oil, more viscous version of PLX-022	6	1.55 (0.061)	67 (9.7)
PLX-024	Oil, compatible with elastomers; more viscous version of PLX-014 oil	3	1.47 (0.058)	69 (10.1)
PLX-014 Grease	Elastomer-compatible	2	1.65 (0.065)	62.3 (9.03)
PLX-025	PLX-014 oil with Teflon-swelling agent	2	7.80 (0.307)	13.0 (1.89)

*All products tested were supplied by Pacer Lubricants, Inc.

At the end of this reporting period, Pacer Lubricants submitted for evaluation two new candidates, PLX-030 and PLX-031, which contain additional additives to improve performance at moderate temperatures while maintaining excellent performance at 316°C (601°F). These candidate lubricants will be evaluated in the lubricant test facility in October 1979.

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 PDCs 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 under laboratory conditions on the cutting of rock with individual PDC cutters have established a predictive capability for the performance of full-scale bits. Demonstrations under laboratory conditions with full-scale bits have proven this predictive capability. Smith Tool Co. and Christensen Diamond Products built prototype, full-scale bits (Figures 27 and 28) for downhole simulated testing in May 1978. 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 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 terminated after several attempts were made to obtain data.

The S-1 bit was redesigned and, during this reporting period, was fabricated and designated the S-1, Modified. The body of bit S-1, Modified, contains several holes which, by interference press fitting, accommodate the cemented tungsten-carbide studs with attached PDC cutters. During the fabrication of the bit, it was discovered that these cutter location holes had been bored slightly oversize. To correct the fault, the holes were enlarged, plugged with steel identical to that of the bit body, and rebored to the correct size.

Following this fix, both the S-1, Modified, bit and the C-1, Christensen, cast, hard-matrix bit were considered ready for field testing.

In June 1979, the site for a tentative field test for both the S-1, Modified, bit and the C-1 cast, hard-matrix bit was identified at the Union Oil exploratory hole in the Baca Field, New Mexico. This operation was expected to be ready to accommodate S-1 and C-1 bit tests by late August or early September 1979. However, the tests could not be confirmed for this time frame, and, at the end of this reporting period, the tentative tests were planned for mid-October.

In addition to the tentative Baca test site, the possibility of drilling tests at the Los Alamos Scientific Laboratory hot dry rock site near the Valles Caldera, New Mexico, was being investigated at the end of this reporting period.

Figure 27. Smith (S-1) PDC Geothermal Drill Bit

Figure 28. Christensen (C-1) PDC Geothermal Drill Bit

The General Electric Co. Research and Development Center has recommended that, in order to accelerate the field test program for the second-generation Stratapax™ bits, the range of geothermal parameters acceptable for testing be broadened to include others than the drilling of very hard rock and/or the utilization of air-mist fluids. In order to assist in the identification of potential field tests for geothermal Stratapax™ bits, a summary was prepared outlining the kinds of test sites which might be available. Also, a list was established of what might be learned with respect to bit integrity and drilling performance as a function of drill site characteristics. Consideration will be given to these recommendations should the Baca tests not materialize.

5.2 Drilling Fluids

After several equipment problems were solved, dynamic flow loop tests of representative mud mixtures at moderate pressures were proceeding satisfactorily at the close of this reporting period. Design of a high-pressure drilling-mud testing instrument and of a facility to house it reached an advanced stage. Some components were under performance testing, with others on order or in final design phases. A new project was initiated to gain a fundamental understanding of clay particle interactions under various chemical and temperature environments. This basic research is expected to lead to the design of drilling-fluid systems for use in geothermal drilling.

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 project provides for the establishment of a mud-test laboratory, for the design and fabrication of a 288°C (550°F), 20.7-MPa (3000-psi) flow loop, and for a moderate amount of drilling-fluids testing.

Status and Results -- Effort during this reporting period was largely devoted to repair and replacement of the flow loop equipment and debugging of the system. The primary problem concerned the performance of the feed pump and check valves. The flow loop experienced no problems in pumping water or thin mixtures of mud. But, as the mud density was increased, the fluid flow was interrupted by pump failure and/or clogging of the check valves. Three different pumps and three different types of check valves were tried in various combinations. Midway in the reporting period, the problems appeared to have been overcome with the use of a new, brass-gear feed pump.

At that point, a flow loop test was run as follows. Stabilization tests were conducted on the mud sample specified by M. Chenevert, consultant to the project. This mixture was a less viscous version of the original mud, which was too thick to flow in the test loop. The composition is indicated below.

1. Add to 5250 cm³ (1.4 gals) distilled water:
  - 150 grams (0.33 pounds) sea salt (10 ppb equivalent)
  - 150 grams (0.33 pounds) bentonite clay (10 ppb equivalent)
  - 300 grams (0.66 pounds) Rev dust (20 ppb equivalent)
  - 300 grams (0.66 pounds) Baroco clay (20 ppb equivalent)
2. Adjust the pH value to 9.5 by adding caustic soda.

The mud temperature was increased in 28°C (50°F) increments from 93.3°C (200°F) to 176.7°C (350°F). At each temperature, the mud was allowed to stabilize, and samples were withdrawn for rheological tests. The flow loop temperature, pressure, and flow rate and the rheometer test results are given in Table 10. Some abnormal readings were noted, hence, confirmation tests were undertaken.

Table 10

Results of High-Temperature/High-Pressure Flow Loop Tests

Test No.	Time P.M.	Temperature °C (°F)	Absolute Pressure MPa (psi)	Flow Rate cm ³ /s (in ³ /s)	Viscometer Readings		Initial Gel kg/m ² (lb/100 ft ²)	Plastic Viscosity Pascals (cp)	Yield Point kg/m ² (lb/100 ft ²)
					Ø 600 Degrees	Ø 300 Degrees			
1	3:13	Room Temp.	8.96 (1 300)	7.143 (0.436)	75	67	2.00 (41)	0.008 (8)	2.88 (59)
2	4:13	93.3 (200)	8.96 (1 300)	6.944 (0.424)	26	22	1.17 (24)	0.004 (4)	0.59 (12)
3	5:13	121.1 (250)	10.34 (1 500)	7.012 (0.428)	30	23	0.54 (11)	0.007 (7)	0.78 (16)
4	6:13	148.9 (300)	12.07 (1 750)	5.56 (0.339)	27	34	0.68 (14)	0.007 (7)	0.98 (20)
5	7:30	176.7 (350)	14.48 (2 100)	4.9 (0.299)	45	40	1.95/1.61 (40/33)	0.005 (5)	1.71 (35)

On 28 June, tests were initiated on a Baroid mixture with fresh water. The tests were terminated when it was discovered that the pressure transducers used to measure viscosity were generating faulty signals. Numerous tests with water and Baroid drilling mud indicated that two of the Validyne pressure transducers, or indicators, were indicating pressure differences that were in error by several orders of magnitude. The systems were calibrated several times, and it was noted that the calibration seemed to shift at high operating pressures (6.9 MPa [1000 psi]). It was also noted that the zero pressure differential would shift at high pressures. Subsequent analysis led to solving the problem by increasing the torque on the transducer head bolts to approximately 11.3 N·m (100 in.-lb) and by proper bleeding of the transducers prior to running the system.

At the end of the reporting period, a successful run was made on Baroid mud, 858 kg/m³ (8.6 lb/gal). The results are illustrated in Figure 29. The mud ran for almost 10.5 hours and reached a temperature of 254°C (490°F) before it plugged the flow lines. Prior to plugging, the pH dropped rapidly, and caustic soda could not be added fast enough to keep the pH constant.

Since the equipment problems appeared to have been overcome, a decision was made to extend the contract until the end of December 1979 to permit the completion of the scheduled mud-mixture tests. The composition of the mud mixtures are shown in Table 11.

Figure 29. Results of Flow Loop Test on Baroid Mud

Table 11

Mud Mixture Compositions

<u>Mud Mixture</u>	<u>Chemical Composition</u>	<u>Supplier</u>
IMCO	15 ppb Durotherm	IMCO
Driltherm	5 ppb bentonite	
	25 ppb Driltherm	
	0.5 ppb caustic soda	
Magcobar	12-15 ppb Geo-Gel	Magcobar
Geo-Gel	3-5 ppb Magcogel	
	1-5 ppb Resinex	
	1-3 ppb Cypan	
	1-2 ppb caustic soda	
Mudtech	15 ppb sepiolite	Mudtech and Baroid
	5 ppb bentonite	
	20 ppb brown coal	
	2.5 ppb Cypan	
Baroid	10 ppb bentonite	Baroid
	10 ppb sepiolite	
	25 ppb lignite	
	0.5 ppb caustic soda	
Milchem	15-20 ppb sepiolite	Milchem and Baroid
Mud	1 ppb caustic soda	
	1-5 ppb modified lignite	
	1-2 ppb sodium-polyacrylate	

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

Contractor: NL/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 — Work leading to the fabrication of the test instrument and the facility to house it continued throughout this reporting period. Efforts included designing systems, subsystems, and components; ordering and fabricating components; and testing component performance. Specific activities are discussed in the following paragraphs.

A preliminary design for a pit to house the pressure vessel and most of the other high-pressure equipment was completed and reviewed. In the unlikely event of a pressure vessel failure, the function of the pit is to contain any missiles and vent the high-pressure gas safely. Current design includes a pit which is 8 feet square and 15 feet deep, a reinforced, removable cover, and underground ducts for pressure relief. This approach was taken rather than that of designing the building to contain a pressure vessel failure. Arrangements are being made for Sandia to review the design. Review of architectural drawings for the rest of the building are expected to be completed during October 1979. Location of the building site has been tentatively selected in a new NL/Baroid Petroleum Services complex now being designed. However, this new facility may not be completed in time to permit completion of this project on the contract schedule. The issue had not been resolved at the end of this reporting period.

National Forge Co. was selected as supplier of the pressure vessel. Detailed design of the vessel continued during this reporting period to include the vessel's internal cooling system which was an add-on proposal by National Forge. A forging has been scheduled, and design work is continuing pending review and approval of the contract by the DOE contracting officer. This approval is required since the vessel cost will exceed \$10,000.

Three tests of the prototype filter were performed. Tests were run at 176.7°C (350°F) and 3.5 MPa (500 psi) for 90 minutes. Although total amounts of filtrate collected were similar, the amounts of spurt-loss filtrate varied. Also, the filtration rate at the end of the first test was increasing while the ending filtration rates for the second and third tests were decreasing. Leakage of the slurry under the edges of the filter medium was not apparent. The lack of reproducibility in the bentonite filtration tests using the prototype filter was attributed to varied settling conditions in the vertical test chamber. Horizontal tests of the filter medium were reproducible. Uniform mixing of the drilling fluid is incorporated into the full-scale instrument. A decision was made to complete development of the full-scale filter rather than spend time on further prototype development and modification.

Major elements of the high-pressure argon supply system have been designed. The pump to supply 41.4 MPa (6000 psi) of liquid argon to a vaporizer has been received, together with a safety control system. The detailed design for the argon supply system remains to be done.

The corrosivity instrument electronics have been selected, but a commercially available corrosion sensor probe capable of withstanding maximum pressure and temperature requirements could not be identified. A new probe has been designed, but the insulation coating technique, spray coating with ceramic insulation, must be tried and tested. This activity is planned for October 1979.

Three weight transducers, two for filtrate weighing and one for the densitometer, have been ordered, along with a differential pressure transducer. These transducers will be vented and should be capable of operating at 138 MPa (20 000 psi). Verification tests are planned. Design changes

put the torque transducer behind schedule, but it is ready now for fabrication. Ordering is under way for some of the bearings, gears, fasteners, and other standard small parts for the instrument, which was designed for the inside of the pressure vessel.

A microcomputer development system (MDS) and a terminal have been purchased, and the development of software for controlling the system operation and for storing data is in progress. Certain available software is being modified for use. A multitask operating system (MTOS) was chosen for its real-time flexibility at a sacrifice of some sophistication which is available in a disc operating system. The MTOS has been partially proof tested. Software for the MTOS has been debugged and tested with the analog/digital signal conversion board and input/output board. Individual stepper motor control systems will be tested when they arrive, and task software programming will begin in October 1979. Development of the microcomputer software to control and monitor data from the instrument is running about 6 weeks behind schedule because of a lack of manpower; however, this delay is not expected to prolong the overall project.

5.2.3 Drilling Mud Chemistry

Contractor: Texas Tech University
Principal Investigator: N. Güven

Project Objective -- This project will result in a fundamental understanding of clay particle interactions under the influence both of various chemical species and elevated temperatures similar to the conditions encountered during geothermal drilling activities. On the basis of this understanding, clay-based, geothermal drilling-fluid systems, complete with the additives dictated by downhole conditions, will be designed for use in geothermal drilling.

Status and Results -- The project was initiated in the latter part of this reporting period. Hydrothermal studies on the stability of attapulgite were conducted. X-ray diffraction was used initially to determine the extent of the attapulgite-to-smectite conversion under hydrothermal conditions. Since X-ray diffraction does not provide morphological information, electron microscopy was used to determine the morphology of the smectite formed and to gain information on the conversion mechanism.

The attapulgite used was the commercially available material known by the trade name "Floridan attapulgite 150" from Georgia/Florida deposits. X-ray diffraction analysis shows that the material contains about 20 to 30% smectite in addition to attapulgite. Feldspars, quartz, and small quantities of illite ore are the impurities found in the material sample. During the hydrothermal treatments in the temperature range of 149° to 315°C (300° to 600°F), these impurities do not seem to be affected. The main phase changes occurring in these reactions involve attapulgite and smectite. The following discussion is therefore related to the properties and relative amounts of attapulgite versus smectite in the drilling fluids after various treatments.

The results of the hydrothermal runs are summarized in Table 12 for the pure attapulgite, attapulgite/NaCl, attapulgite/CaCl₂, and attapulgite/KCl systems. The results show that considerable amounts of attapulgite transform to a smectite during the runs at 204° and 260°C (400° and 500°F). The conversion seems to be fully completed at 316°C (600°F) in the attapulgite/NaCl, attapulgite/CaCl₂, and attapulgite/KCl systems. At moderate temperatures, 204° and 260°C (400° and 500°F), the salts added to the systems affect differently the conversion of attapulgite to smectite. CaCl₂ seems to promote the conversion more than the chlorides of potassium and sodium.

Electron microscopy studies of the smectite products formed during hydrothermal treatment of attapulgite/salt systems were in progress at the end of the reporting period. The results thus far show that, although the attapulgite to smectite transformation begins before 204°C (400°F), the morphological changes become apparent only at temperatures greater than 260°C (500°F). For the attapulgite/KCl system, these changes progress from fibrous attapulgite at <260°C (500°F) to lamellar smectite at 260°C (500°F) to fluffy smectite at 316°C (600°F) to pronounced lamellar morphology at 371°C (700°F).

Attapulgite particles occur as fibers or as bundles of fibers in the original sample as seen in Figure 30. A fluffy smectite aggregate and an illite (mica) platelet are also seen in the figure. These fluffy smectites make up about 20 to 25% of the sample. Although attapulgite transforms to a smectite at 204°C (400°F), the morphological changes of this transition became apparent after the runs at 260°C (500°F). Figure 31 displays the transition of fibrous attapulgite to lamellar smectite in the attapulgite/KCl system at 260°C (500°F). At 316°C (600°F), attapulgite seems to convert entirely to a fluffy smectite. Figure 32 shows such a smectite in the attapulgite/KCl system. At 371°C (700°F), smectite tends to develop more pronounced lamellar morphology, as seen in Figure 33.

Figures 34 and 35 display typical smectites formed in the attapulgite/NaCl system during the runs at 316°C (600°F) and 371°C (700°F), respectively.

Table 12

**Initial Compositions of the Attapulгите-Based Drilling
Fluids and the Major Phases after the Hydrothermal Treatments**

Run No.	Added to 4% Attapulгите in Distilled Water	Hydrothermal Conditions °C (°F)	Run Time (hours)	X-Ray Data on the Major Phases Before and After the Hydrothermal Reactions			
				Attapulгите d(Å) Intensity*		Smectite d(Å) Intensity*	
1	Attapulгите (starting material)	No Treatment		10.5	100	1.60	60
2a	No additive	149 (300)	24	10.5	100	15.8	63
2b	No additive	204 (400)	24	10.5	90	15.8	100
2c	No additive	260 (500)	24	10.5	23	19.6	100
2d	No additive	371 (700)	16			15.3	100
3a	1% NaCl	149 (300)	24	10.6	100	15.9	34
3b	1% NaCl	204 (400)	24	10.5	74	15.5	100
3c	1% NaCl	260 (500)	24	10.5	28	15.4	100
3d	1% NaCl	316 (600)	16			15.3	100
4a	1% CaCl ₂	204 (400)	24	10.6	100	12.6	15
4b	1% CaCl ₂	260 (500)	24	10.5	3	15.3	100
5a	1% KCl	204 (400)	24	10.6	100	13.0	21
5b	1% KCl	260 (500)	24	10.6	63	12.6	100
5c	1% KCl	316 (600)	16	--	--	14.7	100

*Intensity of the strongest reflection on the pattern is assumed to be 100, and the intensity of the other phase is normalized accordingly.

Figure 30. Attapulgite Fibers and Their Aggregates in the Original Sample. A fluffy smectite aggregate and a mica (illite) lamellar are also seen. Smectites make up about 20% of the sample. Mag: 13 000X

Figure 31. Transition of Attapulgite Fibers into Lamellar (Flaky) Smectite During Hydrothermal Treatment at 260°C (500°F) in the Presence of KCl. Mag: 13 000X

Figure 32. Typical Smectite Particles Formed in the Attapulgite/KCl System During Hydrothermal Treatments at 316°C (600°F).
Mag: 13 000X

Figure 33. Smectite Particles Formed in the Attapulgite/KCl System During Hydrothermal Treatments at 371°C (700°F).
Mag: 13 000X

Figure 34. Typical Flaky Smectites Formed in the Attapulgitc/NaCl System During Hydrothermal Treatments at 316°C (600°F). Mag: 36 000X

Figure 35. Typical Smectite Particles Formed in the Attapulgitc/NaCl System During Hydrothermal Treatments at 371°C (700°F). Mag: 26 000X

5.3 Completion Technology

During this reporting period, effort was directed toward expanding the information base on completion technology and investigating associated problem areas. A casing/liner design and cementing technology study was completed and the injectivity problems of an operating well analyzed. A new laboratory activity to determine formation damage by drilling mud was initiated. Tests of two drilling mud systems were completed. Work was continued on the development of a controlled cavitation technique and of hardware for downhole geothermal well cleaning and scale removal. A new project was begun to provide temperature histories for geothermal well casing design and to investigate the lost circulation problem in geothermal environments.

