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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY
DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT
January-March, 1980

MASTER

Samuel G. Varnado, Editor

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

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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
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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 (DOE/DGE), with program management provided by Sandia National Laboratories. The program emphasizes the development of geothermal drilling hardware, drilling fluids, completion technology, and lost circulation control methods. 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 1983 and by 50% by 1987.

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GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
QUARTERLY PROGRESS REPORT

January-March 1980

1. INTRODUCTION

The high cost of drilling and completing geothermal wells is an impediment to the timely development of geothermal resources in the U.S. The Division of Geothermal Energy (DGE) of the Department of Energy (DOE) has initiated a development program aimed at reducing well costs through improvements in the technology used to drill and complete geothermal wells. Sandia National Laboratories (SNL) has been selected to manage this program for DOE/DGE. Based on analyses of existing well costs, cost reduction goals have been set for the program. These are to develop the technology required to reduce well costs by 25% by 1983 and by 50% by 1987.

To meet these goals, technology development in a wide range of areas is required. The near-term goal will be approached by improvements in conventional, rotary drilling technology. The long-term goal will require the development of an advanced drilling and completion system. Currently, the program is emphasizing activities directed at the near-term cost reduction goal, but increased emphasis on advanced system development is anticipated as time progresses.

The program is structured into six sub-elements: Drilling Hardware, Drilling Fluids, Completion Technology, Lost Circulation Control Methods, Advanced Drilling Systems, and Supporting Technology. Technology development in each of these areas is conducted primarily through contracts with private industries and universities. Some projects are conducted internally by Sandia.

This report describes the program, status, and results of ongoing R&D within the program for the quarter January-March 1980.

FISCAL YEAR 80

LEGEND: **ACTIVITY PERIOD**   ○ **PLANNED START**   ▽ **PLANNED COMPLETION**
                  - - - - -   **RESCHEDULED**   ● **STARTED**   ▼ **COMPLETED**

2. MANAGEMENT

Highlights

- Management -- DOE has requested that Sandia organize, sponsor, and conduct an international conference on geothermal drilling and completion technology. The conference is tentatively scheduled for 21-23 January 1981 at the Four Seasons Hotel in Albuquerque, New Mexico.

- Percussion Drilling Hammer and Bit Tests -- Tests of percussion drilling equipment were completed. A conventional roller-cone bit, two "oil field" hammers with roller bits, and three hammers with solid bits were used to drill into uniform granite samples. The penetration rate was measured for each tool. Two hammers with solid bits achieved a penetration rate of 21.3 m/h (70 ft/h), a rate more than five times as fast as that achieved by conventional, rotary drilling. The hammers were also operated at high temperature--177°C (350°F), and their high-temperature failure modes, caused by plastic valve parts, were identified. Evaluation of the test data and planning of additional efforts are continuing.

- Internal Research and Development--High-Temperature Perforator -- A project to design a downhole perforator capable of functioning properly at temperatures to 300°C (572°F) for geothermal well completion was initiated this quarter.

- Advanced Wellbore Thermal Code -- A project to develop an advanced computer code for predicting transient wellbore temperatures during drilling, circulation, injection, and production in geothermal wells was initiated this quarter. The development will include modification of the existing code to accommodate single-phase compressible flow.

- Development of Improved Cavijet® Nozzles -- A project to increase knowledge of Cavijet® nozzle design principles and to develop Cavijet® nozzles which achieve increased incipient and optimum cavitation numbers was initiated during this reporting period.

- Drilling Fluid/Formation Interactions -- A project to continue the study of drilling fluid/formation interactions under laboratory conditions was initiated near the end of this reporting period. This second phase of the study will investigate filtrate chemistry effects, particle size distribution, and development of laboratory equipment to simulate formation damage in a fractured formation.

Program Planning

An overall assessment of the Geothermal Drilling and Completion Technology Development Program was conducted, and a decision was made to adjust the schedule so that achievement of the program goals would be more compatible with the available resources. The scheduled achievement of the goal to develop the technology required to reduce well costs by 25% by 1982 has been changed to 1983; for a 50% reduction of well costs, the time frame has been extended from 1986 to 1987.

Systems Analysis

Foster-Miller presented a briefing to Sandia on the data it has collected concerning Gulf Oil Company's experiences in abrasive jet drilling. Foster-Miller's efforts on the characterization of abrasive drilling systems are nearing completion.

Scientific Applications, Inc.'s, work on rig rate calculation has been completed and briefed to Sandia. The algorithm for computing rig rates and a review draft of the final report were delivered to Sandia.

BDM presented early results to Sandia on the company's cost-of-energy work. A discussion was also held on the drilling survey work that Sandia is planning.

Livesay Consultants briefed Sandia on the firm's well plan for a "typical" Geysers well and discussed the Imperial Valley well plan that is nearing completion.

Lost Circulation

As part of Sandia's activities to develop a program in lost circulation control methods, a visit was made to Los Alamos National Scientific Laboratory (LANSL) to discuss drilling and completion problems with personnel involved in the Hot Dry Rock program. One of LANSL's biggest drilling problems is lost circulation and the biggest completion problem is maintaining hole competency long enough to run casing. Several ideas for solving some of these problems were discussed, and the impact of lost circulation on well cost was assessed.

In order to learn more about the lost circulation problem in drilling geothermal wells, the following companies were contacted: Magcobar, Exxon Production Research, The Brandt Co., Shell Development Co., Baroid, Amoco, and Loffland Brothers Co. Discussions involved persons with a variety of backgrounds and interests; however, several consensual points were made. Lost circulation may be caused, or aggravated, by drilling techniques. Such techniques include poor solids control and large pressure surges caused by "chasing" the pipe or quick pump starts. It is important to first determine the location, size, and temperature of the loss zone. In the opinion of all persons contacted, more information is needed on the properties of drilling muds and lost circulation additives at elevated temperature.

A visit was made to the Nevada Test Site (NTS) to discuss dual-string drill pipe with Fenix & Scisson personnel. This equipment may reduce the lost circulation problems which prevail in geothermal drilling.

Drilling Fluids

Loffland Brothers Company and Production Operators met with Sandia to discuss planning for a field test of a cryogenic nitrogen generation unit. The test will be conducted in the Baca location in northern New Mexico during May and June of 1980. The purpose of the experiment is to establish performance and cost characteristics of a portable, cryogenic system for generating nitrogen for use as a drilling fluid and to determine the drill string corrosion rates using conventional drilling fluid as compared with the nitrogen drilling fluid. Corrosion is one of the most significant cost factors in drilling in geothermal wells, and the use of a low-density, oxygen-free fluid should substantially reduce these costs. Sandia is responsible for designing the experimental arrangement and for coordinating the tests with Union Oil Company, the drilling contractor, and Production Operators personnel.

A trip was also made to Union Geothermal at The Geysers field to delineate specific areas of responsibility for the planned field test of the portable nitrogen generation unit. The general experimental configuration was discussed in detail, and agreement was reached on the various responsibilities for the test. Through contract with Production Operators, Sandia will supply the nitrogen generation unit, and Union will supply the corrosion probes, corrosion coupons, and several sections of new drill pipe so that the corrosion rates can be accurately measured. The plan calls for drilling with aerated water for approximately 3 days. During that time, drilling will begin at a depth of 1067 metres (3500 feet) and stop at 1295 metres (4250 feet). At this level, the nitrogen system will be activated and used in drilling for 3 days to approximately 1524 metres (5000 feet). A shift will then be made back to the air-water mixture to drill the well to a total depth of about 1829 metres (6000 feet). Then, the nitrogen unit will be reactivated, and nitrogen will be circulated in the well without drilling for about 3 days so that the corrosion rates can be established. Union Geothermal will supply six new joints of drill pipe. Three will be placed at the top of the well and three at the bottom of the well. The pipe will be inspected before and after the use of the different fluids so that corrosion rates can be determined.

Completion Technology

Exxon Production Research visited Sandia for briefings on a number of Sandia's energy programs. During the course of these briefings, Exxon described its work on analytical and experimental verifications of the processes involved in displacing drilling mud by cement during completion of oil wells. Since this topic is of utmost importance in geothermal wells, Sandia made a follow-up contact with Exxon. Exxon extended an invitation to Sandia to visit its Houston facility and also arranged a visit to Halliburton, Inc., to observe other experimental work. These visits and subsequent discussions will guide future work in cement placement technology development for geothermal wells.