5.3.1 Completion Technology Consultation

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

Project Objective -- The project objective is to provide consulting services and assistance to the geothermal drilling and completion technology effort in the formulation and implementation of the long-range DOE/Sandia Geothermal Well Technology Development Program. Specific objectives of the project include (1) assistance in the definition and review of current completion technology programs, (2) evaluation of field millipore 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 -- Completion Technology Company (CTC) assisted in a Sandia review of completion projects within the Geothermal Drilling and Completion Technology Program to

1. Establish priorities for tasks listed on the program network planning chart, relative to well-completion activities,
2. Interpret and update certain listed tasks, and
3. Suggest organizations that may be able to assist Sandia in accomplishing listed tasks.

Evaluation of Injectivity Tests -- The previous semi-annual report contained a summary of an engineering study which included suggested test methods to evaluate long-term injectivity of Magma's spent-brine reinjection wells in the Niland known geothermal resource area. Early in this reporting period, Magma submitted injection well performance data on Well IW-5 and requested that Completion Technology Company interpret these data.

The series of flow-rate/wellhead pressure pairs submitted by Magma were analyzed. These data indicated that the permeability height (kh) of the well is about 40 000 mD/ft, or about 10% of the expected kh. This

suggested that an impairment exists in the immediate vicinity of the borehole.

Higher apparent-kh values were obtained in the test when fracture pressures were reached or exceeded. Because fresh water was used in the test, there is no reason to believe that potable ground waters were contaminated by fracturing. Further, it is most likely that the fracture orientation was horizontal; Hubbert and Willis' methods were used to reach this conclusion (Mechanics of Hydraulic Fracturing, SPE-T.P. 4597, October 1956). This further reduces any probability of the injected water reaching the ground waters.

One possible reason for the low kh is the liner configuration. The liner set opposite a 122-metre (400-foot) alternating sand and shale section has 3.175-mm (0.125-inch) wide, parallel side slots which are 63.5 mm (2.5 inches) long; there are 32 slots per foot. Core descriptions provided by Magma show the presence of loose and weakly cemented sands in parts of the sand/shale section. It is not uncommon for wells completed in the fashion described to be impaired by unrestrained sand flow and slot blocking.

One method of improving the injectivity of this well is to test for frac healing in a second injection test, followed by pulling the liner, under-reaming or acidizing to clean the wellbore, and recompleting the well with a gravel pack and a wire-wrapped liner. If frac healing does not occur, the fractured interval will require scabbing, after which the remaining interval can be recompleted using a gravel pack.

Casing/Liner Design Study -- Studies of the state of the art of casing/liner design and cementing technology were completed and draft reports prepared. Part 1 of the report is concerned with failure modes and cementing limitations. The study discusses potential problems with geothermal casing during and after installation, emphasizing the weaknesses and limitations of the state of the art of cementing. The report is an interpretation and compilation of both common and relatively unknown failure mechanisms that should be considered in design and installation of casing strings. Part 2 of the report discusses basic casing design considerations such as tension, burst, collapse, and buckling. Use of American Petroleum Institute specifications and guidelines and other manufacturer data are outlined in the study. Equations for calculating loading and applying design factors are also presented. A sample casing design problem for a deep, geopressured/geothermal well is presented to illustrate concepts for designing surface casing, intermediate strings, tieback casing, and liners. Thermal considerations for geothermal well design are also included.

The report was nearing publication at the close of this reporting period. Papers based on the report were presented at the Annual Meeting of the Society of Petroleum Engineers (SPE) and at the GRC meeting held in late September 1979. An article based on the SPE paper will appear in World Oil magazine in October 1979. In addition, a third technical paper combining the SPE and GRC papers has been prepared for presentation at the American Society of Mechanical Engineers conference in February 1980.

Cement-Inflatable Packers -- CTC met and reviewed with Los Alamos Scientific Laboratory (LASL) personnel application objectives of cement-inflatable packers in the HDR geothermal program. Preliminary designs for various cement-inflatable packer alternatives were further developed in the meeting. CTC assisted with the preparations for the recompletion of Fenton Hill Geothermal Test Well EE-1. CTC's proposed program for using cement-filled inflatable packers to isolate open hole sections for controlled hydraulic fracturing and selective testing was presented to the LASL committee. Subsequently, a worksheet and a schematic drawing were provided for installing two cement-inflatable packers, Otis seal bores, and a Brown Oil Tool hanger on a 14-cm (5-1/2-inch) liner suspended in a 25-cm (10-inch) open hole below a 19.4-cm (7-5/8-inch) cemented casing. CTC also coordinated acquisition of this special equipment and other required equipment and services. A separate contract between LASL and CTC was executed for further work involving the installation activities.

5.3.2 Geothermal Formation Damage

Contractor: Terra Tek, Inc.
Principal Investigator: D. Enniss

Project Objective -- The objective of this project is to determine drilling mud formation invasion effects upon permeability as a function of (1) varying stagnation times, mud types, and temperature and (2) backflow duration.

Status and Results -- The project was initiated during this reporting period. Procedures were defined for handling and testing samples for simulated formation damage testing, and, using the test system shown in Figure 36, debugging tests were performed to refine and document these procedures. These tests were performed at temperature and pressure upon outcrop sandstone samples. Bentonite mud systems were formulated in the Terra Tek Drilling Research Laboratory for this testing. The system performed as expected in all tests, including extended duration testing.

"Stagnation time effects" testing on the East Mesa reservoir material was conducted using two drilling mud systems. HTM-1*, formulated by Mudtech, Inc., (Maurer Engineering) Houston, Texas, and a KCl polymer** drilling-fluid system were evaluated for permeability impairment as a function of temperature and time. Testing was performed at temperature, confining pressure, and pore fluid pressure simulating the in situ geothermal environment of East Mesa. Post-test analysis included scanning electron microscope and X-ray diffraction examination.

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*Formula and mixing procedures were obtained from L. Remont, Mudtech, Inc., Houston, Texas.

**This KCl polymer formulation was used by Republic Geothermal in the Imperial Valley, California.

Figure 36. Mud Circulation System

Minor delays were encountered in obtaining samples of actual field mixtures of geothermal mud systems. These delays were directly attributable to the lack of active geothermal drilling (several wells are scheduled to be drilled later in the fall of 1979) and the lack of storage of any previously used mud system.

Data obtained were being evaluated, and a final report was being prepared at the close of this reporting period.

5.3.3 Cavitating-Jet Descaling Technique for Downhole Geothermal Well Cleaning

Contractor: Daedalean Associates, Inc. (DAI)
Principal Investigators: Dr. A. A. Hockrein, Jr.
Dr. A. P. Thiruvengadam

Project Objective -- The objective of this project is to develop and apply a controlled cavitation technique for downhole geothermal well cleaning and scale removal. Work in this program is expected to build on technology acquired under a previous DOE contract for the development of a cavitation descaling technique for pipes and tubes in geothermal power plants (EG-76-001-2289).

Status and Results -- The information gathered during field testing in the previous reporting period showed that the pressure required to begin removing scale was 41.4 MPa (6000 psi). Higher pressures would remove the scale more quickly. One of the goals of this program is to marry Daedalean cavitating nozzle technology with a coiled tubing unit as depicted in Figure 37. The tubing unit will be used as the delivery system into the well. The advantages of using this type of system are that the coiled tubing unit is extremely portable, is technologically proven, and has inherent cost advantages. The problem area with the coiled tubing unit is in the tubing itself. The pressure limitations on the tubing prevent it from being operated at pressures greater than 27.6 MPa (4000 psi). This pressure allows a safety factor of 2.5.

Representatives of the Nitrogen Oil Well Service Company were contacted and requested to provide several samples of each of the four sizes of high-pressure tubing that are used on their coiled tubing units. Attempts are being made to obtain samples of both new and used tubing in order to determine how severely the tubing burst rating is affected by the usage to which the tubing is subjected on the coiled tubing unit. This evaluation will aid in determining the feasibility of using the tubing at the elevated pressures necessary for the removal of the scale in a downwell situation.

Evaluations of several nozzles were conducted in the Daedalean Fluids Laboratory. These evaluations included the gathering of information on loss coefficient, optimum nozzle distance, jet velocity, and erosion intensity.

Specific design problems concerning nozzle operations in downwell environments were studied, and the effects of increased ambient pressure and temperature on nozzle performance were investigated.

Figure 37. Coiled Tubing Unit Schematic

A review of DAI nozzle performance data is in progress. This review will aid in the selection of the proper nozzle to be utilized in the down-well cleaning head. Important parameters being reviewed include

1. Maximum I_e (intensity of cavitation erosion),
2. Maximum effective nozzle distance at $I_{e \text{ max}}$ point,
3. Optimum C_v (nozzle loss coefficient), and
4. Flow requirements.

Investigations have begun on the effects of an increase in operating depth, up to 762 metres (2500 feet), on the intensity of erosion produced by the nozzle.

The cleaning head design process is underway. A four-nozzle cleaning head will be utilized. The cleaning head rotator is in the initial stages of design, and various hydraulic motor manufacturers are being contacted for product information on a drive motor that would be suitable for cavitation application. The cleaning head rotator is being designed to be compact enough to fit inside a 19.37-cm (7.625-inch) well casing. Enough clearance will be left so that the well flow will carry any scale removed by the cavitating jets past the cleaning head rotator and out of the well to the surface.

Preliminary planning was undertaken on the design of a deep-well simulation chamber. This chamber will simulate operating conditions in a well up to a depth of 3048 metres (10 000 feet). The chamber will be used in the nozzle design process and will be an invaluable tool, useful in the calibration process for all the nozzle designs.

A search was made for samples of various sizes of casing which have accumulated geothermal scale. Well casing samples were sought, with various degrees of scale accumulation from approximately 1.59 mm (0.06 inch) to an accumulation that completely closed the casing. The samples will be used to evaluate the effectiveness of the nozzles and cleaning heads which are under development. Several scaled pipe sections are being shipped to DAI from the East Mesa test facility of the DOE.

5.3.4 Temperature History and Lost Circulation Experience in Geothermal Wells

Contractor: Enertech Engineering and Research Co.
Principal Investigator: G. Wooley

Project Objective -- The objective of this project is to provide well-bore temperature histories required for geothermal well casing design and to provide a synopsis of causes of and control methods for lost circulation in geothermal environments.

Status and Results -- This project was initiated near the end of this reporting period. At the close of the period, an information survey format

and plan had been designed. Acquisition of data will begin in October 1979.

The study of geothermal well temperature histories will include the following tasks:

1. Establish typical undisturbed, in situ, temperature distributions using both literature data sources and direct contacts with geothermal operators.
2. Determine typical thermomechanical properties for various geothermal formations. Many of these data are available either in the literature or from service or production companies; however, any deficiency in the data base will be identified and evaluated for possible future research.
3. Establish the range of wellbore temperatures histories encountered during geothermal drilling and circulation, and employ the GEOTEMP code to determine casing and formation temperature histories for both typical and atypical conditions. These calculations will yield temperature fields existing at cement set time.
4. Discuss typical production and injection schedules with geothermal operators to determine flow variables. Employ the GEOTEMP code to determine typical casing and formation temperature histories for the production and injection phases of geothermal well operations.
5. Modify the output of GEOTEMP to be compatible with finite-element, thermal, stress analysis codes such as ADINA.

The study of lost circulation problems in geothermal well drilling will include the following tasks:

1. Assess the importance of the lost circulation problem in geothermal drilling and completion.
2. Provide a listing of lost circulation materials presently available and in general use by the drilling industry.
3. Provide an outline and assessment of general practices for preventing lost circulation from occurring and the methods most commonly used.
4. Make recommendations for new approaches which may be used in preventing lost circulation.
5. Compare findings representative of the geothermal industry to those of the petroleum industry to identify similarities of approach which may be useful in the geothermal industry.

5.4 Advanced Drilling Systems

Effort on the development of advanced drilling systems continued to concentrate on erosion and cavitation technology and the development of downhole motor bearings and seals during this reporting period. A full-scale bearing/seal package laboratory test facility was constructed, and tests of bearing/seal packages with commercially available downhole motors are expected to begin early in the next reporting period. The first phase of the development of a cavitation damage test standard for rock was completed. Work continued on the design of an erosion drilling under-reamer. Nozzle experiments were conducted at simulated downhole pressures and with polymer added to the jet fluid in an attempt to increase standoff distances. Field tests of the hybrid water-jet/roller-cone bit were nearing completion and exhibiting penetration rate improvements. The evaluation of Cavijet™ cavitating jets for deep-hole rock cutting was completed, and a new project was initiated to conduct a feasibility and preliminary design study of a downhole pressure-pulsing device for use with cavitating jets.

5.4.1 Improvement of Downhole Drilling Motor Bearings and Seals

Contractor: Terra Tek, Inc.
Principal Investigator: G. Tibbitts

Project Objective -- 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 will operate with a 6.9-MPa (1000-psi) pressure drop across the bit at a 121°C (250°F) circulation temperature.

Status and Results -- The project began in 1976 with funding from what is now DOE/DGE. Sandia picked up funding from April 1978 through October 1979 by additional contracts. Work on this program has been divided among four major efforts:

- The testing of many candidate lubricants and selection of one that will function successfully at 316°C (600°F).
- The testing of candidate seals in a machine designed to simulate the seal environment in the actual bearing/seal package.
- The design, construction, and debugging of a bearing/seal package that will be compatible with most downhole motors.
- The design and construction of a full-scale downhole motor test facility that can be used for laboratory tests of the bearing/seal package assembled to various downhole motors.

The status and results of each of these activities are described in the following paragraphs.

• Lubricant Testing and Evaluation

Testing and evaluation of candidate high-temperature lubricants for use in the bearing/seal package tests have been completed, and Pacer

PLX-014 was selected as the best candidate. The lubricants were ranked by measuring the width of the wear scar left on a block by a lubricated rotating wheel. As lubricant performance improves, the wear scar width decreases. After testing the candidate lubricants at 204°C (400°F), it was discovered that some of the graphite contained in the Pacer PLX-014 lubricant had settled out. Thus, the sample tested had not contained its full quantity of graphite. The lubricant was thoroughly mixed, and two more tests, Nos. 100 and 101, were run at 204°C (400°F). The wear scar widths were consistent with previous results. One test, No. 102, was run on the Pacer PLX-014 at 288°C (550°F), and two tests, Nos. 103 and 104, were run on the Pacer PLX-014 at 316°C (600°F). The Pacer PLX-014 performed as well at 316°C (600°F) as at 204°C (400°F). These results are shown in Table 13.

Table 13

Test Results of Pacer PLX-014 Lubricant

<u>Test Number</u>	<u>Average Wear Scar Width mm (inch)</u>	<u>Test Temperature °C (°F)</u>
100	1.78 (0.070)	204 (400)
101	2.21 (0.087)	204 (400)
102	1.73 (0.068)	288 (550)
103	1.09 (0.043)	316 (600)
104	1.04 (0.041)	316 (600)

Since Pacer PLX-014 was formulated for compatibility with Viton seal compounds, this requirement prevented the use of certain extreme pressure (EP) lubricant additives. Since no Viton seals will be in contact with the lubricant in the bearing/seal package, the PLX-014 lubricant will be revised to include these EP additives and will be tested as soon as the new formulation is received.

• Seal Testing

This reporting period was devoted primarily to assessing test results and refurbishing the seal test machine. Two tests, DMT-027 and DMT-028, were performed, with the test machine reconditioning being done after the first test. The modification primarily involved the installation of tapered roller bearings at the top and the bottom of the main shaft. The bearings will reduce inadvertent radial runout and axial motion and will simplify the introduction of controlled runout in future tests. After installation of new seals, thermocouples, and oil lines, the seal tester was reassembled, pressure tested, and calibrated for the continuation of the test program.

The assessment of the results was based on the first 28 tests, the last 10 of which are shown in Table 14, and these general conclusions were drawn:

1. The elastomeric seals that have been tested, or variations on their basic design, will never reach the goal of a 200-hour life.
2. Non-elastomer seals have inherent lubricating qualities and are not as damaging to the surface finish of the rotating shaft as the elastomer seals tested. The non-elastomer seals can operate without the introduction of external lubricants, and therefore can operate on a highly polished shaft, generating less torque and heat, wearing less, and exhibiting longer life.
3. The life of non-elastomer seals is increased with improved shaft surface finish.
4. The non-elastomer seals tested have been made primarily from graphite or graphite-like material which migrates out of the seal cavity as it is worn from the seal surface by the rotating shaft. If the rate of migration is constant, then the seal life is improved by increasing the amount of material in the seal cavity.
5. Reducing the clearance between backup system and rotating shaft essentially to zero increases the life of non-elastomer seals.

The majority of recent tests have been conducted with the non-elastomer seals using the graphite/metal matrix or the Grafoil®-BeCu packs. The graphite/metal-matrix design is shown in Figure 38. These seals are formed from powdered graphite which is cold pressed into a woven metal core in a chevron-shaped cross section. The adhesive binder in the assembly is heat cured, producing a relatively hard and brittle seal. Each generation (I, II, III) has used a different binder with the graphite.

The Grafoil® is a graphite-like material manufactured by Union Carbide. The Grafoil®-BeCu seal is formed by sandwiching a preformed 0.127-mm (0.005-inch) thick, chevron-shaped ring of beryllium-copper between two layers of Grafoil®. A diagram of the seal is shown in Figure 39. The Grafoil® is soft and slippery to the touch because it is nearly pure graphite. The material exhibits little resilience or recovery, so the beryllium-copper rings were added to provide some resilience. The rings have perforations in them to achieve better bonding with the Grafoil®.

Backup Systems. Tests with these seals have aimed at improving the backup system by reducing their diametral clearances around the shaft to zero. Early in the testing, a conventional aluminum-bronze backup ring machined to a very close fit (0.025 mm [0.001 inch]) was tried, but the seal cavity constraint on the ring outer diameter caused the thermal expansion to close the ring on the shaft, stopping rotation.