Drilling Hardware

Discussions were held with Dyna-Drill concerning its development of a new geothermal turbodrill. Dyna-Drill initiated the development of this tool as a direct result of our Workshop on Advanced Drilling Systems which was conducted in January 1979. The main problem in utilizing a turbodrill in geothermal environments is premature failure of the bearing and seal package. This problem arises because of high-temperature degradation of the elastomers and greases commonly used for these applications. Dyna-Drill has developed a new bearing/seal package. This package has been tested at low temperature. Dyna-Drill intends to test this turbine in a geothermal well in Brawley, California. If the test is successful, the company may be interested in working with Sandia to further improve the bearing and seal package. This new development by private industry may allow acceleration of our program in the development of downhole motors and high-speed bits.

Los Alamos National Scientific Laboratory (LANSL) has a critical need to drill highly accurate directional holes in the Hot Dry Rock program. LANSL has purchased two turbodrills from Maurer Engineering. These turbodrills use unsealed bearings and are powered by water. The bearings are unsealed because of the current nonavailability of high temperature seals.

A 19.7-cm (7.75-in.) Maurer turbodrill was used with some degree of success in a previous Hot Dry Rock well. Subsequently, an effort was made to construct two 13.7-cm (5.375-in.) turbodrills for use in the lower part of the hole where the bit diameters are smaller. These turbines were recently tested at the Gearhart-Owen facility in Dallas and failed. Two basic problems were identified. The first is the control of the speed of the turbine. In the field test, speed was either 0 or 2000 rpm, with very little operation at speeds in between these two extremes. This lack of speed control is a function of blade design and bit torque. The second problem is premature failure of the thrust bearing. In the 13.7-cm (5.375-in.) turbodrill, higher bearing loads are encountered and the unlubricated bearings are inadequate.

As presently designed, it is unlikely that LANSL will be able to use the two turbodrills. DOE/DGE requested that Sandia provide assistance to LANSL in trying to correct some of the problems with the existing turbodrill. Meetings have been conducted with Maurer and LANSL to coordinate the effort. The main constraint is that LANSL needs an operating turbine by 1 July 1980; delivery of a tool by that time frame cannot be assured. However, Sandia will assist LANSL in performing laboratory tests to determine the bit weight and torque requirements that would be needed to control the speed of the turbine. We will also assist by testing a sealed bearing package based on the results of our bearing and seal package development program. A series of laboratory tests commencing in mid-April are planned. If these tests are successful, it may be possible to provide a turbine which would operate for a sufficiently long period of time to meet the LANSL requirements.

Supporting Technology

Sandia National Laboratories' studies indicate that coating rubber seals, O-rings, or packers with a chemically resistant film may improve the capability of these parts to survive severe environments in geothermal or deep oil and gas wells. These environments include high temperatures (150 to 360°C [302 to 680°F]), high pressures (up to 48.3 MPa [7000 psi]) and corrosive well fluids such as water, steam, brine, CO², and H₂S, all of which cause elastomers to fail from extrusion and thermochemical degradation.

Sandia tests conducted at the University of Arizona and designed to simulate downhole conditions involved coating elastomer pieces with Parylene C, a polymer, or tetrafluoroethylene (TFE), a fluorocarbon similar to Teflon. Neither coating had been used previously to coat elastomers, although both had been used extensively as environmental barriers for metals, ceramics, fabrics, and plastics.

A 0.037-mm- (0.0015-inch-) thick film of Parylene C was deposited onto elastomers by Union Carbide's vapor phase, pyrolytic method, while a 0.038-mm- (0.0015-inch-) thick film of TFE was deposited on other samples by glow discharge polymerization, a diffusion bonding technique.

Both coatings provided significant environmental resistance to brine, temperature, and pressure; however, the Parylene C-coated equipment lost flexibility and adhesion when used in dynamic seal applications. Delamination was observed, for example, when Parylene C-coated seals were evaluated as a drilling bit seal at 200°C (392°F) and 90 rpm in the presence of grease and an abrasive.

Because of the bonding technique, TFE proved to be the more successful coating in dynamic applications. The coating also appeared to aid lubrication. Dynamic wear tests, performed by Smith Tool Co. showed that TFE-coated O-rings did not delaminate, ran cooler than non-coated rings, and exhibited improved abrasion resistance.

The results of these tests, although preliminary, are promising and suggest that seal life can be extended by use of TFE coatings. The extended seal life, in turn, should lead to reduced drilling costs.

Planned tests will include a number of stress/relaxation experiments designed to monitor the sealing force excited by elastomers in a variety of simulated downhole environments.

Upgrading of Flexible Steel Pipe

Consideration is being given to the investigation of the use of ethylene propylene diene (EPDM) compounds to upgrade flexible steel pipe for geothermal drilling applications. The manufacturer of this pipe, Coflexip, has stated that thermoplastic layers are used to protect the steel layers from corrosion and abrasion and also to render the pipe leakproof. These thermoplastic layers must not bond to the steel layers during flexing. However, the current design cannot be used at temperatures

above 100°C (212°F) because the thermoplastic extrudes into the steel, spiralled section; the extrusion increases the stress in the steel interlock, and the stress results in premature fatigue-type failure. While EPDM is a good material to try because it is extrusion resistant and stable toward brine, it might not be suitable and might even fail for the following reasons:

1. Thermoxidation -- While EPDM is very resistant to brine, the thermoplastic compound is also very vulnerable to oxidative attack. As much as 200 ppm of O₂ may occur in drilling fluids due to entrained air. If this is the case, aging studies with drilling fluids containing some air should be conducted.
2. Abrasion -- Since one of the functions of the thermoplastic layers is to protect the steel from abrasion, the abrasion resistance of EPDM relative to the thermoplastic now being used should be determined.
3. Adhesion -- A Coflexip Bulletin states that the success of the company's pipe is partly due to the fact that, during flexing, the layers act independently. This independent action is attributable to the fact that there is no bonding or sticking between the layers. While this condition may not be a problem, the coefficients of friction of any new materials should be determined and compared with those of the material now used.
4. Strength -- EPDM is not as strong as the thermoplastic now used. This property raises the question of the level of tensile strength required for the geothermal drilling application.
5. Permeation -- One of the functions of the thermoplastic is to protect the steel layers against corrosion; this requirement raises the question of how effective EPDM is relative to the thermoplastic now used.

The development of the potential test project includes consideration of the above factors as well as attention to materials other than EPDM, such as Teflon and/or Tefzel.

Reports and Presentations

A list of significant presentations made and reports published during this reporting period is compiled in Appendix A.

3. DRILLING HARDWARE

Drilling hardware, such as bits and reamers, with improved penetration rates and life are required to reduce well drilling costs. The approach to achieving these performance goals includes the development and demonstration of a new drill bit concept, the improvement of existing hardware systems and sub-systems, and research into new materials and on rock-fracture/cutter wear mechanisms. Projects are presently underway to design and develop high-temperature seals and lubricants for sealed bits; design and demonstrate drag bits using polycrystalline diamond compact (PDC) cutters; design, fabricate, and test a prototype, downhole, replaceable drill bit; and investigate rock-fracture/cutter wear mechanisms and the effects of drilling fluids on the required cutting force, wear mechanisms, and wear rates of PDC cutters. The status and progress of these activities are described within this section.

A completed project on unsealed geothermal drill bit development has identified new materials for use 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. Six third-generation (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, and 70% more hole was drilled to gage than with a conventional control bit. 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 are projected to save a minimum of 4% of the total cost of wells drilled in The Geysers.

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 oil tested at 317°C (603°F), while showing, as expected, an average load-carrying capability somewhat less than the oil, 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 little leakage observed.

A prototype of the continuous chain drill concept, in which the cutting surfaces can be replaced without removing the bit from the hole,

was successfully field tested in drilling granite at the Nevada Test Site (NTS) in June 1979. 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 the six chain link sets were (1) footage drilled, 12.7 metres (41.6 feet); (2) weight on bit, 28 kN (6400 pounds); and (3) rate of penetration, 1.2 m/h (4.0 ft/h). A second field test was conducted in September 1979, but internal hydraulic leakage occurred. This problem has been corrected and a third field test at NTS is planned for June 1980. A parallel effort to develop an all-PDC chain link for the drill has also been initiated.

Full-scale drag bits, modified to use PDC cutters, have been successfully demonstrated in field tests. Both the Christensen (C-1) hard-matrix and the Smith (S-1[modified]), steel-bodied, PDC bits were tested at a location in the Baca field, New Mexico. Testing was in andesite, the basement formation for the geothermal wells being drilled by the Union Geothermal Company of New Mexico. The tests were run at depths of approximately 1676 to 1707 metres (5500 to 5600 feet). The C-1, hard-matrix bit drilled successfully, with penetration rates up to 0.007 m/s (85 ft/h) at bit weights up to 88 964 newtons (20 000 pounds) and rotary speeds as high as 70 rpm. Cutter wear was not excessive, and the bit was still usable after the test. On the average, a 50% increase in penetration rate over that of a conventional bit was obtained. The S-1 (modified), steel-bodied bit was found to be so aggressive in drilling this formation that bit weights greater than 44 482 newtons (10 000 pounds) could not be used. Instantaneous penetration rates as high as 0.014 m/s (170 ft/h) were obtained at a rotary speed of 60 rpm. In general, the penetration rate was so fast that a bit weight of 44 482 newtons (10 000 pounds) could not be maintained. Since these tests were limited to approximately 15.2 metres (50 feet) each, bit lifetime could not be established. Additional field testing is planned.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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○ PLANNED START
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3.1 Continuous Chain Bit

Sandia National Laboratories
Technical Consultant: J. St. Clair (505) 844-7678

Project Objective

The objective of this project is to design, fabricate, and test a prototype downhole replaceable drill bit.

Project Status

The Prototype II, Mod 2, continuous chain drill bit field tests were conducted at NTS during the period 5-20 June 1979. The results were included in the April-September 1979 Semi-Annual Report. A follow-up field test at NTS was initiated in mid-September 1979. Unexpectedly rapid wear of the chain link cutting surfaces was experienced, and the tests were terminated after determination that field repair of the drills could not be made. Post-test analysis of the Mod 3 chain drills revealed that the mud flow channel in both bit bodies had ruptured. The failure is believed to have occurred during pre-drilling, surface, cycling tests.

Redesign and fabrication of a Mod 4 chain drill are nearing completion. Additional field tests are tentatively scheduled for June 1980. A parallel effort to develop an all-polycrystalline diamond compact (PDC) chain link is continuing.

Quarterly Progress

An in-depth, finite element stress analysis and evaluation was made of two methods for reworking the two chain bit bodies that were ruptured in the September 1979 field test. The method selected uses a 1.91-mm- (0.075-inch-) thick cover plate with an improved weld joint. This rework procedure is considered adequate to allow the drill to survive the anticipated downhole environment expected in the planned 1980 field test. The rework is progressing slowly because of difficulties encountered in obtaining a reliable welding procedure. A simulated bit body has been welded and is being evaluated before final welding of the two bit bodies that will be used in the field test.

The field test, originally scheduled for April 1980, has been slipped to June 1980. The primary reason for the delay is that the pivot chain links built by Christensen, Inc., were not acceptable because the Stratapax™ cutters were not properly located. Nine new chain links must be built because rework was not feasible.

Preparations for the next field test of the continuous chain drill are proceeding. A review was made of the drilling instrumentation records for the September 1979 field tests. The instrumentation system used in the

September 1979 test was adequate; however, some additional instrumentation and changes in operating procedures have been established. The additional requirements are listed in Table B-1, Appendix B.

The June 1980 field test will also be conducted at NTS, and nine sets of chain links will be used. Photographs of the field test site during the September 1979 test are shown in Figures 1 and 2. The proposed drilling test plan for the June 1980 test is shown in Appendix B and is being coordinated with NTS.

A manufacturing engineering effort was started to evaluate the feasibility of fabricating chain link bases using the investment casting, lost-wax process. Consolidated Casting Company, Dallas, Texas, was consulted concerning this manufacturing process. A part is now machined, and the unit cost has varied between \$100 and \$200. The unit cost for production quantities of an investment casting is estimated to be about \$5.00. A limited-development project to obtain sample parts and small production quantities is being established. If successful, this technique could greatly reduce the cost of the chain links.

Design layout and engineering calculations are proceeding in the effort to build a full Stratapax™ chain link for the Prototype II chain bit. The link base and matrix pad for holding the synthetic diamonds will be made from a single-piece investment casting using 17-4 PH stainless steel. This design will require increased clearance between the Stratapax™ cutting surface and the bit face to allow drilling fluid velocity to be reduced. This design will provide tool-controlled Stratapax™ placement which should result in a better final product. The full Stratapax™ chain links will allow the chain bit to drill at a higher penetration rate, particularly for medium and soft formations.

A preliminary drawing of an all-Stratapax™ chain link investment casting has been completed and forwarded to Consolidated Casting Company, Dallas, Texas, for review, comment, and pre-quote cost information. The final design work will be completed within Sandia's priorities for drafting support and for getting a Stratapax™ optimization computer program on line.

Figure 1. Continuous Chain Bit Field Test Site

Figure 2. Continuous Chain Bit Field Test Site

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>GEOTHERMAL ROCK BIT</u> <u>SEALS AND LUBRICANTS</u> <u>TERRA TEK</u> SEAL DESIGN AND TESTING LUBRICANT TESTING													

LEGEND: ——— ACTIVITY PERIOD
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3.2 Seal and Lubricant Development for Geothermal Rock Bits

Contractor: Terra Tek, Inc.
Principal Investigator: R. R. Hendrickson (801) 582-2220
Contract Period: 10 July 1979 to 10 May 1980
Contract Number: 13-8783 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to design and develop improved tri-cone roller bits for geothermal applications. The project has two thrusts: (1) to substitute high-temperature steels in unlubricated bearings and (2) to develop high-temperature seals and lubricants for lubricated bearings.

Project Status

Research bits incorporating steels with higher hardness at high temperatures have demonstrated less wear than production bits in the simulated downhole environment. Third-generation unsealed bits have been field tested successfully, and this new technology is being commercialized by a leading bit manufacturer.

A seal tester and a lubricant tester have been fabricated to simulate in-use conditions: 300°C (572°F), 34.5 MPa (5000 psi), translation, rotation, and eccentricity. Most available elastomers have been tested and shown to be inadequate. Nonelastomeric seals and coated-elastomer seals are being designed and tested. Six life tests have been run on coated-elastomer seals, and results compare favorably with previous, successful, Viton seal tests. Spring-loaded face seals have undergone preliminary tests, and the elastomeric side-seal system has been perfected.

Lubricant screening tests, while eliminating several products from further consideration, have established the exceptional high-temperature performance of Pacer PLX-014 oil. A grease based on this oil has also been compounded and is ready for field evaluation. An oil (PLX-022), not compatible with elastomers, has been developed for use with all-metal seals.

A follow-on program of seal and lubricant tests was initiated in July 1979 under a new contract. Two elastomeric seals of EPDM compounds and two Utex Industries proprietary elastomeric seals have been tested. Only the EPDM seal supplied by L'Garde, Inc., did well; however, confirmation tests of this seal will be required. Two new oils for all-metal seals were tested, but both have been rejected. The testing of new candidate seals and lubricants is continuing.

Quarterly Progress

Metal Bellows Face Seal -- The three first-generation face seals were received from Bel-Flex Products, Inc., and subjected to life tests in the

seal test facility. The first two tests were run using the chrome oxide mating discs and 600 newtons (135 pounds) of spring force. The first test was cut short due to problems with the test fixture which damaged the bellows. The second test lasted 4.5 hours and was terminated due to leakage. Subsequent examination revealed loss of the chrome oxide from the primary seal ring.

The third test was run with approximately 300 newtons (968 pounds) of force, using a CBS-600, carburized steel, mating disc. This test ran 8 hours and was terminated due to leakage. The cause of leakage is assumed to be warping of the primary seal ring.

The following actions are planned for design of the second-generation, all-metal seals:

1. Observation of warp versus temperature with an optical flat and monochrome light source (HeNe laser) in an air oven and
2. Change of materials and/or heat treat for the primary seal ring.