Three other zero clearance backup systems have been designed; two have been tested, and the third will be tried on upcoming tests.

The first new backup system consists of an SAE 660 bearing-bronze ring and an O-ring, as shown in Figure 40. The lip on the inside diameter of the bronze ring is undercut to minimize contact area with the rotating

Table 14
Completed Tests

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	ΔP^* MPa (psi)	RPM	Duration (hours)	Chrome Shaft Coating Finish (rms) μm ($\mu\text{in.}$)	Diametral Clearance: Shaft to Backup Rings mm. (in.)
019	I. Graphite/metal matrix	3	Aluminum bronze	10.3 (1 500)	412	4.55	0.41 (16)	0.254 (0.010) + o.d. & i.d.
020	I. Graphite/metal matrix	1-top 2-bottom	Aluminum bronze	10.3 (1 500)	412	13.05	0.33 (13)	0.254 (0.010) + o.d. & i.d.
021	Grafoil®-BeCu	3	Aluminum bronze	10.3 (1 500)	412	5.90	0.43 to 0.46 (17 to 18)	0.051 (0.002)
022	J-M Uneepac®	3	Aluminum bronze	10.3 (1 500)	412	10.62	0.43 to 0.46 (17 to 18)	0.076 (0.003)
023	J-M Uneepac®	3	Aluminum bronze	10.3 (1 500)	412	26.55	0.43 (17)	0.381 (0.015)
024	Grafoil®-BeCu	3	Phosphor bronze	10.3 (1 500)	412	40.9	0.10 (4)	0.025 (0.001)
025	II. 171 graphite/metal matrix	3	Teflon & phosphor bronze	10.3 (1 500)	412	2.03	0.10 to 0.20 (4 to 8)	0.025 (0.001)
026	II. 171 graphite/metal matrix	3	Teflon & phosphor bronze	10.3 (1 500)	412	1.98	0.10 to 0.20 (4 to 8)	0.025 (0.001)
027	III. 194 graphite/metal matrix	3	Phosphor bronze	10.3 (1 500)	412	23.5	0.10 to 0.20 (4 to 8)	0.025 (0.001)
028	II. Grafoil®-brass	3	SAE 660 bronze	10.3 (1 500)	412	6.0	0.10 (4)	0.025 (0.001)

* ΔP = pressure differential applied to seal

shaft and to introduce a weak area into the ring that will allow the backup ring lip to flex under pressure. This flexibility effectively reduces to zero the clearance between backup ring and rotating shaft. This backup system has the capability to compensate for wear, and it can successfully use an O-ring because the pin prevents any rubbing between the O-ring and backup ring.

Figure 38. Graphite/Metal-Matrix Seal Pack Cross Section Detail

The position and depth of the undercut in the backup ring can be optimized for contact area, wear compensation, and operating pressure. These parameters will be changed as this backup system increases the life of the non-elastomer seal types.

By custom machining the backup ring lips to fit each shaft sleeve within a 0.025-mm (0.001-inch) clearance on the diameter, the loss of seal material has been reduced; consequently, the endurance of non-elastomer seals has been significantly improved. The longest lived Grafoil®-BeCu seal, with more than double the life of the next longest test of this seal type, and the longest lived graphite/metal-matrix seal, with an increased life of 55% over the next longest test of this seal type, were both backed up with the SAE 660 bearing-bronze ring with the flexing lip.

The second new backup system consists of a TFE ring and an SAE 660 bronze ring, as illustrated in Figure 41. The TFE ring is soft and will

flex under pressure, forcing the bronze ring to zero clearance with the rotating shaft. This is another "pressure-to-close" backup system with material to compensate for wear.

Figure 39. Cross Section of Grafoil®-BeCu Seal Pack

Tests have demonstrated that the TFE and bronze backup system does not improve the life of non-elastomer seals. The wear modes observed indicate that short seal life is typical of this backup ring system.

An analytical study performed by D. Dareing, Maurer Engineering, has resulted in the third backup ring design (Figure 42). The backup leaves

are designed so that there will be approximately 0.127 mm (0.005 inch) theoretical interference with the shaft when the seals are subjected to 10.3 MPa (1500 psi) differential pressure. Phosphor-bronze leaves ranging from 0.397 to 0.794 mm (0.016 to 0.031 inch) thick will produce the desired interference fit. Leaves of 0.397 and of 0.794 mm (0.016 and 0.031 inch) will be used as seal backup ring systems in selected follow-on tests.

Figure 40. Cross Section of SAE 660 Bronze/O-Ring Backup Ring

Test DMT-027, completed on the graphite/metal matrix-type seals, resulted in a seal life of 23.5 hours. The seal pack used an improved binder agent, type III, and the flexing lip backup ring system. Although removing and replacing the seal several times during the course of the test may have shortened its life, this is the longest test on this type seal. The graphite/metal-matrix seals leaked and failed gradually during the second half of the test. The torque during the test was higher than the torque generated by the Grafoil® seals under similar conditions.

The last test completed on the Grafoil®-type seals, and the last test completed in this reporting period, was DMT-028, with a total run time of approximately 3 hours. The seal was a Grafoil®-brass type, which was tested for the first time, with a flexing lip backup; the seal was tested under the same conditions as DMT-024, which ran for 40.9 hours. This seal

Figure 41. Cross Section of Teflon/SAE 660 Bronze Backup Ring

Figure 42. Cross Section of Third New Backup System Design

differed from previous Grafoil®-BeCu seals in that the 0.127-mm (0.005-inch) beryllium-copper preformed ring was replaced with a 7.62-mm (0.30-inch) preformed ring of yellow brass. The test was performed under normal conditions; however, the shaft was removed and reinstalled approximately 12 times to make repairs, and this may have damaged the seal.

Seal Fabrication. An important discovery about the makeup and fabrication process of the Grafoil® seals was made while closely examining the failed seals and their construction. The Grafoil®-BeCu and Grafoil®-brass seals, as supplied, are manufactured according to recommended practices. The Grafoil® is supplied to the seal manufacturer as a thin ribbon which is wrapped on a mandrel and then cold pressed to the chevron cross section as illustrated in Figure 43.

Figure 43. Grafoil® Seal Fabrication

If the seals continue to be made from the ribbon form of Grafoil®, a new forming process should be considered because the present seals have many paths for leakage. Two solutions are apparent. One would be to layer the ribbon perpendicular to the axis of rotation before forming. The other solution would be to use another form of the Grafoil®, a form made in square-cross-section rings laminated with the ribbon but with the plane of the laminations perpendicular to the axis of rotation.

An interesting characteristic of Grafoil® in the ribbon form is the difference in thermal conductivity, K , with direction (Figure 44). This leads to a secondary problem of heat conduction. During testing, it was believed that an advantage of the Grafoil® material was its high thermal conductivity. With the ribbon layered as it is, heat transfer is primarily axial, whereas radial heat transfer would give better seal cooling. This may not be of great importance in existing seals, but if Grafoil® rings are used with elastomer rings in a hybrid seal, a change in laminate orientation could be significant. Inquiries into new methods of fabricating Grafoil® seals were initiated near the end of the reporting period.

Seal Geometry and Shaft Finish. The effects of the number of seal rings and of shaft surface finish on seal life were evaluated during this reporting period. Elastomer seals were tested on shafts of 0.31 to 0.41 μm (12 to 16 $\mu\text{in.}$) rms finish as recommended by the manufacturer, and non-elastomer seals were tested on shafts of 0.10 to 0.20 μm (4 to 8 $\mu\text{in.}$) rms finish, with some exceptions. Between tests DMT-019 and DMT-020, the surface finish was improved from 0.41 to 0.33 μm (16 to 13 $\mu\text{in.}$) rms. The number of graphite/metal-matrix pressure rings was decreased from 3 to 1, but the seal life increased by nearly a factor of three. Of the two parameters that were changed between DMT-019 and DMT-020, that is, the shaft surface finish and number of pressure rings, it is believed the greater effect on the seal life was due to the improved shaft finish, because reducing the amount of seal material should reduce the life of the seal. Further tests may reveal an optimum finish, but for current tests, the surface finish will be 0.10 μm (4 $\mu\text{in.}$) rms for all shafts.

Figure 44. Grafoil® Ribbon Thermal Conductivity

As stated above, it is believed that decreasing the number of seals or the amount of sealing material has a negative effect on the life of non-elastomer seals. Conversely, it appears that, with elastomer seals, one pressure ring will perform longer than three pressure rings under the same conditions. In a seal pack of more than one ring, the first ring does all the sealing initially. This pressure on the first ring is transmitted to the rest of the rings, loading them and creating radial forces on the shaft due to the Poisson effect. Consequently, the torque is higher, and the pressure rings not sealing any fluid are heated, worn, and destroyed first.

Both the Grafoil® and graphite seals deteriorated when in contact with heated lubricant. The Grafoil® tended to come apart in small flakes. In the graphite seals, the heat weakened the adhesive binder, resulting in the release of graphite powder. Both the Grafoil® flakes and graphite powder migrated to the low-pressure side of the seal pack. It appears that the life of the Grafoil® and graphite seals increases with the number of seals in a pack or the amount of carbon material in the seal cavity. Thus, the cross-sectional shape of the non-elastomer seal may not be as critical as it is for elastomer seals.

Canted and Hybrid Seals. The elastomer canted-seal concept has been fabricated into a 12.7-mm (0.5-inch) wide seal pack as detailed in Figure 45 and will be tested in the current test series. The seal pack contains two pressure rings. The pressure rings have been compounded in Buna-N with cotton duck reinforcing and in lubricated Buna-N with cotton and nylon reinforcing. The canted seal eliminates the sliding line contact of the pressure ring on the shaft, thus reducing the damage to the shaft finish.

Figure 45. Cross Section of Canted Seal Pack

The hybrid-seal concept, a combination of elastomer and non-elastomer materials, will also be included in future tests. A hybrid seal offers the possibilities of increasing the life of elastomer seals and extending the upper temperature limits of the elastomer. The pressure rings could be of any of the higher temperature elastomeric compounds alternated with rings of solid Grafoil® material. This seal concept for the Johns-Manville seals, used as working seals in the seal test vessel, proved a successful solution for extending seal life.

Redundant Seals. A large number of conceptual designs for redundant seals were screened, and two were selected for detailed design. The drawings for these seals were being finalized at the close of the reporting period.

The first candidate redundant seal, illustrated in Figure 46, contains a check valve which remains open until leakage past the primary seal exceeds a critical rate. When this happens, the check valve closes, allowing the high-pressure fluid to pressurize and activate the spare seal. This spare or redundant seal undergoes no wear until it is activated because it is not subjected to differential pressure prior to that time.

Figure 46. Redundant Drilling-Motor Seal

The second redundant-seal design utilizes a holder supported by a shear pin as shown in Figure 47. With low leakage rates, only a low pressure drop is generated by the fluid leaking through the small port in the holder. As the leakage rate increases, the pressure drop increases until the hydraulic force on the holder exceeds the strength of the shear pin, allowing the holder to move downward. When the holder reaches the bottom of the chamber, the seal ring closes the port in the holder, allowing the pressure to activate the spare seal contained in the holder.

Figure 47. Redundant Drilling-Motor Seal

• Bearing/Seal Package

Two major modifications were made to the original bearing/seal package (Figure 48). The bearing/seal package initially contained wire mesh springs to support the thrust bearings against bit loads generated by the bit. In related tests, it was discovered that wire fragments can break loose from the wire mesh springs, fall in the thrust bearings, and lead to catastrophic bearing failure. Hence, the wire mesh springs in the bearing/seal package were replaced with Belleville Springs as shown in Figure 49.

Figure 48. Bearing/Seal Package

The second major change in the bearing/seal package design was aimed at reducing the high temperatures generated by the rotary seals. As initially designed, heat generated by the seals had to be dissipated radially through the motor housing and through the rotating shaft.

A heat-flow analysis by D. Dareing of Maurer Engineering showed that temperatures in excess of 1038°C (1900°F) could be generated at the seal/shaft interface by Buna-N seals. This temperature corresponds to a 10.3-MPa (1500-psi) drop across the seal and a rotary speed of 212 rpm; the temperatures generated would lead to rapid failure of the seal since Buna-N rubber has a temperature limitation of 177°C (350°F). These high temperatures are generated because the low thermal conductivity of rubber limits heat flow through the seal to the outer housing. The operating temperature of Grafoil® seals is much lower than the operating temperature of Buna-N seals (319°C [607°F] versus 1066°C [1950°F]) because the higher thermal conductivity of Grafoil® allows much of the heat to escape through the seal to the outer housing and because the sliding friction is lower with Grafoil® seals.

The temperature of the seals can be lowered significantly by reducing the thickness of the shaft so that drilling fluid can flow next to the sleeve and remove some of the heat generated by the seals. The shaft

Figure 49. Bearing/Seal Package Utilizing Belleville Springs

cut-out modification is shown in Figure 50. Note that a constriction has been placed in the shaft's inside diameter; this creates a small pressure drop to force fluid to flow through the cooling passage. By redirecting the drilling fluid flow, the temperature of the Buna-N seal would be reduced from 1066°C (1950°F) to 188°C (370°F), and the temperature of the Grafoil® seal would be reduced from 319°C (607°F) to 161°C (321°F). Changes in the shaft thickness have less effect on the Grafoil® seal temperature than on the Buna-N seal temperature because more heat flows through the Grafoil® to the housing.

Figure 50. Redesigned Bearing/Seal Package

Six motor manufacturers were contacted for information on shaft runouts in existing motors and to obtain drawings required to design interface parts to adapt the bearing/seal package to the motors. On the basis of replies received, drawings for the interconnecting parts between the bearing/seal package and two motors, Dyna-Drill and Eastman Whipstock, were prepared. The drawings were released for quotations at the close of this reporting period, after review and approval by the motor manufacturers.

• Bearing/Seal Package Test Facility

The Bearing/Seal Package Test Facility has been constructed to test and evaluate the performance of the package in the laboratory under simulated downhole conditions. The test facility allows controlled and repeated tests of the bearing/seal package at simulated pressures, temperatures, rotational speeds, mud circulation, and dynamic loads. The

facility is completely instrumented to measure and record load, torque, rpm, mud inlet and outlet pressures, hot water system pressure, hot water system temperature, and bearing/seal package temperatures. The bearing/seal package is completely instrumented with thermocouples to measure bearing and seal temperatures. The bearing/seal package is also instrumented with lubricant extraction ports. Tubes run from the ports through the upper closure to the lubricant extraction bench. This system allows the sampling of lubricants during running to test for metal particles that indicate bearing wear and possible bearing failure.

The main component of the test facility is a pressure vessel composed of a tube 30.5 cm (12 inches) inner diameter (i.d.) by 40.6 cm (16 inches) outer diameter (o.d.) by 4.9 metres (16 feet) long. Closures are attached to both ends of the tube by means of Grayloc clamps and seal rings.

The dynamic actuator, which provides the axial load on the bearing/seal package, is attached to the upper closure. The actuator shaft extends through the upper closure and is assembled to the string of the cross-over sub, bearing/seal package, nozzle sub, fluid return sub, and fluid impact sub. The fluid impact sub is attached to the lower thrust-bearing assembly, which reacts to the loading of the bearing/seal package. The hot water jacket is placed around the bearing/seal package and is attached to the upper closure. The hot water jacket has an outside diameter of 29.2 cm (11.5 inches) and is 213 cm (84 inches) long.

After assembly, the test string is lowered into the pressure vessel tube, the upper closure is clamped to the tube by the Grayloc clamp, the mud inlet and outlet piping are connected to the ports on the upper end, the hydraulic supply and return lines are connected to the dynamic actuator, and the pressure transducers and thermocouples are connected to the electronic control console.

At the lower end of the pressure vessel tube, the lower closure is attached to the vessel by a Grayloc clamp. The lower cap, the motor hanger, and the hydraulic drive motor are assembled to the lower closure. The hydraulic drive motor is coupled to a splined shaft which engages the bottom of the lower thrust-bearing assembly and rotates the bearing/seal package. The complete assembly is shown in Figure 51.

During the first part of this reporting period, debugging activities were completed and operational checks were made at the Bearing/Seal Package Test Facility. The first five tests will check the function of all systems in the test facility and study the response of the bearing/seal package to various thermal inputs. Table 15 shows the test parameters for each test.

Test BSP-01 was completed during this reporting period. The test ran for 2 hours. A 227-kg (500-pound) constant load was placed on the bearing/seal package by the dynamic actuator. The bearing/seal package was rotated at an average of 25 rpm with peaks to 40 rpm. Water was pumped through the bearing/seal package at a flow rate of $63 \times 10^{-3} \text{ m}^3/\text{s}$ (10 gpm). The nozzle sub contained one 6.35-mm (0.25-inch) diameter nozzle. The pressure at the test facility inlet port was 0.57 MPa (82 psi), and the pressure at the

Figure 51. Bearing/Seal Package Test Facility

Table 15

**Bearing/Seal Package
Test Matrix**

Constant Conditions**A. Bearing/seal package**

1. Bearing types: Torrington No. 40 TP114 (thrust)
Torrington No. HJ 881240 (radial)
2. Shaft surface: Chrome-plated AISI 4340 steel
3. Shaft finish: 0.10 μm (4 $\mu\text{in.}$) rms
4. Lubricant: Texaco EP 85-90 (BSP-01)
Pacer PLX-014 (BSP-02 to BSP-05)
5. RPM: 250 (except BSP-02)

B. Mud system

1. Mud flow: 0.003 m^3/s (40 gpm) (BSP-03 to BSP-05)
2. Pressure drop: 5.2 MPa (750 psi) (BSP-03 to BSP-05)
3. Mud properties: 948 kg/m^3 (9.5 lb/gal) water base

**C. Dynamic actuator
loading:**

Constant -- 44.5 kN (10 000 lb)

Variable Conditions

<u>Test No.</u>	<u>Test Seal</u>	<u>Duration (hours)</u>	<u>Temperature °C (°F)</u>	<u>Soak Time (hours)</u>	<u>Soak Temperature °C (°F)</u>
BSP-01	Uneepac® Style 405	2 to 8	93.3 (200)	None	None
BSP-02	Grafoil®	8	93.3 to 260 (200 to 500)	30 min per each 14°C (25°F) increment	121.1 (250) in 14°C (25°F) increments
BSP-03	Grafoil®	24	93.3 (200)	None	None
BSP-04	Grafoil®	12	71.1 (160)	4	121.1-260 (250-500)
BSP-05	Grafoil®	To failure	71.1 (160)	4	121.1-260 (250-500)

outlet port was 0.06 MPa (8 psi). The hot water system temperature was maintained at 93.3°C (200°F) throughout the test. When disassembled, the bearing/seal package showed few signs of wear or deterioration. Before reassembling, a photographic record was made of all internal parts.

The Bearing/Seal Package Test Facility has been further debugged. Operational checks have been made of the system pressure and flow control. A pressure of 5.7 MPa (825 psi) has been applied in the hot water system and mud circulation system. Loads up to 44.5 kN (10 000 lb) have been applied to the bearing/seal package. Measurements of load and pressure have been made, and the dependence of torque on these variables is being evaluated.

Bending stresses in the shaft of the bearing/seal package are produced by deviation forces on the drill bit. Analysis of these stresses was undertaken, and frequency analysis of the highly cycled shaft was also initiated. The bearing/seal package shaft was mathematically modeled and a computer program written to predict the magnitude of stresses at critical points in the shaft. The computer program was used to determine the effect of sleeve clearance and bit-force vectors on stress magnitude.

Another computer program was written to establish the natural torsional frequencies of the bearing/seal package shaft. These natural frequencies are being compared with frequencies expected from rotational exciting forces to check for possible resonance.

A fatigue analysis of the bearing/seal package shaft is being developed based on the bending stress calculations mentioned above and on appropriate S/N data.* This could be important with high-speed turbodrills (500 to 1000 rpm) because of the large number of stress reversals in a typical bit run. A parametric study was completed in September 1979.

The results of the three programs mentioned above--(1) fatigue analysis of the bearing/seal package, (2) natural frequencies of the bearing/seal package, and (3) bending stresses of the bearing/seal package--are being printed by Maurer Engineering and will be released during October 1979.

The bearing/seal package tests will resume early in the next reporting period. Upon completion of the first five tests, analysis of the bearing/seal package will be performed and initial conclusions drawn.

5.4.2 Development of Geothermal Erosion Drilling Systems

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

Project Objective -- The objective of this project is to design, fabricate, and demonstrate erosion drilling hardware useful for geothermal

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*S/N = the relationship between stress S and the number of cycles N before failure of the material.

well drilling and completion. There are three primary objectives of this project:

1. Development and demonstration of an erosion drilling under-reamer for use in geothermal injection wells,
2. Field testing of a hybrid water-jet/roller-cone bit, and
3. Development of a cavitation damage test standard for rock.

Status and Results — In the development of the cavitation damage test standard, experiments on metals were completed early in this reporting period. The vibratory erosion testing was carried out using a Branson ultrasonic transducer, Model No. 160. The horn used had an exponential profile which transferred ultrasonic vibrations from the converter to a specimen mounted on the tip of the horn. This vibrated the specimen at the required frequency with a predetermined amplitude. Tests were carried out on both nickel and titanium samples. The specimens were vibrated in a test liquid in a 0.8-litre (0.85-quart) glass beaker surrounded by a cooling bath thermostatically regulated to $22 \pm 1^\circ\text{C}$ ($71.6 \pm 1.8^\circ\text{F}$). The specimens were cleaned and weighed before being attached to the horn and tested. They were then immersed to a depth of approximately 13 mm (0.51 inch) and vibrated at the operating frequency of the instrument.

In the stationary erosion tests, the test specimen was located within a specially designed anvil. This anvil was submerged in a liquid bath and oriented so that the specimen surface lay parallel to the oscillating horn tip at a small, predetermined distance from it. The test liquid was pumped from a thermostatically controlled cooling sump to the test container, where it overflowed into a collecting trough and then was returned to the sump for recirculation. Both titanium and nickel samples were also used in this test series for comparison with data obtained from the vibratory cavitation tests. These samples were first cleaned and degreased using methyl-ethyl ketone and were then allowed to dry before being weighed on a balance with a sensitivity of 0.1 mg (0.0015 grains).

In the stationary specimen method, all the American Society for Testing Materials (ASTM) standard parameters were utilized, with the exception of the specimen location and the size of the containing beaker. These modifications were made because a larger-than-standard anvil was used to incorporate larger-than-standard sample sizes. This modification resulted from previous research on smaller test samples of rock. While these samples held together under the stationary specimen testing, it was not possible to maintain specimen integrity under the high-speed, cavitating-water-jet-liquid impact. Sample size was therefore increased, and this in turn required a larger anvil and therefore a modification to the size of the test apparatus.

In all stationary and vibratory testing, Branson ultrasonic transducer power settings of 20, 40, or 60% of maximum were used. The mass loss of the specimens due to cavitation erosion was determined periodically, usually at 1-hour intervals. Two forms of data representation were developed: the mean depth of erosion and the cumulative depth of erosion as proposed by the ASTM Standard.

Two standoff distances were considered in the stationary specimen testing. It was not possible to operate the stationary specimen test program at a setting of 60% on the Branson instrument since the instrument overheated and switched itself off at frequent intervals at this power setting. Accordingly, the stationary specimen tests were run at 20 and 40% power settings only.

The experiments were carried out three times to observe reproducibility, and arithmetic means were computed from the data obtained. Representative data are shown in Figures 52 and 53. Test results agreed with those described in the ASTM Standard. At the end of an 8-hour test period, differences were noted in the shape of the developing curves. It was postulated that part of this difference was caused by use of commercial water rather than distilled water, as recommended by the ASTM Standard. However, it was not practical to use distilled water in the high-speed cavitating flow test program because of the large volume of liquid required; therefore, since a correlation was being sought between the two methods of testing, the program was undertaken with commercially available water.

The test results are summarized in Figure 54, which shows the following:

1. Titanium is more erosion resistant than nickel.
2. A horn tip erodes considerably more in a free condition (up to 600%) than when it is located over a stationary specimen.
3. A stationary specimen erodes more than the equivalent sample located on a horn tip (Figure 55, after Scott) but still less than it would if the sample were freely vibrated on the horn tip, without an underlying target plate.
4. The standoff distance between the specimen and the horn controls the erosion rate of both surfaces.
5. The erosion rate displays an apparent linear relationship to the amplitude of tip vibration (expressed as a power percentage on the graph).

The cavitation study was continued in the testing of the proposed ASTM stationary specimen test. However, a variety of rocks was used for the target materials. Using a modified ASTM standard test method, the evaluation of the cavitation erosion resistance of rocks was completed on eight different samples. The eight rock samples used in these experiments comprised three types of granite, three types of marble, sandstone, and dolomite. From the basic rock samples available, cores measuring approximately 5 cm (2 inches) in diameter and approximately 2.54 cm (1 inch) thick were cut using a diamond saw. The rock discs were then surface-ground on both flat ends to produce parallel surfaces within ± 0.05 mm (0.002 inch). Because of the relatively high porosity and permeability of some of the rock samples, which caused variations in the moisture content, a straightforward cleaning and weighing was not practical. The specimens were maintained in a constant humidity environment with stabilizing time periods established before and after testing in order to ensure that the specimens reached a stable moisture content. The weighing was repeated twice over an interval of 24 hours to ensure that a stabilized weight had been achieved.

Figure 52. Original Results of Three Cavitation Tests (Nickel Tip). A nickel specimen on the horn tip was tested at a 20% power level.

Figure 53. Original Results of Three Cavitation Tests (Titanium Tip).
A titanium specimen was used on the horn tip at a 20% power level.

Figure 54. Cumulative Depth of Erosion (CDE) Arithmetic Means of Nickel and Titanium Specimens. Arithmetic means of the CDE of horn and stationary specimens of nickel and titanium are plotted as a function of time.

Figure 55. Vibratory versus Stationary Specimen Erosion Rate of Nickel Tip and Specimen. After Scott (M.S. thesis, UMR, 1979).

The ASTM standard method of vibratory cavitation testing stipulates certain parameter values which should be used in the program. The recommendations were followed except as follows:

1. The equipment would vibrate at 19.15 kHz only. Hence, this frequency was used instead of 20 kHz.
2. The tests could not be carried out in an 800-ml (0.2-gal) beaker because of the size of the anvil and the test specimens in use. A cubical container, approximately 0.31 metre (1 foot) on a side, was used.
3. The standoff distance between the horn tip and the specimen was adjusted by thickness gages within an accuracy of 0.025 mm (0.001 inch) to a value of 2.032 mm (0.008 inch) instead of 2.5 mm (0.098 inch). The erosion rate obtained at the latter standoff distance was so slow that the large-scale testing program planned would have been impractical. Accordingly, the closer standoff distance was used in the program.

The rock types chosen for the tests exemplify the different internal structures which rock can possess. The three granites typified coarse, crystalline rocks and had a crystalline structure composed of several different minerals, each of which was directionally anisotropic. Conversely, the marble was crystalline rock and was generally composed of one mineral. The dolomite had a relatively fine structure. The sandstone was slightly coarser and somewhat more weakly cemented.

Analysis of the results was based on an evaluation of the graphical plots of the data. These plots are the averages of four test runs. Cumulative and mean depths of erosion for all specimens are plotted in Figures 56 and 57.

The results of the tests on the three granite samples are, to an extent, a function of the locations on the samples at which the tests were carried out. The zone of influence of the cavitation attack was very localized in regard to area and depth of the samples, and the crystal size of the granite tended to dwarf the crater size (Figure 58). Initial analysis of the results has shown that, with time, there is a decay of the rate at which erosion occurs. However, this may in part be due to the relatively large crystal structure of the granite under attack. All three granites suffered approximately the same kind of damage; i.e., cavitation tended to concentrate along the crystal boundaries and differentially attack the softer minerals present in the granite. The result for a typical sample (granite No. 2) can be seen in Figure 58, which shows gross and detailed views of a sample after attack.

The photomicrograph of the surface damage (Figure 58) shows the different responses of the three different minerals composing the granite sample. The platelike isolation of the feldspar, to the more amorphous but still large-grained failure of the quartz, and the small-fragment failure of the mica can be clearly identified. The response of the feldspar illustrates an anisotropic structure.

Figure 56. Mean Depth of Erosion of All Specimens

Figure 57. Cumulative Depth of Erosion of All Specimens

(a)

(b)

Figure 58. Granite Sample (a) and Surface Damage by Cavitation Attack (b)

It is difficult to derive totally conclusive results from the tests carried out in granite because of the wide variation observed in the structure of the samples. However, in all three cases, there was a clear reduction in the penetration rate with time, which for two of the granites appeared to be almost coincident at the longer time periods. In the earlier parts of the program, there was a wide discrepancy in the amount of material moved. The grain structure of the three granites is approximately equivalent, although the composition differs considerably. The three granites tested do not form a set that has been widely tested under conventional water-jet (i.e., erosion without cavitation) attack. Therefore, their exact behavior cannot be predicted. It has been found, as a more general rule, that, the larger the crystals of the granite, the more easily the granite is penetrated by conventional water-jet attack. On the other hand, the relative concentrations of the different minerals may make the larger grained rock more difficult to cut conventionally.

The deformation curves for the marble follow very closely the curves developed for the granite, although the three different marble samples are much finer in structure than the granite. Marble No. 2 is the closest to a clearly crystalline structure. Its structure is perhaps the reason why the curve for marble No. 2 is the lowest in terms of cumulative depths of erosion, with the much more rapid attenuation in the penetration rate with time. However, it should be realized that the irregularities in the curve may be due to penetration along the crystal boundaries of the rock, during which the erosion rate apparently reduces until a crystal is isolated. Then the penetration rate markedly increases. This erratic process would result in a relatively large scatter in the penetration rate. Some scatter was in fact observed in the data.

Analysis of the surface damage suffered by the marble samples again shows the orientation of the cracks around the crystal boundaries in the sample. This is shown for marble sample No. 1 in Figure 59. A measure of the damage to the rock samples can be obtained by sidelighting the rock target, since the stressed calcite responds differently to light. This technique revealed that the rock had been stressed beyond the cavity by the cavitation attack; the stresses extended beyond the area in which damage is visible directly and optically.

Based on an examination of the data for the dolomite and sandstone, it is clear that the penetration rate for the dolomite, which is a much finer grained material than any other tested (Figure 60), is greater than that for any other rocks. The reason for this could be that the grain size of the dolomite lies much closer to the erosion size of the impacting jets on the rock surface. The comparability in size would make it easier to remove individual crystals and attain a steadier penetration rate than would be the case for the other rock types. In fact, there is a much lower variation in rate with the dolomite than there is with the crystalline rocks. The rate is most equivalent to that achieved in the sandstone, whose damage criterion is much the same (Figure 61).

Examination of the data for all the rock types reveals that the dolomite is eroded much more rapidly than the other rocks, followed in turn by the finest grained marble (No. 3), two granite samples (Nos. 1 and 3), the sandstone, the second granite sample (No. 2), and the second marble

(a)

(b)

Figure 59. Marble Sample No. 1 (a) and Surface Damage by Cavitation Attack (b)

(a)

(b)

Figure 60. Dolomite Sample (a) and Surface Damage by Cavitation Attack (b)

(a)

(b)

Figure 61. Sandstone Sample (a) and Surface Damage by Cavitation Attack (b)

(No. 2). The third marble, which erodes at almost the same rate as the dolomite, is the finest of the three grained marbles. It, therefore, has a higher possible penetration rate. On the other hand, the sandstone, although it has a finer grain structure, has many more cracks. Because of the quantity of natural cracks in the sandstone, the cavitation-induced cracks in that rock would tend to grow less than would similar cracks in the more tightly bonded granites and marbles and finer grained, but much less permeable, dolomites.

From the initial analysis of the results, it is difficult to find a common characteristic describing the behavior of equivalent types of rocks. For example, some of the granites followed a response much closer to that of the marble than they did to other granites. Nor is it possible, at this stage, to correlate the response of the rock to cavitation attack with the behavior of rocks under high-pressure, water-jet cutting. For example, the dolomite, which is the most easily eroded by cavitation attack, is, conversely, one of the hardest rocks to penetrate by conventional water-jet cutting. This suggests that a combined cavitating-jet system might be used in penetrating dolomite.

The experiments described above were carried out in order to standardize conditions for testing rock resistance to cavitation attack. Insofar as possible, the tests were carried out under those conditions stipulated by ASTM, although it was necessary to modify some of the test conditions in order to allow testing of the rock specimens. The results generated to date have not made possible the anticipated benefit of applying this test to other aspects of the water-jet program. However, a better understanding of these results and an interpretation of the usefulness of the tests may come when the tests are carried out using the modified Lichtarowicz cell. Fabrication of the enlarged version of the Lichtarowicz cell has been completed and a test program designed. Testing of rock samples using the modified cell was initiated near the end of this reporting period.

Erosion Drilling Under-Reamer -- Work continued during this reporting period to develop an erosion drilling under-reamer capable of enlarging a standard 22.5-cm (8.86-inch) diameter reinjection well out to a diameter of 2 metres (6.6 feet), over an increment of 70 metres (230 feet), at a well depth of 2000 metres (6562 feet).

Because of conflicting results reported by major oil companies in other work where water jets were used to drill rock under confining and borehole back pressures, a preliminary experiment was conducted to evaluate the cutting capability of high-pressure water jets in the laboratory under simulated field conditions. The procedure started with the axial drilling of a 5-cm (1.97-inch) diameter hole in a 15-cm (5.9-inch) diameter, 30-cm (11.8-inch) long, cored, sandstone sample. This specimen was inserted within a modified triaxial cell to generate confining pressures equivalent to those likely to be encountered at 2000 metres (6562 feet), pressures of approximately 42 MPa (6092 psi). A water-jet drilling nozzle was lowered down the central axial hole in the sample and the jet brought up to pressure. The flow of fluid out of this cavity was restricted in order to generate within the cavity a sufficient pressure, approximately 18 MPa (2611 psi), to simulate the 2000 metres (6562 feet) of fluid within the borehole. The test setup is shown in Figure 62. The test revealed that

Figure 62. Water-Jet Preliminary Test Setup

the water jet did not cut the sides of the borehole. This was unexpected because, under free air conditions, the jet used was capable of cutting sandstone out to a distance of 2 metres (6.6 feet). Upon analysis, it was considered that the distance between the nozzle and the rock surface was perhaps too great and that the angle of contact between the jet and the wall of the cavity was too small to achieve satisfactory penetration. However, it was also accepted that there could have been a major deleterious effect on the jet cutting action due to the back pressure of the fluid in the hole. Accordingly, a second experiment was conducted to determine the exact effect of back pressure on the cutting ability of water jets.

The second experiment was designed to find out how rapidly water-jet cutting action was attenuated by the pressure of the borehole fluid. To this end, rock samples were prepared, again from 15-cm (5.9-inch) diameter sandstone cores. In this case, the samples prepared were approximately 10 cm (3.94 inches) thick. Across the upper surface, a diagonal saw cut was made so that the jet would be exposed to a rock surface which sloped away from the nozzle as it rotated around the sample (Figure 63).

Since it was not considered necessary at this stage to include rock-confining pressure in the experiments, the procedure was modified; samples were placed in the chamber unjacketed.

The sample was fixed in position, and the nozzle assembly and the pressure chamber cap were fitted onto the chamber. The nozzle was rotated until it was over the flat upper surface of the rock, and the chamber was slowly raised until contact occurred. The chamber was lowered 6.35 mm (0.25 inch), and the nozzle, which was set on an eccentric radius to the axis of rotation, swung until it was located over the most distant point on the rock. A minimum distance of 6.35 mm (0.25 inch) was established because the rebounding water and debris from the cutting zone still contained a certain energy; if the nozzle were to lie very close to the rock surface, that energy would be sufficient to cause leading-edge abrasion and to rapidly erode the nozzle body. Therefore, this minimum standoff distance was considered necessary. The nozzle was then rotated manually so that it transcribed a circle over the upper surface of the rock sample. As the nozzle rotated, the standoff distance between the nozzle and rock surface decreased. Thus, at some point in the rotation, the jet began to cut. The jet traversed the flat upper surface of the sample and then moved again over a slope away from the nozzle and back to its original position. In this way, two measurements of the effective cutting distance of the jet were obtained. The effects of this test procedure on the sample are shown in Figure 64.