Two of the three seal assemblies tested have been returned to Bel-Flex Products, Inc., for replacement of the bellows. The bellows were crushed by excessive differential pressure which was applied for failure detection.

The failure detection system utilized 0.70 to 1.40 MPa (100 to 200 psi) of differential pressure. Pressure was applied once per hour for 15 minutes to monitor leak-down rate. The failure detection system has been upgraded to permit monitoring of differential pressures as low as 0.07 MPa (10 psi).

Two additional metal bellows face seals were then received and evaluated. The tests were run at 22°C and 75°C (72°F and 167°F), without abrasives or radial eccentricities, to provide baseline data on leakage and wear. The first test ran 15 hours, with failure caused by flex-fatiguing of the outer weld on the bellows. The leakage rate was 0.58 ml/MPa (0.0040 ml/psi). No measurable wear occurred on the chrome oxide sealing surface or on the CBS-600 mating surface.

The second test was terminated at 12 hours due to problems with the seal tester. Leakage and wear were similar to the first test, described previously. The bellows was found to have been crushed by excessive lubricant pressure during the test. A differential pressure of 1.0 MPa (150 psi) was accidentally applied in this test, whereas the maximum differential applied in the first test was 0.70 MPa (100 psi). The maximum differential pressure capability for the bellows is therefore at least 0.70 MPa (100 psi), which is adequate for rock bits.

These two seal assemblies have also been returned to Bel-Flex Products for replacement of the bellows through an improved welding technique.

Face Seal with Elastomeric Side Seal -- Although no further work is planned with this system, the results from the all-metal seal tests give insight into the probable cause of leakage for the elastomeric type. It is most likely that these seals leaked at the face, as did the all-metal

type, and that the elastomeric side seal was not at fault. This system may therefore be viable if the all-metal version can be made to work properly. The elastomeric version is somewhat simpler to manufacture and assemble, but the all-metal seal will have higher temperature capability.

Elastomeric Seals -- Eight Teflon-coated seals were provided by Sandia for testing. These were second-generation types coated with 2 μm (79 $\mu\text{in.}$) of Teflon by the glow discharge system. Parker 4205 Viton and Parker EPDM were the base materials. Six seal-life tests were run on the Viton and EPDM seals, using a 288°C (550°F) soak cycle and a 150°C (302°F) run temperature. One coated, Viton O-ring (Parker No. 4205 compound) provided 50 hours of life. Previous testing indicated uncoated seals of the same type would not work at all when soaked at temperatures of 270°C (518°F) or greater. One coated, Parker EPDM seal provided a life of 34 hours; this result should be compared with that of an identical test on an uncoated EPDM seal in which the seal lasted only 9.5 hours. The Teflon coating is evidently beneficial for increasing both soak temperature and life. The tested seals were returned to Sandia for analysis. These successful tests on the second-generation coated seals also indicate that the coating should be applied to the best elastomeric seals. Sandia has contacted L'Garde, Inc., and Utex Industries to obtain EPDM and HTCR seals for coating. L'Garde, Inc. has already agreed to supply at least four seals in the No. 2-329 configuration.

Testing is nearing completion on a series of four proprietary grades of elastomeric seals provided by Utex Industries, Inc. The design goal for these seals is a 288°C (550°F) soak temperature and 100-hour run time at 150°C (302°F). The results of all tests in this series are presented in Table 1.

The higher installed compression used on tests 238 through 240 is the probable reason for their success. Regarding tests numbers 238 and 240, the tests were terminated for scheduling reasons; the seals were still sealing.

These results are equal to the best previous test results, in which a L'Garde proprietary EPDM compound (267-II-35) survived the 288°C (550°F) soak and ran 104 hours before failure.

Utex RD-217, Utex RD-231, and L'Garde 267-II-35 represent a significant improvement in the temperature capabilities of elastomeric seals for geothermal rock bits. Both provide a soak temperature 28°C (50°F) higher than the temperature provided by the best previous candidate, Parker 4205 Viton.

Utex Industries, Inc., has developed a new, high-temperature elastomer which is commercially available as Utex HTCR. The new compound is similar to Utex experimental grades RD-227 and RD-231, which were developed for the geothermal bit program. HTCR is the second commercial product developed under the program; Pacer Geobond grease was the first. Eight seals were received and are being evaluated.

Radial Lip Seal -- Previous seal-life tests conducted in the seal-test facility indicated that the Fluorocarbon, Inc., first-generation, radial

Table 1

Seal-Life Tests on Utex Seals

Test No.	Grade	Installed Compression, %	Temperature °C (°F)	Soak Time, h	Life at 150°C (302°F), h	Comments
228	RD-217	9.2	288 (302)	2	1.5	Very little grease loss
229	RD-231	8.8	288 (302)	2	1.5	Cuttings found under sealing surface
230	RD-217	7.5	288 (302)	2	0	Long strips of material were torn from the i.d.
231	RD-217	7.5	288 (302)	2	0.5	Severe damage to seal i.d.
236	RD-226	9.4	288 (302)	3	0	Severe abrasive damage to seal i.d.
237	RD-226	8.9	288 (302)	2	0	Very smooth wear on seal i.d. No cuttings found under seal
238	RD-231	10.2	288 (302)	2	92+	Seal i.d. smooth
239	RD-227	10.9	288 (302)	2	52	Seal i.d. abraded near top
240	RD-227	10.7	288 (302)	2	94+	

lip seal had excellent resistance to abrasive damage but that it tended to leak due to shrinkage. Fluorocarbon, Inc., has conducted numerous tests at temperature in an air oven in order to characterize the shrinkage. At least four cycles to 200°C (392°F), followed by cooling to room temperature, were required to stabilize the dimensions of the seal. The seal used for these tests has been sent to Terra Tek with revised recommendations for shaft diameter and gland depth.

The second- and third-generation seals are being fabricated. The second-generation seals are identical to the first-generation but are pre-shrunk.

The third-generation seals will incorporate the following design revisions:

1. The wall thickness of the plastic seal body will be made thinner to reduce the thermally-induced stresses. The seal lips will remain the same.
2. The expander spring will be made thicker to provide adequate rigidity with the thinner seal body. The spring force in the installed position will be the same; the spring material will be 17-7 PH stainless steel.
3. The seals will be pre-shrunk.
4. Gland dimensions will be revised to ensure that the seal will not rotate in the gland, i.e., all sliding will occur at the seal i.d.

Four of the second-generation seals, which have improved shrinkage characteristics, have been received. Evaluation of the seals is underway.

Geobond Grease — This grease is the commercial equivalent of PLX-014 grease, according to Pacer Lubricants, Inc., and is also compatible with elastomers. Five gallons of Geobond grease were obtained for use in the seal tester. A series of ring and block lubricant tests were made to confirm that Geobond grease was, in fact, the same as PLX-014 grease. The results, shown in Table 2, indicate that both surpassed the performance goal of 30 MPa (4.3 ksi) by a substantial margin, but the load capacity of the Geobond may be somewhat lower than that of the PLX-014 grease. Additional tests will be run on Geobond grease to complete the comparison.

Table 2

Performance of Geobond and PLX-014
Greases at 316°C (600°F)

<u>Lubricant</u>	<u>Weight NLGI</u>	<u>Load Capacity MPa (ksi)</u>	<u>Number of Tests</u>
PLX-014	2	62 (9.0)	10
Geobond	2	55 (8.0)	3

Pacer Lubricants, Inc., has provided five, new, candidate geothermal bit lubricants for evaluation. All are based on high-viscosity (molecular weight) synthetic hydrocarbon oils. Four of the five contain no suspended solid lubricants such as graphite, molybdenum, borate, or silicon, because previous tests indicated that solid lubricants in suspension may not be necessary. All are compatible with elastomers. The five new candidate lubricants are

PLX-042: Similar to PLX-014 oil, but with an additional extreme-pressure (EP) additive. PLX-042 and PLX-014 contain suspended graphite.

PLX-043: Contains no solids and is a blend of two oils having different viscosities.

PLX-044: Contains no solids and uses one base oil having a viscosity similar to PLX-043.

PLX-045 and PLX-046: Contain no solids, and both use very high-viscosity base oils.