The tests were carried out at 69 MPa (10 000 psi) pump pressure, using nozzles of 0.75-mm, 1-mm, and 1.6-mm (0.03-inch, 0.04-inch, and 0.06-inch) diameter, with back pressures on the system ranging from 3.45 MPa (500 psi) up to 17.25 MPa (2500 psi) (Table 16). The results of the tests showed that the 0.75-mm and 1-mm (0.03-inch and 0.04-inch) diameter nozzle would be totally impractical for use at the depths intended. Although these nozzles were manufactured to the highest degree of perfection currently available, using electroformed nickel, they were unable to penetrate the rock at hole back pressures above 10 MPa (1450 psi) at standoff distances

Figure 63. Water-Jet Test Setup to Determine the Effect of Standoff Distance

Figure 64. Sample after Test Showing Loss of Cutting Ability with Increase in Standoff Distance

of greater than 6.35 mm (0.25 inch), the minimum distance used in the test experiments. The tests were therefore continued with a 1.6-mm (0.06-inch) diameter nozzle, and this was able to cut the rock when submerged in water, even at a back pressure of 17.25 MPa (2500 psi), out to a distance of approximately 17.5 mm (0.69 inch). This cutting ability indicated that it would be practical to use water jets at a depth of 2000 metres (6562 feet) to cut the necessary cavity, provided that the nozzle bodies were within 12.5 mm (0.49 inch) of the rock surface.

Table 16

Effective Cutting Distance of a High-Pressure-Fluid Jet
under Simulated Borehole Conditions

Nozzle Diameter mm (inch)	Hole Fluid Pressure, MPa (psi)					
	0	3.45 (500)	6.9 (1 000)	10.35 (1 500)	13.8 (2 000)	17.25 (2 500)
Cutting Distance, mm (inches)						
0.75 (0.03)	28.58 (1.125)	15.88 (0.625)	15.88 (0.625)	7.94 (0.313)	--	--
1.00 (0.04)	47.62 (1.875)	22.23 (0.879)	22.23 (0.879)	11.11 (0.437)	--	--
1.60 (0.06)	69.85 (2.75)	--	31.75 (1.25)	23.81 (0.937)	20.63 (0.812)	17.46 (0.687)

Note: The operating jet pressure was 69 MPa (10 000 psi). The rock sample was Berea sandstone.

To ensure that the jets would continue to cut the rock under confinement, these final tests with the 1.6-mm (0.06-inch) nozzle at a back pressure of 17.25 MPa (2500 psi) were repeated with rock-confining pressures of, respectively, 17.25 MPa, 27.6 MPa, and 41.4 MPa (2500 psi, 4000 psi, and 6000 psi). In all cases, the jet proved capable of cutting through the rock. The results of these tests are presented in Table 17.

The experiments provided a possible explanation of the conflicting results reported in field tests of high-pressure jet bits at depths below 2000 metres (6562 feet). Since the location of the jet nozzle on the bit body with respect to the surface being cut varied among bits used, some nozzles may have been located too far from the rock surface for the jet to have effectively reached the rock under the downhole conditions experienced.

Table 17

Effect of Borehole Confinement and Borehole
Back Pressure on Fluid Cutting Ability

Rock Confining Pressure MPa (psi)	Depth of Cut mm (inches)	Borehole Pressure MPa (psi)
0	63.5* (2.5)	0
17.25 (2 500)	11.11 (0.437)	17.25 (2 500)
27.6 (4 000)	8.73 (0.344)	17.25 (2 500)
41.4 (6 000)	6.35 (0.25)	17.25 (2 500)

*Jet pressure in this test was 60.7 MPa (8 800 psi).

Note: The operating jet pressure was 69 MPa (10 000 psi). The rock sample was Berea sandstone. The nozzle diameter was 1.6 mm (0.06 inch). The standoff distance was 6.35 mm (0.25 inch).

The results from the first series of experiments, while demonstrating that high-pressure water jets are capable of cutting at the depths required, still indicated a relatively poor level of performance. The cavity required would take approximately 1 week to excavate, which seemed an abnormally long time. Additional investigations were directed, therefore, toward improving the capability of the jets' cutting performance. The nozzle itself had, for the particular shape chosen, already been optimized in earlier work. Therefore, it was felt that little advantage could be gained by directing any considerable study to this particular parameter at the present time.

In earlier work, the addition of long-chain polymers to the jet fluid had been found effective in improving the throw of the water jet for both drilling and other rock-cutting purposes. It was therefore decided to determine if such an addition could improve the cutting ability of the jet in the current circumstance. Tests were carried out using a long-chain polymer supplied by Nalco Corporation, designated Nalco 625.

The tests were originally carried out using the previous procedures at three polymer concentrations. It was found that the water jets' cutting ability was improved by more than 200% (Table 18). Accordingly, the test program was extended to reexamine the 1-mm (0.04-inch) diameter nozzle. Again it was found that the jet could be made to cut under conditions which were not possible where the jet was operating without the addition of the polymer (Table 18).

Table 18

Results of Adding Polymer on the Effective Jet Cutting Distance

Polymer Concentration ppm	Idle Back Pressure MPa (psi)	Nozzle Diameter mm (inch)	Cutting Distance mm (inches)
100	17.25 (2 500)	1.60 (0.06)	34.92 (1.37)
100	17.25 (2 500)	1.60 (0.06)	34.92 (1.37)
200	17.25 (2 500)	1.60 (0.06)	47.62 (1.86)
300	17.25 (2 500)	1.60 (0.06)	47.62 (1.86)
300	17.25 (2 500)	1.00 (0.04)	28.57 (1.13)
300	10.35 (1 500)	1.00 (0.04)	31.75 (1.25)
300	3.45 (500)	1.00 (0.04)	36.51 (1.44)

Note: The operating jet pressure was 69 MPa (10 000 psi).

The experimental results indicate that the addition of 200 ppm of the polymer is sufficient to greatly increase jet cutting ability. The experiment was repeated at greater concentrations of the polymer. These concentrations did not greatly increase the cutting ability of the jet and did make it more difficult to drive the fluid because of the system's configuration. Since a 200-ppm polymer concentration is a relatively economical addition to the drilling fluid, that concentration will be used in future research.

Subsequent to obtaining the results of this experiment, discussions were held with Dr. G. Howells of Berkeley Chemical Research, Inc., who reported a similar advantage in the use of polymers in water for oil well applications. In this instance, he used his own proprietary chemical, marketed under the trade name "Super Water," and he described a series of experiments in which the chemical was used to clean the "clogged slots of oil well liners." A Super Water solution of 0.3% polymer operated at 62 MPa (8992 psi) was able to clean the submerged liners with an increased effectiveness of up to 30 times. Unpolymerized water jets had not proved

effective at standoff distances greater than 10 times the nozzle diameter, that is, between 0.38 and 0.76 mm (0.015 and 0.03 inch). However, with the polymerized solution, cleaning the plugged slots was achieved at a standoff distance of 11.75 cm (4.63 inches), the maximum distance permitted with this particular oil well liner.

Thus, considerable advantages may accrue from the addition of relatively low concentrations of long-chain polymers to the drilling fluid. Such additions improve the distance at which the water jet cuts under oil well conditions and preclude the need for design changes in the bit.

A second advantage which may develop from the use of the polymers is the reduced friction of the fluid in the flow lines from the pump to the nozzle. Experiments have been carried out to examine the friction losses which occur in pumping at high pressure, and these tests have shown that a reduction of approximately 5% in the friction loss through 4.76-mm (0.19-inch) i.d. piping can be achieved when the polymer is added. The polymer was originally developed to reduce the friction of fluids, an application which may be extended to drilling and rock cutting.

Work continued on the design of the prototype reamer. A plan to use a hollow-shaft vane motor encountered two problems. A supplier could not be identified, and there were indications that a vane motor may "cog" at the rotation speeds proposed. The design of the drive was being reevaluated at the close of this reporting period.

Hybrid Drill Bit Field Test -- The hybrid water-jet/roller-cone bit field test program was initiated this reporting period after redesign of the bit to situate high-pressure jet nozzles on the peripheral point of the drill bit rather than through the center.

The drill was set up in the University of Missouri-Rolla experimental mine, and holes were drilled in the local dolomite. Tests were conducted with nozzle diameters ranging from 1.02 to 2.03 mm (0.04 to 0.08 inch), with the jets axially oriented to the hole and operating with a button tricone. The results indicated that optimal improvement (130%) was achieved with the 1.8-mm (0.07-inch) nozzle at 96.5 MPa (14 000 psi). A larger orifice did not generate the approximately 68.9 MPa (10 000 psi) of pressure required to cut the rock, while smaller nozzles were not quite as effective due to lower flow rates. The pump was set to operate at up to 103.4 MPa (15 000 psi).

After modification of the bits to permit evaluation of other nozzle orientations, the field tests were continued. A tricone bit was used which had been modified so that the jet from a 1.8-mm (0.07-inch) diameter nozzle could be directed at any point along the circumference of the hole gage. Penetration rates in the dolomite were compared as the direction of the water jet was traversed from axially forward to the gage of the tricone bit. Once a threshold pressure of approximately 82.7 MPa (12 000 psi) had been achieved, penetration rate improvements ranged from 200% at the axial direction to 700% at the bit-gage direction.

The field tests were interrupted by a coupling failure. The equipment was repaired and the tests reinitiated at the end of this reporting period.

Publication of the data from these field tests is anticipated during the next reporting period.

5.4.3 Drilling Mud Effects Using Cavitating Jets

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

Project Objective -- The objective of this phase of the project is to establish the effects of drilling mud on the performance of cavitating jets and to determine the feasibility of employing cavitating jets to improve drilling performance of mechanical bits. If feasibility is proven, the results will be used in later phases to optimize cavitating nozzle design and the placement of such nozzles in mechanical bits.

Status and Results -- This phase of the project has been completed, and the project objective has been met. The results obtained over the period of this phase of the research are discussed below. These results indicate that augmentation of mechanical bits with cavitating mud jets is feasible and could substantially improve drilling performance.

Effects of Ambient Pressure. Ambient pressure strongly affects both the ability of a particular nozzle to produce cavitating jets and the performance of such jets in cutting rock. With understanding of cavitation phenomena and careful design, however, nozzles can be built which cavitate effectively at the high ambient pressures encountered downhole. This point is illustrated in Figures 65 and 66.

In Figure 65, the average depth of cutting rate, $\bar{h}_{avg}$, for a stationary Cavijet™* nozzle in Indiana limestone is plotted against ambient pressure, P_a , for a variety of nozzle pressure drops, Δp . These data were obtained with the high-pressure facility at the DRL. Each set of data points is the result for a single set of runs at a particular value of Δp . The curves are averaged curves for many sets of data at those values of Δp .

The curves show that, for each value of Δp , $\bar{h}_{avg}$ increases to a peak value, $\bar{h}_{peak}$, and then decreases to a monotonic value as the ambient pressure increases. This behavior is typical for cavitation phenomena. At a given Δp , the number of cavities in a cavitating jet generally decreases as ambient pressure rises; however, the collapse rate of these cavities, and hence the rock damage caused by individual cavities, increases with ambient pressure. These opposing effects result in an optimum ambient pressure where maximum overall rock damage occurs for each value of Δp . As ambient pressure increases further, cavitation within the jet finally ceases, and the average depth of cutting rate reaches a value corresponding to the cutting rate achieved with pure (noncavitating) jet erosion.

The ambient pressure at which this value is reached is directly proportional to Δp for a given nozzle design. The constant of proportionality

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*Cavijet™ is a registered trademark for the cavitating nozzles patented and marketed by Hydronautics, Inc.

Figure 65. Typical Results from Four-Nozzle Testing with Plain Mud: 6.4-mm (0.25-in.) Cavijet™ Nozzle; 1.6-cm (0.62-in.) Standoff

Figure 66. Scaling of the Stationary-Nozzle Test Results
for the Plain CaviJet™ Nozzle

is known as the incipient cavitation number σ_i . The cavitation number is defined as $\sigma = P_a/\Delta p$; thus, σ_i is that value of σ and, therefore, those particular combinations of P_a and Δp , at which cavitation ceases. For values of σ less than σ_i , cavitation occurs; no cavitation occurs when σ exceeds σ_i .

The cavitation number can be used to scale the results shown in Figure 65. By dividing P_a by Δp and $\dot{h}_{avg}$ by $\dot{h}_{peak}$ for points along each curve in the figure, these curves can be collapsed as shown in Figure 66. The significance of this scaling is that it allows rock-cutting tests to be performed at lower ambient pressures and nozzle-pressure drops, as long as the ratios of these values are maintained identical to those obtained at higher pressures. In this project, this scaling allowed translating-nozzle tests and more extensive stationary-nozzle tests to be conducted at lower cost at Hydronautics' lower pressure facility.

Effects of Nozzle Pressure Drop. Nozzle pressure drop affects jet cutting performance. This effect is described by the cavitation number. At a particular cavitation number, the average depth of cutting rate increases rapidly with Δp .

There exists an optimum cavitation number, σ_{opt} , defined as that value of σ for which $\dot{h}_{avg}$ is a maximum, i.e., $\dot{h}_{avg} = \dot{h}_{peak}$. From Figure 66, it is seen that $\sigma_{opt} \approx 0.4$, regardless of P_a or Δp . The data of Figure 65 can thus be plotted as shown in Figure 67 to yield the relation

$$\dot{h}_{peak} \propto \Delta p^{3.1}.$$

The significance of this result is twofold. First, it illustrates the advantages of even small increases in pump pressure. Second, this relation together with the graphical correlation of Figure 66 can be used to determine the average depth of cutting rate at any combination of Δp and P_a .

These correlations have been established only for the rock type used in these tests--Indiana limestone. The extrapolation scheme for other rock types would first require verification of the Indiana limestone correlations for those rock types. There is a good indication that the correlation between $\dot{h}_{peak}$ and Δp is valid for other rock types, such as Georgia granite. There are not enough data, however, to verify the exact shape of the curve of $\dot{h}_{avg}/\dot{h}_{peak}$ versus σ for other rock types, but the general curve shape is universal for all types of cavitation and materials. There is also some indication that, for a particular nozzle, the value of σ_{opt} is approximately constant regardless of rock type. There is even some indication that the relation of $\sigma_{opt} \approx \sigma_i/4$ is valid for different nozzle designs. These questions remain to be resolved by further research.

The incentive for resolving these questions is, if these correlations could be shown to be universal, then a single test could be conducted in any rock type at any combination of ambient pressure and nozzle pressure drop and the results extrapolated to predict average depth of cutting rates at all other values of P_a and Δp . This would reduce dramatically the number of tests required to characterize the resistance of different rock types to cavitating-jet attack.

Figure 67. Dependence of Cutting Rate on Nozzle Pressure in Stationary-Nozzle Tests with Mud

Effects of Nozzle Design. The fact that σ_1 and, therefore, the ambient pressure and depth at which cavitation ceases for a particular Δp , is a function of nozzle design is illustrated in Figure 68. These data are from stationary nozzle tests at DRL. In this case, cutting rate effectiveness is defined as $e_h = \dot{h}_{avg} / P$, where P is the hydraulic power expended at the nozzle.

The Cavijet™ nozzles, specifically designed to induce cavitation, have higher values of cutting rate effectiveness over a larger range of ambient pressures than either the Leach and Walker or the Smith nozzles, neither of which is designed for cavitation. Furthermore, the Cavijet™ nozzles reach the characteristic monotonic value of e_h at higher ambient pressures than the other nozzles, indicating a greater effectiveness at depth.

Effectiveness at depth is a function of incipient cavitation number σ_1 . Figure 68 indicates that the Cavijet™ nozzles have values of σ_1 in the range of 1.6 to 2.0, whereas the Leach and Walker and the Smith nozzles have values of σ_1 in the range of 1.0 to 1.2. The goal of further cavitating-jet research should be an optimization of nozzle design in order to establish higher values for the incipient cavitation number. This goal will be pursued in the second phase of this project.

Effects of Drilling Mud. The use of mud instead of water as the cavitating fluid appears to have no detrimental effects on jet performance over the range of conditions tested. This concept is illustrated in Figure 69, where cutting rate effectiveness, e_h , is plotted against nozzle pressure for both a Cavijet™ nozzle and a Leach and Walker nozzle.

Comparison of the mud data and water data curves for either nozzle shows that the use of mud actually increases the cutting rate effectiveness for nozzle pressure drops less than 15 to 20 MPa (2200 to 2900 psi). This result is attributed to the inherent erosivity of the mud particles, which contributes substantially to the jet effectiveness at lower nozzle pressures. As nozzle pressures are increased, cavitation damage increases so rapidly that erosivity of the mud particles becomes an inconsequential contributor to the overall jet effectiveness.

The results shown in Figure 69 are for a 1100-kg/m³ (9.3-lb/gal) mud. Similar results have been obtained for muds ranging up to 1400 kg/m³ (11.9 lb/gal).

Effects of Exposure Time. In order to determine the effects of exposure time on the rock-cutting performance of a stationary nozzle, it was necessary to conduct many tests at various exposure times. Due to cost limitations, it was not feasible to conduct these tests at the high-pressure DRL facility. Instead, the tests were conducted at Hydraulics' facility.

The results for three different rock types are shown in Figure 70. It was determined that the data can be characterized by exponential curves of the form

$$h = h_{max} (1 - e^{-t/\tau})$$

Figure 68. Comparison of Various Nozzles Tested at the Drilling Research Laboratory; Stationary-Nozzle Tests with Four-Nozzle Tool

INDIANA LIMESTONE SPECIMEN NO. 3
PLAIN CAVIJET™ NOZZLE

INDIANA LIMESTONE, SPECIMEN NO. 3
LEACH AND WALKER NOZZLE

Figure 69. Comparison of Water versus Mud Effect on Cutting Rate Effectiveness;
1.1-g/cm³ (9.3-lb/gal) Mud Density

Figure 70. Comparison of Stationary-Nozzle Cutting Results for Three Rock Types

where $h_{\max}$ and τ are empirical constants for a particular nozzle and rock type. It was also determined that

$$\tau \propto \Delta p^{-1/2}$$

and

$$h_{\max} \propto \Delta p^{3/2}.$$

Effects of Nozzle Translation -- Although stationary nozzle tests reveal important information about cavitating-nozzle performance, nozzles mounted on rotary drilling bits will have translational velocity relative to the rock surface. Accordingly, translating nozzle tests were conducted at Hydronautics.