Testing of these five new candidates will be completed by mid-April 1980.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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3.3 Geothermal Polycrystalline Diamond Compact Drill-Bit Development

Contractor: General Electric Company, Corporate
Research and Development (CRD)
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 30 June 1976 to 31 May 1980
Contract Number: DE-AC04-76ET27142
Technical Consultant: C. Huff (505) 844-8796

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 with high-pressure sintered polycrystalline diamond compacts (PDCs) for the cutting edges. The scope of this contract includes instrumented rock-cutting experiments, diamond compact wear and failure mode analysis, rock removal modeling studies, bit design and construction, full-scale laboratory testing, and field testing.

Project Status

From experiments at atmospheric conditions on the cutting of rock with individual PDC cutters, a predictive capability has been established for the performance of full-scale bits. This has been demonstrated with laboratory testing of full bits. Single-cutter tests have been run at simulated downhole conditions, and the data have been analyzed. The redesign and fabrication of the S-1 bit (modified), necessitated by the catastrophic failure during the November 1978 field test, has been completed. Both the S-1 (modified) bit and the C-1, cast, hard-matrix bit were field tested in the Baca field, New Mexico, in October 1979. The S-1 bit demonstrated a penetration rate several times greater than typical rates for rock bits in similar formations. Work is progressing in preparation for the field testing of the third-generation bits.

Quarterly Progress

The detailed wear examination of geothermal Stratapax™* bits S-1 (modified) and C-1, which were successfully tested in the Baca field, New Mexico, at the end of October 1979, has been completed. Only six cutters on bit S-1 (modified) showed significant wear. One Stratapax™ blank, lost due to a fracture which apparently originated in the cutter tungsten-carbide substrate, was included in the wear category. The wear appeared to be due to insufficient cooling, a condition which can be improved by minor changes in the bit body junk slots to permit free passage of drilling fluid around the cutters.

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*Trademark, General Electric Company, U.S.A.

Bit C-1 (cast, hard-matrix body) had seven moderately worn Stratapax™ cutters. However, unlike bit S-1 (modified), the wear pattern of the cutting structure was not symmetrical. The significant wear was confined to one side of the bit. Careful examination of the worn diamond compacts indicated that these cutters probably were thermally damaged when the bit was fabricated. The technique for brazing the Stratapax™ blanks and their carbide supports onto cast, hard-matrix bit bodies has been refined by the bit manufacturer since the C-1 bit was constructed; hence, this thermal damage should not be a problem with future bits. On the other hand, the natural diamond stones set in the hard matrix to cut the gage of the hole showed heavy damage, primarily fracture and crushing. The high penetration rate achieved by this bit resulted in a material removal rate too great for these natural diamonds to accommodate without failure. The dulling of the gage-cutting structure was probably responsible in part for the high torque generated by bit C-1, as compared to bit S-1 (modified).

An economic analysis of drilling costs as related to arbitrarily chosen Stratapax™ bit costs has been completed for the specific case of drilling in Baca Location No. 1. In order to protect drilling performance and cost information that the producer considers proprietary, the analysis will be reported as a series of break-even-cost and percentage-cost savings curves as functions of penetration rate and bit life for rock bits and Stratapax™ bits. The main purpose of this analysis is to identify the penetration rate/bit-life target for the third-generation field test to be run in the Baca field, New Mexico. The analysis indicates that the S-1 (modified) bit design, with some minor changes to improve cooling and increase bit life, should perform well enough to demonstrate drilling cost reductions.

The recently completed drilling economic analysis will be expanded by utilizing the computer-based, geothermal well, cost-simulation technique developed by Sandia.¹ Work on this phase of the project is being coordinated with Sandia.

A firm agreement was reached with Union Oil Company to run the final field test for this project at The Geysers, California. Union Oil Company recommended that two Stratapax™ bits be tested at each location, the Baca and The Geysers, in order to ascertain optimum performance. In each case, one bit would be tested under varying conditions of rotary speed and bit weight, to be followed immediately by an identical bit operated in the manner that the prior test showed to be best. The second tool would be tested for bit life. The Union Oil Company recommendation has been included in the field test plan, and the funding required to fabricate two additional Stratapax™ bits for testing along with the two bits originally planned is being provided. Negotiations for construction of four bits have been initiated.

The bit performance results obtained during drilling in the Baca field, New Mexico, indicate that the steel-bodied, stud-type design is the best choice for further development on this project. Although the cast, hard-matrix design shows promise for durability, the higher penetration rates obtained at significantly lower bit weights and with markedly lower torques, are very important considerations. For relatively shallow wells such as those in the Baca field, New Mexico, and The Geysers, California,

drilling cost analysis shows that increasing the rate of penetration is the most important factor to reduce costs with relatively expensive tools such as PDC bits. In addition, reduction in bit weight and torque can increase the life of drill pipe and drill collars and reduce the chances of twist-offs. Also, the performance of the natural diamond stones used on the hard-matrix bit to cut the hole gage was poor in the harsh geothermal environment. Most of these stones were either crushed or cleaved. The failure of the natural diamonds was a major reason for the higher torque generated by this design. Therefore, knowing that the drilling conditions in The Geysers will be at least as rigorous as those in the Baca field, a decision was made to concentrate on steel-bodied, stud-mounted, Stratapax™ bits for the final phase of the project. Smith Tool, Irvine, California, will fabricate the four bits.

Stratapax™ bit S-1 (modified), used in the Baca field tests and no longer required for this project, was shipped to Sandia for repair and subsequent use in laboratory drilling experiments in another Sandia project. These full-scale laboratory drilling tests at Terra Tek in a parallel project have provided valuable Stratapax™ drill blank wear and cutter geometry information pertinent to the design of the third-generation geothermal bits that will be constructed and tested in this project. These experiments consisted of testing two Stratapax™ bits, using preheated, 260°C (500°F) air to simulate conditions at The Geysers. Drilling was conducted in three rock types; Carthage marble, Nugget sandstone and Sierra white granite. One bit, provided by Christensen, Inc., was of the cast, hard-matrix variety, having gage cutters with only a -7° back rake. The other was the S-1 (modified) bit which was tested successfully in the Baca field. The S-1 bit had the old-style, -20° back rake, -5° end clearance cutters in the gage. These were replaced with -25° back rake, -25° end clearance cutters developed by Sandia. The difference in Stratapax™ drill blank wear due to the difference in cutter geometries was very pronounced. Drilling one hole 0.9 metre (3 feet) into Nugget sandstone, at 25.3 m³/min (1000 ft³/min), using 260°C (500°F) air produced diamond layer spalling and severe wear for all the -7° back rake gage cutters. Four holes under the same conditions produced no apparent wear of the -25° back rake cutters on the S-1 (modified) steel-bodied, stud-type bit.

Based on these experimental results, the designs for the third-generation bits targeted for the Baca field, New Mexico, and The Geysers, California, will be modified to include -25° back rake, -25° end clearance, stud-mounted, Stratapax™ cutters.

The -25° back rake, cemented carbide stud is a Sandia special design and would normally be a long-lead-time item to procure. However, Security Division, Dresser Industries has a surplus of these studs and will furnish one hundred at cost. Thus, the cutter design change should not delay fabrication of the bits for the Baca field tests.

A presentation on the basic wear mechanism of PDCs in rock-drilling applications was given at the Energy-Sources Technology Conference, 3-7 February 1980, in New Orleans, Louisiana. Included in this presentation were wear characteristics observed in the bits which had been field tested in this project in New Mexico in October 1979. Sandia included a discussion of the drilling performance of these bits in a presentation at the same meeting.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PDC WEAR MECHANISMS</u> <u>TEST SUPPORT</u> <u>GENERAL ELECTRIC</u> EFFECTS OF DRILLING FLUIDS ROCK FRACTURE/CUTTER WEAR CONSULTATION FINAL REPORT													JAN 81

LEGEND: ——— ACTIVITY PERIOD

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3.4 Wear Mechanisms for Polycrystalline Diamond Compacts as Utilized for Drilling in Geothermal Environments

Contractor: General Electric Company
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 16 November 1979 to 6 December 1980
Contract Number: 13-9406 (Sandia)
Technical Consultant: C. Huff (505) 844-8796

Project Objective

The objective of this project is to provide technical assistance during Sandia's evaluation of the performance of PDCs in drill bits for use in geothermal environments. The technical support will concern (1) the determination of the effects of drilling fluids on the required cutting force, wear mechanisms, and wear rates of PDC cutters and (2) consultation on rock fracture and cutter wear mechanisms in the development of a model of the rock fracture mechanism as a function of cutting edge configuration.

Project Status

Coordination of the project activities with related work and participating organizations has been completed. Preparation of the test facilities and equipment is progressing on schedule. Procurement of three rock types for use in the PDC cutter tests is nearing completion.

Quarterly Progress

As a part of the rock-fracture and cutter-wear mechanisms experiments, General Electric is assisting Sandia in the evaluation of the performance of PDC drilling in air in order to simulate conditions encountered in formations such as The Geysers, California. The 21.6-cm (8.5-inch) diameter Stratapax™ steel-bodied, stud-type bit, designated S-1 (modified), which has been designed, fabricated, and successfully tested in the field, has been used for full-scale laboratory drilling. This bit, together with three spare Stratapax™ cutter/stud assemblies, were shipped to Sandia, where several worn cutters on the bit are being replaced. Results of these tests are reported in Section 3.3 of this report.

A meeting was held with Sandia to discuss related Sandia work on rock-cutting tool temperature, rock fracture, and bit hydraulics modeling programs. The purpose of the meeting was to coordinate the single-cutter rock-cutting experiments of this project with the Sandia work so that useful information can be provided for the Sandia modeling studies.

The three rock types that will be used for the PDC single-cutter experiments of this project are Nugget sandstone, Sierra white granite, and Tennessee marble. The sandstone has been purchased and shipped; the granite has been ordered, and a cost quotation for the marble is expected soon.

In support of this program, the General Electric rock-cutting facility is being expanded to include a large 137-cm (54-inch) diameter, vertical turret lathe. This machine, which will be devoted exclusively to rock cutting, is capable of much heavier, and more realistic, cuts at higher cutting forces than the smaller lathe which has been used in the past. The smaller instrumented lathe has been relocated and will be retained for more delicate experiments such as rock-cutting heat-generation determinations. The installation of the enlarged General Electric rock-cutting facility is proceeding on schedule. The 137-cm (54-inch) vertical turret lathe is in place, and its electrical system is being wired. This new laboratory will be completed in time to begin PDC single cutter experiments on schedule.

4. 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. The approach to developing improved drilling fluids includes basic research into the morphology of clay particles, laboratory investigation of the properties of drilling fluids at high temperature and pressure, development of aqueous foam drilling fluids, development and field demonstration of the generation of inert gas drilling fluids, and the development and field testing of high-temperature drilling muds. Projects are progressing with the objectives of determining the high-temperature/high-pressure rheological properties of drilling muds, of gaining a fundamental understanding of the morphology of clay particles under the influences of high temperature and various chemical compounds, of identifying and developing 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, of demonstrating a technique of N₂ generation from diesel engine exhaust using a catalyst, and of field testing a high-temperature drilling mud. The status and progress of these activities are described within this section.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>AQUEOUS FOAM</u> <u>DRILLING FLUIDS</u>													
ADVANCED SCREENING													
CORROSION TESTS						●							
HIGH-TEMPERATURE STABILITY TESTS										○			

LEGEND: ——— ACTIVITY PERIOD
              - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories
Technical Consultant: P. Rand (505) 844-7953

Project Objective

This project will identify and develop aqueous foams for use in geothermal applications. The foams will be capable of operating in elevated temperature environments to 310°C (590°F) and will exhibit chemical and foaming stability and anticorrosive and antioxidant properties.

Project Status

An initial report has been issued defining the basic problems to be encountered, the various solutions thought to be obtainable, and a project procedure. Initial surfactant screening has been completed. Fifty-six surfactants have been evaluated before and after exposure to a temperature cycle reaching 260°C (500°F). Twelve surfactants were selected for further testing. The evaluation of these surfactants in various chemical environments at 260°C (500°F) has been completed. Six surfactants, selected because of their good performance in the chemical environment tests, have been evaluated after exposure to 310°C (590°F) in deionized water. Four of these surfactants showed good to excellent performance and are now being evaluated in various chemical environments at 310°C (590°F). Surfactant evaluation at 260°C (500°F) is continuing on new surfactants that have been recommended.

Quarterly Progress

Additional surfactants were obtained from companies that supply foaming agent systems to the drilling industry. These proprietary surfactants were evaluated by the standard project procedure after exposure to temperatures of 260°C (500°F) and 310°C (590°F). Qualitative ratings on surfactant performance after exposure to these temperatures in various chemical environments are presented in Tables 3 and 4. The ratings at 260°C (500°F) are an update of the data published in the October-December 1979 Quarterly Progress Report. The ratings at 310°C (590°F) are new information. The ratings are assigned on the basis of comparative tests run on surfactant solutions before and after exposure to the test environments shown in the tables. The comparative tests include solution pH, foam drainage times, and foam cell structure uniformity. The data indicate that several surfactants are promising for geothermal applications.

Corrosion coupons are being machined for use in the corrosion tests on selected surfactant solutions.

An autoclave, which will allow evaluations of foams at high temperature, has been ordered.

Table 3

Effect of High Temperatures and Various Environments
on Surfactant Solutions--Qualitative Ratings

Chemical Type	Trade Name	Wt-% Active Ingredient	Environment					
			DI-H ₂ O Air	DI-H ₂ O Nitrogen	1.0 M NaCl Air	0.1 M NaOH Air	0.1 M HCl Air	Brine-I Air
Alpha olefin sulfonate	Lakeway 301-10	0.5	E	E	E	E	E	E
Alpha olefin sulfonate	Sulframin 14/16 AOS	0.5	E	E	G	E	E	E
Coco betaine	Velvetex BC	0.5	E	E	E	G	E	E
Proprietary anionic	Thermophoam BW-D	0.5	E	E	E	E	P	E
Proprietary anionic	Schwebel S-1100	0.5	E	E	P	E	P	E
Alkyl aryl sulfonate	Ninex N-300	0.5	G	G	U	G	U	NT
Alkyl ethoxylate	Witconol SN-90	1.0	E	E	E	E	U	E
Alkyl ethoxylate	Tricol LAL-23	1.0	G	E	E	P	U	E
Amine ethoxylate	Varonic K215 LC	1.0	G	G	G	G	G	NT
Alkyl amide sulfonate	Igepon TC-42	0.5	P	E	U	P	U	NT
Alkyl aryl polyether sulfonate	Triton X-200	0.5	G	G	U	U	U	NT
Proprietary anionic	Adofoam BF-1	0.5	G	P	U	P	U	NT
Alkyl aryl ethoxylate	Witconol NP-120	1.0	P	E	P	P	P	NT
Alkyl ester sulfonate	Lanthanol LAL-flake	0.5	U	U	U	U	U	NT

Notes: DI-H₂O indicates deionized water

Temperature Cycle

Room temperature to 260°C (500°F) -- 2 hours

Hold at 260°C (500°F) -- 2 hours

260°C (500°F) to room temperature -- 3 hours

Test Volume

0.25-l (0.07-gal) solution in 0.5-l (0.13-gal)
stainless-steel pressure vessel

Ratings: E -- Excellent
G -- Good
P -- Poor
U -- Unsatisfactory
NT -- No Test

Table 4

**Effect of High Temperatures and Various Environments
on Surfactant Solutions--Qualitative Ratings**

Chemical Type	Trade Name	Wt-% Active Ingredient	Environment				
			DI-H ₂ O Air	DI-H ₂ O Nitrogen	1.0 M NaCl Air	0.1 M NaOH Air	0.1 M HCl Air
Alpha olefin sulfonate	Lakeway 301-10	0.5	G	E	E	E	P
Alpha olefin sulfonate	Sulframin 14/16 AOS	0.5	G	G	P	E	U
Proprietary anionic	Thermophoam BW-D	0.5	E	E	P	E	U
Ethoxylated alcohol	Witconol SN-90	1.0	E	E	U	P	U
Ethoxylated alcohol	Tricol LAL-23	1.0	P	NT	NT	NT	NT
Coco betaine	Velvetex BC	0.5	U	NT	NT	NT	NT