Typical results are shown in Figure 71. These data can be characterized by curves of the form

$$h' = h'_{\max} (1 - e^{-D/V\tau'}) ,$$

where D is the diameter of influence of the jet, determined from stationary tests, and $h'_{\max}$ and τ' are empirical constants; $h'_{\max}$ and τ' have the same dependence on Δp as do $h_{\max}$ and τ for stationary nozzle tests.

The significance of the data shown in Figure 71 to the design and operation of cavitating-jet-augmented bits is twofold. The first point deals with placement of the nozzles on the bit. The closer the nozzles are placed to the periphery, the higher is the translation velocity for a given bit rotational speed, and therefore, the lower is the mean depth of erosion per revolution of the bit. This relationship would seem to suggest placement of the nozzles closer to the center of the bit; however, peripherally-mounted jets are more effective at destressing the rock face, which aids the mechanical breakage of the rock. This highly complicated jet/mechanical element interaction requires study in order to define the optimum placement of nozzles on a particular bit.

The second significant point seen from the results shown in Figure 71 is that, for a given bit with established nozzle locations, higher penetration rates should result from higher bit rotational speeds. The character of the mean depth of cut versus translation velocity curves is such that an increase in velocity does not result in a proportional decrease in mean depth of erosion. For example, if velocity is doubled from V_1 to V_2 , mean depth of erosion decreases from h_1 to h_2 , such that $h_1 < 2h_2$. In a given time period, however, the nozzle traveling at velocity V_2 makes two passes to every one pass made by the nozzle traveling at velocity V_1 . The total depth of cut in a given time period would, therefore, be greater for the higher bit rotational speed.

Effects of Nozzle Standoff Distance. A limited number of tests were conducted to determine the effects on nozzle performance of the standoff distance between the nozzle and the rock. Over the range of 1.6 to 2.9 cm (0.63 to 1.14 inch), the most effective distance was the smallest, 1.6 cm (0.63 inch). The test configuration precluded testing with smaller distances; however, results from earlier research confirm that an optimum

Figure 71. Exponential Curve Fit to Slot Cutting Test Results

exists between 1.3 and 2.5 cm (0.51 and 0.98 inch). Larger or smaller standoff distances result in the cavity collapse zone occurring at a point other than the rock face.

Results of Jet-Augmented Mechanical Bit Tests. Although placement of nozzles within a bit has not yet been optimized, a limited number of tests were run to compare the penetration rates of a standard, 2-cone bit with those of the same bit augmented by CaviJet™ nozzles. The results, as shown in Figures 72 and 73, are mixed.

In the relatively hard Colton sandstone (Figure 72), the CaviJet™-augmented bits displayed higher penetration rates over a larger range of ambient pressures than did the bit with the standard Smith nozzles. These results are encouraging in light of the fact that the flow discharge rate of the Smith nozzles was 39% higher than that of the CaviJet™ nozzles. It has been demonstrated that the penetration rate of mechanical bits is highly dependent on bottomhole cleaning and, therefore, on hydraulic power expended at the nozzles. The CaviJet™-augmented bit was thus dealt a severe handicap because of the failure to size the nozzles to deliver identical flow rates and thus hydraulic power. Its good performance under these conditions is encouraging.

The effects of this reduced hydraulic power are more clearly illustrated in Figure 73. For both bits, the penetration rates in the softer Indiana limestone are generally 2 to 3 times higher than those in the Colton sandstone. These higher penetration rates place an even greater burden on the hydraulics to remove the drilled solids. The hydraulic handicap suffered by the CaviJet™-augmented bit in this case overcomes its performance potential, and penetration rates are lower than those of the standard bit.

A fair evaluation of the CaviJet™-augmented bit tested under these conditions is difficult. The results for Colton sandstone, however, were encouraging enough to cause NL/Hycalog, co-sponsor of this project, to embark on an extensive field testing program of CaviJet™-augmented bits. Future tests, both in the field and in the laboratory, will size CaviJet™ nozzles so as to provide flow rates identical to those used in the comparison bits.

Conclusions and Future Plans -- The results summarized above indicate that cavitating jets perform well under high ambient pressures, and their use with mechanical bits to improve drilling performance is feasible. More research is required in order to optimize nozzle design and to understand the effects of rock type and mechanical bit nozzle placement. The second phase of this research will be directed toward resolving some of these questions.

A primary task in Phase II will be to study ways of increasing incipient cavitation numbers for CaviJet™ nozzles. Visual and audio means of determining σ_1 will be used to rank various nozzle designs. A parallel investigation of the interaction between the jets and different rock types will be conducted. The results of these tests should identify nozzle design changes which result in higher values of σ_1 and more effective rock cutting.

TESTS AT DRILLING RESEARCH LABORATORY

BIT: 20-cm (7.875-in.) dia., TWO-CONE ROLLER BIT (SMITH)

EXTENDED NOZZLES: TWO, 6.4-mm (0.25-in.) ORIFICE DIA.

NOZZLE STANDOFF: 1.6-cm (0.625-in.) (EITHER TWO SMITH
OR TWO CAVIJET^{TM} NOZZLES)

NOZZLE PRESSURE: 16.5 MPa (2400 psi) (NOMINAL)

DRILLING FLUID: MUD, 1.1 g/cm³ (9.3 lb/gal)

ROTATION: 60 rpm

BIT WEIGHT: 44.5 kN (10 000 lb)

ROCK: COLTON SANDSTONE

Figure 72. Comparison of Penetration Rates in Colton Sandstone; $\Delta p = 16.5$ MPa (2400 psi)

Figure 73. Comparison of Penetration Rates in Indiana Limestone; $\Delta p = 16.5$ MPa (2400 psi)

Using the optimum nozzle designs resulting from these studies, the cutting ability of the jets will be widely characterized. A broad range of rock types, both permeable and impermeable, will be tested over a range of ambient and nozzle pressures. These tests will be conducted primarily in the Hydronautics facility; however, some testing will occur at the DRL facility in order to verify the scaling laws previously discussed.

Tests of Cavijet™-augmented mechanical bits will also be conducted. The purpose will be to assess improvements obtainable, under identical conditions, by substituting Cavijet™ nozzles for standard nozzles in the bits tested. The types of bits to be tested will likely include natural diamond, Stratapax™, and roller-cone bits.

In addition, research is currently underway to determine the feasibility of developing a downhole resonator for use with Cavijet™ nozzles to provide pulsing jet pressure. This research is described in the following subsection, 5.4.4, of this report.

Another part of Sandia's cavitating-jet research was an assessment of the use of the destructive forces of cavitation for deep-hole drilling. The report of the assessment is presented in Appendix E.

5.4.4 Downhole Pressure-Pulsing Device

Contractor: Hydronautics, Inc.
Principal Investigator: V. Johnson, Jr.

Project Objective — The objective of this project is to conduct a feasibility and preliminary design study of a downhole pressure-pulsing device for use with cavitating jets. This device would convert steady pressures supplied by the pump into pulsing nozzle pressures, thereby supplying higher-than-average pressures over one-half the cycle. This should greatly increase the effectiveness of cavitation erosion, since tests have shown that rock-cutting rates with Hydronautics' Cavijet™ nozzles increase as the third power of nozzle-pressure drop.

The design of this device will take into account an interesting characteristic of Cavijet™-induced cavitation. The shedding of toroidal vortices and the subsequent formation of cavities in the jet shear zone have been shown to occur with a high degree of periodicity. The pressure-pulsing device will essentially consist of a flow passage immediately upstream of the nozzle which is sized so as to resonate at the vortex-shedding frequency, thereby amplifying the small pressure pulses created by the vortex-shedding phenomenon.

Status and Results — This project was initiated in the latter part of the reporting period. Preliminary design studies have begun with a review of past research and literature on shear and oscillatory flows. Laboratory experiments will begin in November 1979. The review of the literature has revealed two major points to date.

1. A submerged jet tends to structure itself into periodic vortices whose Strouhal number is approximately 0.3. If the jet is excited

at its exit at the preferred frequency with only a very small percentage of its energy, the jet becomes highly structured at the Strouhal number of approximately 0.3. Thus, surrounding the jet exit with an annular Helmholtz resonator cavity tuned to the preferred frequency should cause maximum structuring of the jet and presumably a higher incipient cavitation number. Several designs utilizing this concept are being considered.

2. If an edge, a second orifice, is placed downstream of the jet exit, there results an impingement feedback mechanism that can cause self-sustained oscillations. Several designs incorporating this concept of amplifying the jet structure are under consideration.

5.5 Supporting Studies

During this reporting period, two new supporting studies were initiated, and one was completed. Development of a computer code for predicting transient wellbore temperatures during drilling, circulation, injection, and production in geothermal wells was completed to include sensitivity studies and correlation with field data. A project to characterize erosion drilling systems was started. Drilling systems under investigation include abrasive jet drilling, continuous jet drilling with roller-cone augmentation, continuous jet drilling with diamond-cutter augmentation, and cavitating-jet drilling.

5.5.1 Wellbore Thermal Simulator for Geothermal Wells

Contractor: Enertech
Principal Investigator: G. R. Wooley

Project Objective -- The objective of this program has been to develop a computer code for predicting transient wellbore temperatures during drilling, circulation, injection, and production in geothermal wells. The code can handle single-phase, unidirectional or counter-current flow and static, shut-in conditions. Also, the code incorporates all significant sources of energy, such as friction heating and viscous dissipation during circulation, bit work during drilling, and heat of hydration during cementing. Code verification against data from actual wells and sensitivity studies on the importance of the various input parameters were conducted.

Status and Results -- The thermal simulator program is operational for full-scale geothermal well simulation. Correlation of field data has been completed and a production base case established. The sensitivity studies on the required data for the computer code have also been completed.

During this reporting period, the GEOTEMP code was improved to better model the conductance of heat through a naturally convecting fluid in a wellbore annulus. The original code formulation defined the overall conductance U across a naturally convecting fluid by

$$\frac{2\pi}{U} = \frac{1}{h_i r_i} + \frac{\ln(r_o/r_i)}{K_{eff}} + \frac{1}{h_o r_o},$$

where

r_i = inside radius,

r_o = outside radius,

h_i = surface convection coefficient at r_i ,

h_o = surface convection coefficient at r_o , and

K_{eff} = effective fluid thermal conductivity.

However, the published measurements of heat flux through a naturally convecting fluid annulus, measurements which establish the value of K_{eff} , have included natural convection at the inside and outside walls. That is, the effective conductivity accounts for natural convection at each surface and in the annulus fluid. Therefore, the conductance across the fluid has been reformulated to

$$\frac{2\pi}{U} = \frac{\ln(r_o/r_i)}{K_{eff}}.$$

Calculations made for a sample injection case demonstrated the convergence of GEOTEMP as the finite difference grid used in the calculations is refined and as the time step-size is reduced. Figure 74 summarizes the effect of the vertical grid size on the computed temperature profile; from the profile, convergence is evident.

Convergence must also occur as the time step-size decreases. A curve showing the temperature distribution after 8 hours is given in Figure 75. The following three conclusions were clear from these tests:

1. Time step-size does not significantly influence the computed temperature profile.
2. The time step-size has a stronger effect on temperature near bottomhole than at shallower depths.
3. Fluid temperatures do converge as time step-size is reduced.

These two tests provide evidence that the numerical schemes employed in GEOTEMP converge as grid spacing and as time step-size are reduced.

Sensitivity studies on the required data for GEOTEMP were completed during this reporting period. The variables investigated were

1. Fluid flow rate,
2. Fluid inlet temperature,
3. Fluid density,
4. Fluid viscosity,
5. Undisturbed earth temperature distribution,
6. Thermal conductivity of soil, and
7. Well depth.

Each of these quantities was varied over the range of expected values to establish the impact of each on the downhole temperature computations. Two temperature comparisons were made: the steady-state temperature profile and the transient behavior at one depth. These two comparisons were made for two or three values of the above variables during each of the following conditions:

1. Injection,
2. Production,
3. Forward circulation, and
4. Reverse circulation.

Figure 74. Effect of Depth Increment on Injection Fluid Temperature

Figure 75. Effect of Time Increment on Injection Fluid Temperature

Illustrative of the sensitivity studies is the effect of flow rate on bottomhole temperature shown in Figure 76. At higher flow rates, two results are clear: bottomhole temperature cools faster, and the steady bottomhole temperature achieved is lower. Of course, the reverse directions of bottomhole temperature movement occur with high inlet temperatures. Figure 77 shows the effect of flow rate on temperature profile. For lower flow rates, the profile tends to follow the undisturbed geothermal temperatures, but, at high rates, the fluid temperature changes very little as it travels down and back up the hole. The profiles given in Figure 77 occur after a long time period. For shorter times, the profiles are closer to the initial or undisturbed temperatures.

Complete details of the sensitivity studies will be presented in the project's Part II report, "Comparison of GEOTEMP Predictions to Field Data and Evaluation of Flow Variables," along with a summary of the overall project. Publication of the report is expected early in the next reporting period.*

As part of the Sandia casing design effort, GEOTEMP was used in an analysis of radial thermal gradients in a producing well. The report of the analysis is presented in Appendix F.

5.5.2 Characterization of Erosion Drilling Systems

Contractor: Foster-Miller Associates, Inc.
Principal Investigator: J. Harding

Project Objective -- Sandia personnel are conducting a study to assess the performance potential and economics of erosion drilling systems for geothermal resource recovery. Data characterizing the performance of erosion drilling systems investigated in the past are needed as input to this study. The objectives of this project are to gather, analyze, and present these data. In particular, this project will supply data for the various systems relating to

1. System hardware requirements and costs,
2. Penetration rates,
3. Bit lifetimes,
4. Operating and rig costs,
5. Downtime,
6. Maintenance requirements,
7. Operational characteristics,
8. Time requirements for necessary operations, and
9. Impacts on other drilling and completion operations.

In addition, areas of potential system improvements and increased efficiency; required technology and hardware development; and additional analytical, experimental, and field work requirements will be identified.

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*The Part I report, Development of Computer Model and Acquisition of Field Temperature, was published December 1978.

Figure 76. Sensitivity of Bottomhole Temperature to Flow Rate during Forward Circulation

Figure 77. Sensitivity of Steady Temperature Profile to Inlet Temperature during Forward Circulation

Status and Results -- The project was started in the latter part of this reporting period. Initial effort has been concerned with a state-of-the-art assessment to identify, gather, and analyze all data from current and completed programs related to erosion drilling. Erosion drilling systems under investigation include abrasive jet drilling, continuous jet drilling with roller-cone augmentation, continuous jet drilling with diamond-cutter augmentation, and cavitating-jet drilling. Available laboratory data on rock drilling with pulsed, continuous, abrasive, or cavitating jets will be analyzed and, if found adequate, extrapolated to field conditions. The information gathered is being expressed as functions of operating pressure, drilling-fluid flow rate, drilling-fluid properties, well depth, and rock type, where possible. Results will be made compatible with the Sandia well cost simulator. Coordination has been made to assure this compatibility between the project output and the simulation model.

The remaining project tasks will be initiated in the next reporting period. These tasks will include system definitions and costs, system operating characteristics and requirements, system impact on other drilling operations, and identification of system weaknesses requiring technology improvement.

SECTION 6

FUTURE PLANS

The future plans of the Geothermal Drilling and Completion Technology Development Program will continue to emphasize the 25% cost-reduction goal through 1982. Concurrent with the pursuit of that goal will be an increasing effort in the area of advanced drilling systems to meet the 50% reduction goal.

During FY80, work will continue on the development of downhole motor bearings and seals, on the PDC drill bit, on the PDC reamer, on the continuous chain drill bit, and on bit hydraulics studies. Modification of selected laboratory facilities will be undertaken to extend high-speed/high-torque/high-pressure-drilling test capabilities. Development of corrosion-resistant drill stem steels will also continue. Fluid technology research will continue on aqueous foams, on the basic chemistry of drilling muds, and on drilling-fluid properties at high temperature and pressure. The laboratory demonstration of an N_2 generation system utilizing catalytic conversion of diesel engine exhaust will be conducted and evaluated. In addition, a field test of a cryogenic N_2 generation system will be conducted. Efforts in completion technology will continue with the development of cavitation descaling techniques, studies of thermal effects on casing, and investigations of geothermal formation damage from drilling muds. New completion work planned will involve development of a well-life prediction model, high-temperature thread compounds, and casing/cement equipment. The on-going state-of-the-art study of lost circulation control will be completed. The lost circulation problem will be further examined by the initiation of projects concerning geological factors, bottomhole pressure control, plugging/sealing material, and instrumentation/testing requirements. The development effort concerned with advanced drilling systems will be expanded from the current work on cavitating jets and downhole motor development to include new projects on percussion drills, high-speed bits, directional drilling, and downhole motor design and testing. Supporting studies will include the current effort to characterize erosion drilling systems and the start of a new project to develop an advanced wellbore thermal simulation code encompassing compressible flow and other factors that will expand the utility of the simulator.

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APPENDIX A

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APPENDIX B

Significant Meetings, Visits, and Presentations

Significant Meetings, Visits, and Presentations

Meetings and Visits

Visit to University of Missouri, Rolla, MO, by D. Glowka and M. Timmerman, to review the development of a geothermal under-reamer, 4 April 1979.

Visit to Chevron Research, by P. Rand and A. Kraynik, to discuss Chevron experience in using foam as a drilling fluid, April 1979.

Meeting with V. Johnson of Hydronautics, Inc., to discuss present and future high-pressure cavitating-jet drilling research, 20 April 1979.

Visit by J. Dewan of Schlumberger Limited, to obtain information on the Geothermal Drilling and Completion Technology Development Program, May 1979.

Meetings with Smith Tool, Co., Hughes Tool Co., Reed Rock Bit Co., and Dresser Industries, to present results of the roller-cone drill-bit development program using high-temperature steels, May 1979.

Visit by G. Thomas of the University of California, Berkeley, to explore areas of cooperation in the development of modified dual-phase steel, 9 May 1979.

Visit by M. Goodman and G. Wooley of Enertech Engineering and Research Co., to discuss additional development of the Wellbore Thermal Simulator, 30 May 1979.

Visit to Foster-Miller Associates, Boston, MA, by C. Carson and D. Glowka, to discuss a project to characterize erosion drilling systems, 21 June 1979.

Semi-annual meeting of the Geothermal Drilling and Completion Advisory Panel, to review the Geothermal Drilling and Completion Technology Development Program's current activities and future needs, 26-28 June 1979.