Notes: DI-H₂O indicates deionized water

Temperature Cycle

Room temperature to 310°C (590°F) -- 2 hours

Hold at 310°C (590°F) -- 2 hours

310°C (590°F) to room temperature -- 3 hours

Test Volume

0.25-1 (0.07-gal) solution in 0.5-1 (0.13-gal)
stainless-steel pressure vessel

Ratings: E -- Excellent
G -- Good
P -- Poor
U -- Unsatisfactory
NT -- No Test

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>FLOW LOOP TESTER</u> <u>UNIV. OF OKLAHOMA</u> TESTING	EXTENSION												

LEGEND: ACTIVITY PERIOD
                 RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.2 Determining Temperature Limits of Drilling Fluids (Flow Loop Tester)

Contractor: University of Oklahoma
Principal Investigator: E. F. Blick (405) 325-5011
Contract Period: 1 August 1978 to 15 April 1980
Contract Number: 13-0346 (Sandia)
Technical Consultant: A. Maish (505) 844-3601

Project Objective

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

Project Status

Sufficient testing has been accomplished using a modified flow loop at Magcobar to demonstrate the existence of a large discrepancy between ambient data as normally taken in mud laboratories and the actual characteristics of the fluid under dynamic, simulated downhole conditions. A new flow loop has been fabricated at the University of Oklahoma, and testing of muds has begun. Repetitive malfunctions of the test equipment have delayed the test program. However, correction of all problem areas was accomplished in September 1979. The contract was extended to permit the completion of scheduled mud tests.

Quarterly Progress

Reports of progress for January-March 1980 were not received. These activities will be consolidated with the final project report anticipated in the next reporting period.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
HT/HP MUD TESTER													
NL BAROID													
INSTRUMENTATION													
1. FILTER													
2. FILTER MEDIUM													
3. DENSITOMETER													
4. CORROSIVITY													
5. RHEOLOGICAL													
INTEGRATE INSTRUMENTATION													
HIGH-PRESSURE GAS SYSTEM													
INTEGRATED SYSTEM													
TEST TWO FLUIDS													
CONTRACTING (DOE)													

COMPLETE

NEW SCHEDULE
UNDER
DEVELOPMENT

CONTRACT EXTENSION PENDING

LEGEND:

———— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.3 Development of High-Temperature/High-Pressure Drilling Mud Research Instrumentation

Contractor: NL Baroid
Principal Investigator: K. L. Walter (713) 527-1100
Contract Period: 1 April 1978 to 31 March 1980
Contract Number: DE-AC04-77ET27144
Technical Consultant: A. Maish (505) 844-3601

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.

Project Status

State-of-the-art studies have been conducted. Three fabrication bids for the pressure vessel were received, and a design was chosen for testing. Design work on the system instrumentation is continuing. A time schedule has been determined for the Microcomputer Development System software development. The installation site for the geothermal drilling fluid test system has been tentatively selected. A contract extension is under consideration, and a new schedule is being developed.

Quarterly Progress

The rheometer torque transducer has been assembled. Preliminary testing indicates satisfactory linear angular deflection response to applied torque. The transducer is rugged, as shown by repeated returns to zero position following angular and side deflections. Besides strain gage bridge sensors for sensing angular deflection, a variable impedance displacement measuring system will be investigated. Such a system may prove more resistant to change of calibration at high pressures. The semiconductor strain gage for the torque transducer was tested up to 138 MPa (20 000 psi) at room temperature and showed high sensitivity to pressure. Although the full bridge of four strain gages was not tested, this high sensitivity suggests that an alternate sensor be tried. Further testing is dependent upon receipt of a variable impedance proximity sensor. A slightly larger diameter, stiffer, rheometer shaft is being machined. Slightly larger diameter corrosion probes are also being fabricated to facilitate ceramic insulation coating.

P & N Machine Shop fabricated parts for the rheometer torque transducer and prototype filter and will also construct the filter. The main components of the filter assembly were received from the machine shop and

partially assembled. Stainless steel 304 was found unsuitable for the filter body when very small holes were drilled, but 303 was satisfactory. The stainless-steel filter belt and filter media have yet to be ordered. The cooled mounting plate is being fabricated. The two halves of the plate will be vacuum furnace soldered together following initial machining and then will require final machining.

Systran Corporation completed the scope of the software coding and checking needed for the system and broke it down into a series of tasks. Approximately seven experienced-man-months of effort are needed. Based on this scope, three software companies were asked to bid on the work on a fixed price basis. One company could not meet the bid schedule requirements, and Systran's bid was selected over the other bid. Systran's \$55,000 effort can be reduced to \$46,000 provided that Baroid performs the control laws software task. A copy of the Systran scope report is being sent to Sandia and another copy, together with the bids, is being sent to the DOE Contracting Officer when the contract is prepared. Systran Corporation has assigned W. Wessale to begin work on the Geothermal Drilling Fluid Test System (GDFTS) microcomputer software. He has completed the first task, which is to program the driver for the 711 Single Board Computer (SBC). The SBC 711 is an analog-to-digital signal converter. The driver will also compensate for sensor nonlinearities. The second task, which is to supply a driver for the SBC 519, an input/output device, has also been completed. A decision was made to use Fortran F-80 as a programming language instead of PLM-80, following comparative discussions with experienced Baroid personnel. Work on the command line interrupter has begun. The 519 software was checked out with the stepper motor controller.

In order to avoid nonlinearities in the stepper motors speed response to their controllers' signals, frequency synthesizers are being used to relay these signals. One frequency synthesizer has been received and will be tested for its ability to regulate stepper motor rotational speeds.

Two stepper motor controllers have been malfunctioning. The manufacturer's representative will repair or replace one while the other is used. Purchase of a digital output controller to control the drilling fluid temperature and purchase of a backup differential pressure sensor are being investigated.

A system was designed for returning components vaporized from the drilling fluid and condensed on the cooling jacket back into the mud. The system involves an arrangement of spring-deployed spouts.

Drawings for the cooling jacket supplied by National Forge were corrected and returned. The vessel manufacture is in an advanced stage, and reached the point where a completed contract was required. The National Forge and Systran subcontracts were being prepared in the latter part of this reporting period.

Dr. E. A. Ripperger has provided reliable design parameters for the pit to house the pressure vessel. Some redesign of the pit will be required.

A cost estimate was finally received for the building to house the system. The estimate was considered extremely high and was revised downward, and work is underway to authorize construction. Building completion has become the critical path item governing project completion. The current estimate for completion is December 1980. The request for an extension of the main contract is under preparation, together with a new schedule for project completion which reflects the current estimate for completion of the building.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DRILLING MUD CHEMISTRY</u> <u>TEXAS TECH UNIV.</u>													JUN 1981
THERMAL EFFECTS ON THIXOTROPIC PROPERTIES													
ATTAPULGITE													
SEPIOLITE													
SAPONITE	●												
BENTONITE	●												

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

4.4 Basic Understanding of Chemical and Elevated Temperature Effects on Clay-Based Drilling Fluids

Contractor: Texas Tech University
Principal Investigator: N. Güven (806) 742-3110
Contract Period: 15 July 1979 to 15 July 1981
Contract Number: 13-5104 (Sandia)
Technical Consultant: B. Kenna (505) 844-1565

Project Objective

This project will result in a fundamental understanding of clay particle morphology 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.

Project Status

The Texas Tech University Clay and Drilling Fluids Laboratories were remodeled to accommodate the project. The project investigations were initiated in July 1979. X-ray and microscopic studies of the effects of various salts and elevated temperatures on attapulgite have been conducted. Studies of saponite fluids are continuing.

Quarterly Progress

Saponite-based drilling fluids containing 1% of either KCl or CaCl_2 were subjected to hydrothermal treatment in the 93.3 to 315.6°C (200 to 600°F) temperature range. The treated saponite was glycolated to determine if the distinctive lattice expansion along the c-axis had been affected by hydrothermal conditions and/or the salts present. The reaction products were X-rayed, and the results are given in Table 5. The data suggest that saponite does not lose its swelling capability within the temperature range 93.3 to 315.6°C (200 to 600°F) in the presence of the chlorites of potassium and calcium. In addition, the c-lattice dimension before glycolation appears to be smaller in the presence of KCl as compared to the presence of CaCl_2 . Also, the glycolation results show that the capability for c-lattice expansion remains after hydrothermal treatment. Therefore, the swelling characteristics resulting from absorption of water and ions should not be altered within the temperature range of 93.3 to 315.6°C (200 to 600°F) in the presence of either KCl or CaCl_2 .