Visit by E. Peschel of Christensen Diamond Products, Celle, Germany, to discuss Sandia Laboratories' bonding technology for attaching polycrystalline diamond compacts, 27 June 1979.

Visit to General Electric's Special Materials Division, Worthington, OH, by D. Wesenberg, to discuss a new bonding technique used to bond Stratapax™ drill blanks to tungsten-carbide studs, July 1979.

Attendance by J. Barnette at the First Society of Petroleum Engineers Forum on the Physical Control of Solids in Drilling Fluids, Colorado Mountain College, Glenwood Springs, 5-10 August 1979.

Visit by H. Rathkamp of Christensen Diamond Products, Celle, Germany, to discuss the diffusion bonding process for attaching PDC cutters to drill bits, 7 August 1979.

Meeting with V. Johnson of Hydronautics, Inc., and R. Radtke of NL/Hycalog, to discuss the results of Hydronautics' Phase I work on the cavitating-jets project, 29 August 1979.

Visit to the University of Oklahoma, Norman, OK, by A. Maish and J. Barnette, to discuss the status of the flow loop testing of the properties of geothermal muds at high temperatures, 6 September 1979.

Meeting with J. Harding and J. Hannoosh of Foster-Miller Associates, to discuss the interface of Foster-Miller's erosion drilling study with Sandia Laboratories' well cost simulator, 19 September 1979.

Presentations

Geothermal Drilling Research in the United States, SAND79-0574A, by S. Varnado, to Drilling Symposium, French Petroleum Institute, Paris, France, 2-4 April 1979.

Development of High Performance Drill Bits Utilizing Polycrystalline Diamond Compact Cutters, SAND79-0866A, by S. Varnado and C. Huff, to Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, Tulsa, OK, 22-24 August 1979.

Recent Developments in Drill Bit Technology, SAND79-0084C, by B. Busking (Shell Internationale, The Hague, The Netherlands) and S. Varnado (Sandia Laboratories, Albuquerque, NM), to the Tenth World Petroleum Congress, Bucharest, Rumania, 9-14 September 1979.

The Design and Use of Polycrystalline Diamond Compact Drag Bits in the Geothermal Environment, SAND79-0364A, by S. Varnado, C. Huff, and P. Yarrington, to the 54th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, NV, 23-26 September 1979.

Development and Testing of a Downhole Replaceable Continuous Chain Drill, SAND79-0400C, by S. Varnado, J. St. Clair, and H. Togami, to the 54th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, NV, 23-26 September 1979.

Field Test Results of Improved Geothermal Tricone Bits, SAND79-1432C, by A. Maish, to the Annual Meeting of the Geothermal Resources Council, Reno, NV, 24-27 September 1979.

Continuous Chain Bit Development, SAND79-1433C, by J. Barnette, to the Annual Meeting of the Geothermal Resources Council, Reno, NV, 24-27 September 1979.

A Simulator for Sensitivity Analysis of Geothermal Well Cost--Recent Results, by J. Polito, to the Annual Meeting of the Geothermal Resources Council, Reno, NV, 24-27 September 1979.

Aqueous Foams for Geothermal Drilling Fluids I. Surfactant Screening, by P. Rand, to the Annual Meeting of the Geothermal Resources Council, Reno, NV, 24-27 September 1979.

The Sandia/DOE Geothermal Drilling and Completion Technology Development Program, by J. Barnette, to the Annual Meeting of the Geothermal Resources Council, Reno, NV, 24-27 September 1979.

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APPENDIX C

Reports and Publications

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Reports and Publications

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APPENDIX D

Sandia Test Procedures for Testing
Continuous Chain Drill at Nevada Test Site
5-20 June 1979

Sandia Test Procedures for Testing Continuous
Chain Drill at Nevada Test Site 5-20 June 1979

I. Hycalog UH-1 and Christensen MD24 Drilling Procedure

- A. Enter hole and circulate mud at $0.009 \text{ m}^3/\text{s}$ (140 gpm) off bottom to clean up hole.
- B. When hole is clean, start rotation at 50 rpm.
- C. Apply weight on bit slowly until bit starts to drill. Estimated starting weight: 13 to 22 kN (3000 to 5000 pounds).
- D. After drilling 7.6 cm (3 inches), raise bit off bottom 45.7 cm (18 inches) and reduce rotation to 50 rpm. Record change in fluid pressure, then compute the hydraulic pump-off force effect using the Christensen diamond bit calculator.

Example:

Drilling pressure = 6.2 MPa at $0.009 \text{ m}^3/\text{s}$ (900 psi at 140 gpm)

Pressure off bottom = 0.4 MPa at $0.009 \text{ m}^3/\text{s}$ (60 psi at 140 gpm)

$\Delta P = 5.8 \text{ MPa}$ (840 psi)

Christensen computer gives 12.7 kN (2850 pounds) for a 12-cm (4-3/4-inch) hole and a ΔP of 5.8 MPa (840 psi).

- E. Resume drilling at 50 rpm and increase rotation to 100 rpm.
  - F. Apply bit load of 27 kN (6000 pounds) corrected for pump-off force. Calculate penetration rate.
  - G. Establish and maintain a drilling rate of 1.2 m/h (4 ft/hr). Sandia personnel will tell the driller when to add bit weight and at what weight to drill. Maintain 1.2 m/h (4 ft/h) until reaching a maximum bit load of 67 kN (15 000 pounds).
- Note: Pull the bit before reaching 1.2 m/h (4 ft/h) if drilling conditions justify this action.
- H. On reaching a bit load of 67 kN (15 000 pounds), lift 45.7 cm (18 inches) off bottom and reduce rotation to 50 rpm. Record the change in pressure and compute pump-off force as explained in item D.
  - I. Resume drilling at 50 rpm and increase the rotation to 100 rpm. Establish a drilling rate of 1.2 m/h (4 ft/h) or 67 kN (15 000 pounds, corrected for pump-off force). On reaching 67 kN (15 000 pounds) bit load, continue to drill until the rate is reduced to 0.6 m/h (2 ft/h). Then pull the bit.

II. Chain-Drill Field Test Procedure

A. CHAIN SEQUENCE -- Predrilling test using the Sandia test fixture.

1. Chain link sets assembled in following order and impression stamped for identification:
  - a. Link set 10--used
  - b. Link set 9--used (HP)*
  - c. Link set 11--used
  - d. Link set 12--new
  - e. Link set 13--new
  - f. Link set 14--new
  - g. Link set 15--new
  - h. Link set 16--new
  - i. Link set 17--new
  - j. Link set 18--carbide seals
2. START POSITION -- Bit body extended and link set No. 10 engaged with hooks.
3. CONNECT BIT -- Attach drill to test fixture and install nose fixture and splash shield.
4. START RECORDER -- Start instrumentation chart recorder.
5. EXTEND BODY -- Start pumps, increase to $0.01 \text{ m}^3/\text{s}$ (180 gpm) and immediately decrease to $0.010 \text{ m}^3/\text{s}$ (160 gpm). Measure spring extension.
6. LOCK DETENTS -- Apply bit weight of 18 kN (4000 pounds) and wait 15 seconds.
7. ALIGN CHAIN LINK SET NO. 10 -- Raise bit 2.54 cm to 5.08 cm (1 to 2 inches) and increase mud flow to $0.011 \text{ m}^3/\text{s}$ (180 gpm) for 30 seconds. Then reduce mud flow to $0.010 \text{ m}^3/\text{s}$ (160 gpm).
8. INSPECT -- Turn off pumps. Check link alignment.
9. CYCLE 10 to 9 -- Cycle bit from locked position to locked position, link set 10 to link set 9 (note HP for link set 9).
  - a. START PUMPS -- Increase flow to $0.010 \text{ m}^3/\text{s}$ (160 gpm).
  - b. UNLOCK DETENTS -- Apply bit weight of 18 kN (4000 pounds). Turn off pumps. Wait 30 seconds.
  - c. CYCLE CHAIN -- Lift off bottom 25.4 cm (10 inches).

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*(HP) = High-pressure link set to verify chain position under downhole conditions.

- d. EXTEND BODY -- Start pumps, increase flow to 0.011 m³/s (180 gpm) and immediately decrease flow to 0.010 m³/s (160 gpm). Measure spring extension.
- e. LOCK DETENTS -- Apply bit weight of 18 kN (4000 pounds). Wait 15 seconds.
- f. ALIGN CHAIN -- Raise bit 2.54 or 5.08 cm (1 or 2 inches). Increase flow to 0.011 m³/s (180 gpm) for 30 seconds. Then decrease flow to 0.010 m³/s (160 gpm).
- g. INSPECT -- Turn off pumps. Inspect chain alignment.
10. CYCLE 9 to 11 -- Repeat step No. 9 except cycle link set 9 to link set 11.
11. UNLOCK DETENTS -- Apply bit weight of 18 kN (4000 pounds) for 15 seconds and raise bit 25.4 cm (10 inches).
12. PREPARE FOR DRILLING -- Remove deflector shield and prepare bit for drilling.

B. Chain-bit drilling test for link sets 12, 13, 14, 15, and 16, using water for drilling fluid.

1. START POSITION -- Attach chain drill to kelly. Position link set 10 in the drilling position with the body extended and the chain on the hooks.
2. RUN PIPE -- When lowering the drill pipe in the hole, check for proper installation of the bottomhole assembly. Stop off-bottom and circulate at 0.010 m³/s (160 gpm).
3. LOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Then wait for 30 seconds.
4. ALIGN CHAIN -- Raise bit 45.7 cm (18 inches). Increase mud flow to 0.011 m³/s (180 gpm) for 30 seconds. Then reduce mud flow to 0.010 m³/s (160 gpm).
5. CYCLE 10 to 9 -- Cycle bit to bring link set 9 into drilling position.
  - a. MUD FLOW -- Pumps at 0.010 m³/s (160 gpm).
  - b. UNLOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Turn off pumps. Wait 3 minutes.
  - c. CYCLE CHAIN -- Lift off bottom 45.7 cm (18 inches).
  - d. EXTEND BODY -- Start pumps, increase mud flow to 0.011 m³/s (180 gpm). Then immediately reduce mud flow to 0.010 m³/s (160 gpm). Check pressure signature.

e. LOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Wait 30 seconds.

f. ALIGN CHAIN -- Raise bit 45.7 cm (18 inches). Increase mud flow to 0.011 m³/s (180 gpm) for 30 seconds. Then increase mud flow to 0.010 m³/s (160 gpm). Check pressure signature.

6. CYCLE 9 to 11 -- Repeat step No. 5 to bring link set 11 into drilling position.

7. ROTATION -- Start rotation at 50 rpm.

8. START DRILLING -- Slowly add weight on bit and start drilling. Then increase rotation to 100 rpm.

Note: Diamonds are flat on link set 11, so it may take bit weight of 45 kN (10 000 pounds) to start drilling.

9. STOP DRILLING -- After drilling 15.2 cm (6 inches) or 15 minutes, raise bit 45.7 cm (18 inches) off bottom. Stop rotation.

10. CYCLE 11 to 12 -- Repeat step No. 5 to bring link set 12 into drilling position.

11. ROTATION -- Start rotation at 50 rpm.

12. START DRILLING -- Slowly add weight on bit and start drilling. Increase rotation to 100 rpm and drill 7.6 cm (3 inches).

Note: Diamonds are new and sharp on link set 12. Bit should start drilling at 9 kN to 18 kN (2000 to 4000 pounds).

13. PUMP-OFF -- Raise bit off bottom 45.7 cm (18 inches) and reduce rotation to 50 rpm. Calculate pump-off force using Christensen computer and correction factor of 0.43.

14. RESUME DRILLING -- Resume drilling at 50 rpm and increase rotation to 100 rpm. Establish a drilling rate for bit weight of 20 kN (4500 pounds), corrected for pump-off force. Then increase or decrease bit weight as required to establish a rate of 1.2 m/h (4 ft/h). Sandia will tell driller at what weight to drill. Maintain 1.2 m/h (4 ft/h) until reaching a maximum bit load of 67 kN (15 000 pounds).

15. PUMP-OFF -- On reaching bit weight of 67 kN (15 000 pounds), raise bit off bottom 45.7 cm (18 inches) and reduce rotation to 50 rpm. Calculate pump-off force.

Notes

- a. This procedure is written for drilling at a minimum drilling rate; however, where differences exist, follow the drilling schedule specified for each chain link.
  - b. If the surface drilling conditions indicate bottomhole problems, then cycle the chain or pull the bit prior to the scheduled drilling depth or minimum rate, after evaluation has been made to take corrective action.
16. RESUME DRILLING -- Apply weight on bit and maintain drilling rate of 1.2 m/h (4 ft/h), but don't exceed 67 kN (15 000 pounds) bit weight. Correct bit weight for pump-off force. After reaching 67 kN (15 000 pounds) of bit weight, continue drilling at constant bit weight of 67 kN (15 000 pounds) until drilling rate reaches the rate specified in the drilling schedule.
  17. CYCLE 12 to 13 -- Cycle chain per "Bit Cycling Procedure from Drilling Position."
  18. Repeat steps B-9 thru B-15 for link sets 14, 15, and 16. If circulation can be maintained, drill link sets 17 and 18 with 1126 kg/m³ (9.4 lb/gal) of mud; otherwise drill link sets 17 and 18 with water.
  19. If mud was used last, circulate hole until water returns or for 30 minutes.
  20. Pull the chain drill.

III. Bit Cycling Procedure From Drilling Position

- A. STOP ROTATION -- Raise bit off bottom 45.7 cm (18 inches) and stop rotation.
- B. UNLOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Turn off pumps. Wait 3 minutes.
- C. CYCLE CHAIN -- Raise bit off bottom 45.7 cm (18 inches).
- D. EXTEND BODY -- Start mud pumps. Increase mud flow to 0.011 m³/s (180 gpm). Then immediately reduce mud flow to 0.010 m³/s (160 gpm). Check pressure signature.
- E. LOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Wait 30 seconds.
- F. ALIGN CHAIN -- Raise bit off bottom 45.7 cm (18 inches). Increase mud flow to 0.011 m³/s (180 gpm) for 30 seconds. Then reduce mud flow to 0.010 m³/s (160 gpm).

IV. Procedure for Adding Drill Pipe From Drilling Position

- A. Raise bit off bottom 45.7 cm (18 inches).
- B. Stop rotation.
- C. Turn off pumps.
- D. Add drill pipe.
- E. Turn on pumps 0.010 m³/s (160 gpm).
- F. Start rotation at 50 rpm.
- G. Start drilling and increase rotation to 100 rpm.
- H. Establish rate of 1.2 m/h (4 ft/h) or maximum load 67 kN (15 000 pounds), as applicable.

V. Emergency Procedures

- A. Pressure signature remains low--does not change when chain is cycled.

1. Possible Causes

- a. Detents do not unlock.
- b. Chain fails to open because of friction.
- c. Chain does not open all the way.

2. Corrective Action

- a. Weight on bit of 36 kN (8000 pounds).
- b. Pumps turned off for 4 minutes.
- c. Raise bit 45.7 cm (18 inches) quickly.
- d. Turn pumps on and increase to 0.013 m³/s (200 gpm). Then immediately reduce to 0.010 m³/s (160 gpm).
- e. Check pressure signature.
- f. If pressure signature not correct for item "e," repeat steps "a" thru "e" two more times.

- B. Chain does not align after locking the detents and raising the bit off bottom. Pressure signature is higher than normal.

1. Possible Causes

- a. Alignment cylinder stuck.

- b. High friction in chain, or chain obstructed.
- c. Chain out of sequence and link set 9 in place.

2. Corrective Action

- a. Turn pumps on and increase mud flow to $0.015 \text{ m}^3/\text{s}$ (240 gpm) for 30 seconds. Then reduce mud flow to $0.010 \text{ m}^3/\text{s}$ (160 gpm). Check pressure signature.
  - b. If no change in pressure signature, apply 36 kN (8000 pounds) weight on bit. Turn the pumps off and wait 4 minutes.
  - c. UNLOCK DETENTS -- Raise quickly off bottom 45.7 cm (18 inches).
  - d. CYCLE CHAIN -- Turn pumps on and increase mud flow to $0.013 \text{ m}^3/\text{s}$ (200 gpm). Then immediately decrease to $0.010 \text{ m}^3/\text{s}$ (160 gpm). Check pressure signature.
  - e. If chain cycled, proceed as follows:
    - i. LOCK DETENTS -- Apply bit weight of 22 kN (5000 pounds). Wait 30 seconds.
    - ii. Raise bit off bottom 45.7 cm (18 inches).
    - iii. ALIGN CHAIN -- Turn pumps on and increase mud flow to $0.011 \text{ m}^3/\text{s}$ (180 gpm) for 30 seconds. Then reduce mud flow to $0.010 \text{ m}^3/\text{s}$ (160 gpm). Check pressure signature.
  - f. If pressure signature indicates that chain did not cycle in item "e," then go to Emergency Procedure A.
- C. Cycle chain before reaching drilling rate of 0.6 m/h (2 ft/h).
- 1. Possible reasons for cycling chain bit
    - a. Bit weight starts to fluctuate more than normal (rough drilling).
    - b. Drilling rate drastically changes.
    - c. Fluid pressure shows rapid increase or decrease.
    - d. For any situation that is not considered normal, or when possible damage could occur to the bit.

D. Pull the chain bit for surface inspection.

- 1. Possible reason for pulling chain bit

- a. Chain will not cycle.
- b. After cycling a new set of chain links into place, if
  - i. Drilling rate remains low.
  - ii. Mud pressure remains high or low.
  - iii. Rough-drilling bit load fluctuates.
- c. Pressure signatures are not following cycling sequence.
- d. For any situation that is considered hazardous for the bit, and when damage or loss could occur.

APPENDIX E

AN ASSESSMENT OF THE POTENTIAL OF CAVITATING JETS
FOR DEEP-HOLE DRILLING

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AN ASSESSMENT OF THE POTENTIAL OF CAVITATING JETS FOR DEEP-HOLE DRILLING

Introduction

The cavitation phenomenon has traditionally been regarded as undesirable in fluid-flow endeavors. The realization that its destructive powers might be an advantage in drilling operations has resulted in a more positive attitude towards this phenomenon.

Cavitating jets offer the potential for using hydraulic power more efficiently than do other techniques to better clean the hole bottom and to actually assist mechanical cutters in fracturing rock. The extreme high-impact pressures of cavitation bubbles collapsing on a solid surface give this potential.

The Mechanics of Cavitation -- Cavitation is the formation, growth, and collapse of vapor-filled cavities in liquid flows.¹ In studying and discussing this phenomenon, it is useful to refer to a dimensionless parameter called the cavitation number, defined as

$$\sigma \approx \frac{P_a}{P}$$

where

p_a = ambient pressure surrounding jet and

p = nozzle-pressure drop.

In a general nozzle-flow situation, the value of σ can be varied widely by changing either the ambient pressure or the nozzle-pressure drop. For a given nozzle, there is some value of σ referred to as the incipient cavitation number, σ_i , above which cavitation does not occur and below which cavitation occurs to greater degrees as σ decreases.

Cavity formation is typically a high-speed event, and, as a result, high radial velocities are imparted to the cavity wall and surrounding fluid. The outward inertia of this fluid is the driving force in cavity growth. In using cavitation for drilling, cavity growth assumes less importance than both cavity formation and cavity collapse, since the latter two processes are the controlling factors in rock damage potential.

In the study of cavity collapse, experimental results have shown that maximum collapse pressures in the center of cavities can reach 1035 MPa (1.5×10^5 psi).²⁻³ The general conclusion was that, when cavities collapse, strong shock waves stress and damage the surfaces on which they collapse. A more convincing theory of the cavitation damage mechanism postulates the formation of a microjet upon cavity collapse which pierces the cavity and impinges on the collapse surface. Evidence that the major damage results from microjet rather than shock wave impingement is supplied by experimental⁴⁻⁸ and theoretical⁹⁻¹⁰ studies.

The Effects of Downhole Conditions -- The possibility of employing the destructive forces of cavitation for deep-hole drilling requires a determination of the effects of downhole conditions on the cavitation phenomenon.

Theoretically, ambient temperature should affect cavitation inception through the temperature's influence on vapor pressure and on other factors affecting liquid tensile strength and critical pressure. The critical pressure is negligible when compared to the much larger ambient pressures expected downhole; thus the ambient temperature effect on cavitation inception would be expected to be rather small.

The effects of ambient temperature on cavitation damage were shown experimentally by J. Mousson, who demonstrated that raising the ambient temperature from 10 to 30°C (50 to 86°F) brought about a three-fold increase in the damage rate for bronze.¹¹ No similar studies with rock are known to have been reported.

The effects of ambient pressure on cavitation inception are based on the fact that cavity formation requires a local reduction in pressure; this pressure reduction involves local transformation of energy from potential, in the form of pressure, to kinetic, in the form of velocity. This transformation occurs through the mechanism of vortex formation. The vortex-core velocities are higher than the mean jet velocity, resulting in a local reduction in pressure from that of the ambient atmosphere. The higher the ambient pressure, the greater this reduction--and, therefore, the greater the vortex-core velocities--must be in order to achieve the critical pressure locally.

The only condition for cavitation at high ambient pressures is that the jet shear zone be sufficiently strong to induce high vortex-core velocities. This requires either higher nozzle-pressure drops or improved nozzle designs at the higher ambient pressures encountered downhole. For a given nozzle, there is an approximately linear relationship between ambient pressure and the nozzle-pressure drop required to initiate cavitation. This implies that the incipient cavitation number σ_i ($P_a/\Delta p$) is relatively constant with ambient pressure.

W. Baker has proven that cavitation can occur at downhole conditions.¹² A convergent-divergent nozzle was used in a two-cone, tungsten carbide, insert bit to provide roller-cone cleaning. The bit was run in the North Sea through a depth interval of 441 to 1535 metres (1447 to 5035 feet) with a 1222.2-kg/m³ (10.2-lb/gal) mud. When the bit was pulled, the divergent section of the nozzle displayed extreme surface pitting due to unintended cavitation in the separated region immediately downstream of the

throat of the nozzle. This demonstrates that cavitation can and does occur under high ambient pressures, even in cases where cavitation inception is not a specific design goal.

Cavitation damage increases with ambient pressure since pressure is the driving force for cavity collapse. The higher the pressure, the more rapid and violent the collapse and the higher the microjet stagnation pressures. The peak in cavitation damage as a function of cavitation number reflects the existence of an optimum condition. At high cavitation numbers, fewer cavities are formed, reducing the damage potential. At low cavitation numbers, more cavities are formed, but the damage potential of individual cavities is reduced due to the relatively lower ambient pressures. At some point, an optimum cavitation condition σ_{opt} exists between the number of cavities formed and the damage potential of individual cavities, so that overall cavitation damage potential is maximized.

Since cavitating jets require lower nozzle pressures than noncavitating jets to cut rock, this leads to the conclusion that cavitating jets can potentially be used on existing drilling rigs without costly modifications to drill pipe, pressure seals, swivels, and mud pumps.

The most extensive research in cavitation rock drilling has been conducted by Hydronautics, Inc. Their patented Cavijet™ nozzles have been used to cut rock under simulated downhole conditions. Initial tests demonstrated that cavitating jets produced by these nozzles can effectively cut rock at an equivalent borehole depth of 1768 metres (5800 feet) using a 1198-kg/m³ (10-lb/gal) mud.¹³ These tests demonstrated for the first time the deep-hole drilling potential of cavitating jets and have led to further research, still under way, in the Geothermal Drilling and Completion Technology Program.

Drilling tests were conducted at Terra Tek's Drilling Research Laboratory with a two-cone roller bit under simulated downhole conditions. The bit was run with both the conventional nozzles and with Cavijet™ nozzles. Figure E-1 illustrates certain results of penetration rate versus borehole pressure for the same roller-cone bit using the conventional and Cavijet™ nozzles. The results show that the Cavijet™ nozzles achieve higher penetration rates than conventional nozzles over a wide range of borehole pressures. The Cavijet™ nozzles were deprived of a certain potential for bottomhole scavenging due to 39% less discharge than the conventional nozzles of the same size; higher flow rates through the conventional nozzles accounted for the difference. Furthermore, the Cavijet™ nozzle standoff distance was not optimized for maximum effectiveness in these tests.

Future Cavitation Drilling Research -- The potential of cavitating jets for deep-hole drilling has been shown. In light of this potential, two additional research programs in cavitation drilling are planned. The first of these programs is the second phase of the ongoing research currently funded. This work will concentrate on optimizing Cavijet™ nozzle design, optimizing nozzle placement in mechanical bits, and conducting full-scale laboratory tests of conventional and Cavijet™-augmented mechanical bits.

The second research program, initiated during this reporting period, pertains to the development of a downhole resonator to provide pulsing, nozzle-supply pressures. The advantage of pulsing nozzle pressures is that instantaneous pressures which are higher than the average pressure supplied by the pump are possible. This results in higher damage potentials than are possible with steady jets at the same average pump pressure.

The results of these research programs will be used to assess the feasibility of the concepts and, if promising, to define a long-range research program to develop a practical drill bit incorporating the concepts presented.

BIT: 200-m (7-7/8-in.) DIA., TWO-CONE ROLLER BIT
 EXTENDED NOZZLES: TWO, 6.4-mm (1/4-in.) ORIFICE DIA.
 NOZZLE STANDOFF: 15.9 mm (5/8 in.)
 NOZZLE PRESSURE: 16.6 MPa (2400 psi) (NOMINAL)
 DRILLING FLUID: MUD, 1102.4 - 1114.4 kg/mm³ (9.2 - 9.3 lb/gal)

BIT WEIGHT: 4536 kg (10 000 lb)
 ROTATION: 60 rpm
 ROCK: COLTON SANDSTONE

Figure E-1. Penetration Rate versus Borehole Pressure. The chart shows data for a two-cone roller bit using conventional and Cavijet™ nozzles (Hydronautics data, interim contract report, October 1978).

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APPENDIX F

RADIAL THERMAL GRADIENTS IN A PRODUCING GEOTHERMAL WELL

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AN ANALYSIS OF RADIAL THERMAL GRADIENTS IN A PRODUCING GEOTHERMAL WELL

Introduction

A commonly cited failure in a completed geothermal well is the collapse of production casing due to rapid pressure rises in water pockets trapped in the cement between intermediate and production casing strings. In the transient period when the well is brought in and production begins, large temperature gradients may exist between the inner production casing and the concentric intermediate casing. The stresses induced by differential thermal expansion coupled with highly localized vapor pocket expansion pressures are sufficient to produce catastrophic failure in the inner casing.¹

The wellbore thermal simulator GEOTEMP² has been used to calculate transient temperatures in the flowing fluid, completion, and surrounding soil of a producing well as preliminary thermal input to a casing stress analysis. Radial temperature distributions at a sample well depth of 305 metres (1000 feet) are presented for two typical steady flowing conditions. Particular attention is given to identifying heating rates in the fluid and completion and to the magnitude of the transient gradients existing between the fluid and cement-filled annulus between production and intermediate casing strings.

The Model Production Well

The sample well model chosen is typical of well completions in geothermal fields as widely separated as Southeastern California, New Zealand, and Japan (for example, see References 1, 3, and 4). Figure F-1 represents the completed well and shows the temperature profile in the undisturbed formation. The casing schedule is shown in Table F-1.

For this example, it is assumed that cementing is complete, and the completion is allowed to come to the undisturbed formation temperature prior to producing the well. In general, this would not be the case, as completion temperatures are perturbed during drilling circulation and cementing. Since the circulating fluids tend to elevate the wellbore temperatures, this analysis will yield proportionately higher transient gradients. In addition, it is implicitly assumed that no flashing to steam occurs in the well and that bottomhole pressure is high enough to flow the well at the specified volume without pumping. The steady flow conditions are for high-pressure water entering the borehole at 163°C (325°F) and at least 13.79 MPa (2000 psig), with flow rates of 0.013 and 0.025 m³/s (200 and 400 gal/min); that is, 9000 and 18 000 barrels per day. A cross section of the completion at a depth of 305 metres (3000 feet) is shown in Figure F-2, indicating the location of computed temperatures.

Figure F-1. Well Schematic and Undisturbed Temperature

Table F-1

Casing Schedule

	<u>I.D., cm</u> <u>(inches)</u>	<u>O.D., cm</u> <u>(inches)</u>	<u>Setting Depth,</u> <u>metres (feet)</u>
Production Casing: fully cemented	22.05 (8.68)	24.447 (9.625)	1 524 (5 000)
Intermediate Casing: cemented 518 metres (1 700 feet)	31.67 (12.35)	33.972 (13.375)	762 (2 500)
Surface Casing: fully cemented	48.56 (19.12)	50.80 (20.00)	305 (1 000)
Surface Conductor: fully cemented	72.50 (29.00)	76.20 (30.00)	30 (100)

Note: I.D. = inner diameter
O.D. = outer diameter

Numerical Results and Discussion

Transient temperatures at selected times during startup are shown in Figures F-3 through F-8 for steady flows of 0.013 and 0.025 m³/s (200 and 400 gal/min). The graphs are not true temperature distributions; the discrete computed temperatures have been connected for clarity. In Figures F-3 and F-4 temperatures during the first 12 hours of flow at 0.013 m³/s (200 gal/min) are shown. The fluid is apparently cooled rapidly in the initial flow stage, attaining a temperature of only 99°C (210°F) at 305 metres (1000 feet) and 37°C (98°F) at the surface. It is natural that the production fluid should cool considerably as it first flows in a wellbore that is initially cooler than the reservoir. In this model, the wellbore temperature drops linearly from 163°C (325°F) to 121°C (250°F) at 488 metres (1600 feet) and then drops linearly to surface temperatures on the order of 21 to 32°C (70 to 90°F). The rate at which heat may be removed from the fluid to the formation is dominated by conduction through the radial composite of steel casing, cement-filled annuli, and soil. A simplified formulation of the governing equations shown in Figure F-9 reveals the salient terms in the heat transfer. Since conduction has been neglected in both radial and axial directions in the fluid, the only contributing mechanism is forced convection. In Equation 2, Figure F-9, the

Figure F-2. Well Cross Section at 305-metre (1000-foot) Depth

Figure F-3. Radial Temperatures at 305-metre (1000-foot) Depth

Figure F-4. Radial Temperatures at 305-metre (1000-foot) Depth

Figure F-5. Radial Temperatures at 305-metre (1000-foot) Depth

Figure F-6. Radial Temperatures at 305-metre (1000-foot) Depth

Figure F-7. Radial Temperatures at 305-metre (1000-foot) Depth

Figure F-8. Radial Temperatures at 305-metre (1000-foot) Depth

For the control volume shown, assuming steady flow and constant properties, the following apply:

CONTINUITY

$$(\rho AV)_z = (\rho AV)_{z+dz} = \dot{m} \quad (1)$$

FLUID ENERGY EQUATIONS

$$\frac{\partial E}{\partial t} = \dot{m} h_{in} - \dot{m} h_{out} - Q_{conduction}$$

$$\rho C_p \Delta V \frac{\partial T_f}{\partial t} = \dot{m} C_p \frac{\partial T_f}{\partial z} \Delta z - \bar{U} A_s (T_f - T_s)$$

$$\frac{\partial T_f}{\partial t} + v \frac{\partial T_f}{\partial z} = - \left(\frac{2\bar{U}}{\rho C_p r_o} \right) (T_f - T_s) \quad (2)$$

SOLIDS CONDUCTION EQUATION

$$\frac{\partial T_s}{\partial t} = \left(\frac{k}{\rho c} \right)_s \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_s}{\partial r} \right) \quad (3)$$

Figure F-9. Equations Governing Heat Transfer

fluid temperature gradient in the flow direction is weighted by the flow velocity in the convective term. The term on the right couples the fluid convection with the conduction in the completion and soil. The coupling coefficient may be seen to be an effective time constant; a ratio of the inner heat transfer coefficient and the fluid thermal capacity. The pipe Reynolds number at the flow rates in question are on the order of 5 000 000. For such a highly turbulent flow, the heat transfer coefficient at the inner wall is high (depending on the fluid temperature, coefficients have computed values from 1702 to 2270 W/m²·K (300 to 400 Btu/h·ft²·°F), resulting in a strong coupling between the fluid/solid temperatures. The single parameter in the transient conduction is the ratio of thermal conductivity to heat capacity--the diffusivity, as shown in Equation 3, Figure F-9. The thermal diffusivity is an indicator of the thermal response of the material to an imposed heat flux. Materials such as cement and soil have a relatively low conductivity to thermal capacity ratio, and their thermal response is slow compared to the steel casing for example.

Although significant heat loss occurs in the first hour of flow, as shown in Figures F-3 and F-4, the fluid temperature increases to approximately 80% of its steady value after 4 hours of flow. The annulus cement is heated at a considerably lower rate, producing large differences in temperature during this period. This trend is demonstrated in the thermal response curves for the fluid and cement plotted in Figure F-10. Although the temperatures are most rapidly increasing at very early times, the greatest radial temperature gradients occur after approximately 1 hour of flow. In this first case, the temperature difference between fluid and cement is 32.5°C (58°F) after 1/2 hour and 34.2°C (61°F) after 1 hour. It is of further interest to note in Figure F-5 that the completion and fluid temperatures are quasi-steady after 12 hours of flow but the soil temperatures continue to climb at a much lower rate even beyond a 30-day period.

The bulk fluid Reynolds number is the dominant parameter in the convection, governing the rate of energy transport by the fluid. The internal pipe-heat transfer coefficient scales as the Reynolds number taken to a power less than unity and, consequently, is proportional to the fluid velocity. However, the radial heat flow is strongly dependent on the conduction rate in the soil, and an increase in the flow velocity could reasonably be expected to affect, to a greater extent than the completion temperatures, the rate at which the fluid temperature increases with time. In Figures F-6 through F-8 the transient wellbore temperatures are plotted for a flow rate of 0.025 m³/s (400 gal/min). In the first 1/2 hour of flow, the fluid temperatures are higher by an average of 11.2°C (20°F) over those at the lower flow rate, and the fluid reaches a near-steady value after 2 hours. Furthermore, the annulus temperatures are not significantly different. Comparison of the response of fluid and cement at this flow rate, as shown in Figure F-11, reveals a much steeper time rate-of-change of fluid temperature within the first 2 hours of flow, with the result that the radial temperature gradients are more severe, as expected. As in the previous case, the maximum temperature difference between fluid and annulus occurs after approximately the first 1/2 hour of flow when ΔT is 43.7°C (78°F). Beyond the first 12 hours of flow, the soil temperatures continue to increase slowly, and from Figure F-8, it is apparent that the increased production rate does not significantly increase the rate at which the far field is heated.

Figure F-10. Thermal Response Curves for the Fluid and Cement

Figure F-11. Thermal Response Curves for the Fluid and Cement

Conclusions

Transient radial temperatures in a producing geothermal wellbore have been computed at a sample depth of 305 metres (1000 feet) for steady flow rates of 0.013 and 0.025 m³/s (200 and 400 gal/min) and are plotted in Figures F-3 through F-8. It is shown that, although the fluid undergoes considerable cooling in the initial production period, its temperature increases to a near-steady value of 160°C (320°F) within hours; for flow rates of 0.013 and 0.025 m³/s (200 and 400 gal/min), this takes approximately 4 and 2 hours, respectively. During this period, the rate at which the completion is heated is considerably lower, and large temperature gradients occur in the completion. This occurs principally because of the high heat capacity of the completion materials. The most severe gradients occur between the inner production casing and the intermediate casing. At the lower flow rate, the temperature drop between fluid and cement-filled annulus is 34.2°C (61°F) after the first hour of flow; for twice this flow, the temperature drop is 43.7°C (78°F) in the same time period. It is significant that these gradients occur within an annulus gap width of 4.3 cm (1.7 inches). An investigation of the heat transfer mechanisms in the wellbore indicates that the severity of the gradients are dependent on several variables:

1. Initial production flow rate,
2. Entering (bottomhole) temperature,
3. Initial undisturbed wellbore temperatures, and
4. Completion and formation thermal properties.

The heating trends and radial temperature distributions presented in this preliminary study can be used to assess the magnitude of potential casing stresses produced by differential thermal expansion. Continuing work in this area will include an effort to correlate in detail the sensitivity of radial temperatures to the aforementioned variables. In addition, the transient boiling occurring in cement vapor pockets trapped in casing annuli will be examined to deduce the magnitude of local pressures and their dependence on heating rate.

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