The previous quarterly progress report presented the results of treating saponite with H_2O and NaCl on the basis of electron microscopic observations. In general, the saponite morphology did not change significantly until the temperature reached 315.6 and 371.1°C (600 and 700°F). At these temperatures, the saponite particles tend to form thick, platy, and, perhaps, more organized aggregates.

Table 5

X-Ray Diffraction Data on Saponite/Salt Systems Exposed to Hydrothermal Conditions

System	Hydrothermal Conditions °C (°F)	c-dimension before/after Glycolation, Å	Other Minerals Present in Saponite Clay*				
			<u>mica</u>	<u>feldspar</u>	<u>chlorite</u>	<u>calcite</u>	<u>dolomite</u>
Saponite/KCl	93.3 (200)	14.4/17.3	+	+	+	-	+
Saponite/KCl	148.9 (300)	13.6/17.3	+	+	+	-	-
Saponite/KCl	204.4 (400)	13.6/17.3	+	+	+	-	-
Saponite/KCl	315.6 (600)	14.9/18.0	+	+	+	-	-
Saponite/CaCl ₂	93.3 (200)	15.0/17.3	+	+	+	-	-
Saponite/CaCl ₂	148.9 (300)	14.7/17.1	+	+	+	-	-
Saponite/CaCl ₂	204.4 (400)	14.7/17.0	+	+	+	+	-
Saponite/CaCl ₂	260.0 (500)	15.8/17.3	+	+	-	+	-

*These impurities collectively make up less than 10% of the sample and are part of the original sample. X-ray diffraction analysis of materials at concentrations less than 5% is tenuous at best; therefore, the appearance/disappearance of these minerals from sample to sample is not unexpected.

Note: + = presence
- = absence

Electron microscopic observations taken this quarter reveal that, for the saponite/KCl runs, saponite particles look like those observed in saponite/NaCl runs at 204.4 and 260°C (400 and 500°F). Commonly, the particles are in larger aggregates at lower temperature ranges and in smaller aggregates at higher temperatures, the latter state occurring as the result of dispersion. X-ray diffraction of saponite/KCl run at 371.1°C (700°F) showed a sharp decrease in saponite reflection. However, electron microscopic study did not reveal any significant change in the saponite particles at 371.1°C (700°F). Figures 3 through 7 show the typical saponite particles found in each sample.

Figure 3. Large Aggregate of Saponite after the Run at 93.3°C (200°F) in Saponite/KCl System.
Mag: 13 000X

Figure 4. Typical Form of Saponite Aggregate after the Run at 148.9°C (300°F) in Saponite/KCl System.
Mag: 13 000X

Figure 5. Smaller Saponite Aggregates Developing after the Run at 204.4°C (400°F) in Saponite/KCl System. Dark bands around the edges of particles indicate possible dissolution. Mag. 19 500X

Figure 6. Typical Form of Saponite Aggregate after the Run at 315.6°C (600°F) in Saponite/KCl System. Mag. 32 500X

Figure 7. Small and Scattered Saponite Aggregates due to Dispersion after the Run at 371.1°C (700°F) in Saponite/KCl System. Mag: 13 000X

For the saponite/ CaCl_2 runs, aggregates of fluffy saponite were common at low temperature ranges, -93.3 to 148.9°C (200 to 300°F), and were not similar to those found in H_2O and NaCl systems. Those aggregates also change from smaller aggregates to larger ones at higher temperatures, 204.4 to 260°C (400 to 500°F). The saponite/ CaCl_2 run at 260°C (500°F) showed a morphology which looked like that in saponite/ H_2O run at 371.1°C (700°F). The similarity may indicate that the effect of CaCl_2 on saponite at 260°C (500°F) is approximately equal to that of H_2O and NaCl at 371.1°C (700°F). The thick and platy aggregates found in saponite/ CaCl_2 run at 260°C (500°F) are probably the result of calcium substitution in the interlayer cation sites; calcium binds the structure more tightly than other monovalent cations. Figures 8 through 11 show the typical aggregates found in the sample.

Figure 8. Fluffy Aggregates of Saponite after the Run at 93.3°C (200°F) in Saponite/ CaCl_2 System.
Mag: 22 100X

Figure 9. Fluffy Aggregates of Saponite after the Run at 148.9°C (300°F) in Saponite/CaCl₂ System. Mag: 13 000X

Figure 10. Platy Particles Developing around the Saponite Aggregates after the Run at 204.4°C (400°F) in Saponite/CaCl₂ System. Mag: 32 500X

Figure 11. Platy Particles Developing around the Saponite Aggregates after the Run at 260°C (500°F) in Saponite/CaCl₂. The aggregates have become larger. Mag: 28 600X

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>CATALYTIC INERT GAS GENERATION (DIESEL) ENGELHARD</u>													
TEST RIG FABRICATION	→	▼											
PARAMETRIC TESTS	●	→	▼										
DURABILITY TESTS			●	→	▼								
DATA ANALYSIS		●	→	→	▼								
FIELD PACKAGE SPECIFICATIONS			●	→	→	→	▼						
FINAL REPORT								▼					

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

4.5 Inert Gas Generation from Diesel Exhaust: Catalyst System

Contractor: Englehard Minerals & Chemicals Corporation
Principal Investigator: I. T. Osgerby (201) 321-5230
Contract Period: 1 August 1979 to 30 April 1980
Contract Number: 13-5071 (Sandia)
Technical Consultant: B. Kenna (505) 844-1565

Project Objective

The objective of this project is to demonstrate catalytically supported thermal combustion as a means of generating an inert gas from the exhaust stream of a commercially available diesel engine. An existing, proprietary catalyst will be used with supplemental No. 2 fuel over the load range of the diesel engine to achieve this objective. This performance objective will be evaluated over an extended period of time to verify that the catalyst activity can be retained under operating conditions consistent with the intended field application.

Project Status

The project was initiated in August 1979. The test rig design and fabrication have been completed, the facility debugged, and the unit demonstrated. The parametric test program has been completed, and the durability tests are progressing.

Quarterly Progress

The parametric test program was completed this quarter. The optimum fuel settings for maximum NO_x reduction were determined at several catalyst inlet reference velocities at the maximum engine load condition of 60 kW (80.4 hp). Figure 12 shows the NO_x, CO₂, and CO emissions versus fuel/air ratios, at-catalyst and overall. Difficulties with the O₂ analyser train prevented reliable O₂ measurements from being made. Thus, although low O₂ (< 10 Vppm) measurements were indicated, after fuel was added for combustion, high background levels of ≥ 400 Vppm reduced confidence in these data.

During the conduct of the parametric program, tests were carried out at several load settings of the diesel generator set. At each setting, the total gas flow was adjusted to vary catalyst inlet reference velocity. Catalyst fuel flow was varied to obtain a range of stoichiometries. The results obtained at 100% load, 60 kW (80.4 hp); at 80% load, 48 kW (64.3 hp); and at 60% load, 36 kW (48.3 hp) are presented in Tables 6 through 9 and Figures 13 through 18. Data are illustrated only for the 60-kW (80.4-hp) and 48-kW (64.3-hp) load settings because no discernable effect of load was evident by comparing Figures 13 and 16, 14 and 17, and 15 and 18.

 Figure 12. NO_x, CO₂, and CO Emissions versus Fuel/Air Ratio

Figure 13. O₂, NO_x, and CO Concentrations versus Fuel/Air Ratio at 60-kW (80.4-hp) Load

Figure 14. Converter Exhaust NO_x versus CO at 60-kW (80.4-hp) Load

Figure 15. Converter Exhaust O_2 versus CO at 60-kW (80.4-hp) Load

Figure 16. O₂, NO_x, and CO Concentrations versus Fuel/Air Ratio at 48-kW (64.3-hp) Load

Figure 17. Converter Exhaust NO_x versus CO at 48-kW (64.3-hp) Load

Figure 18. Converter Exhaust O_2 versus CO at 48-kW (64.3-hp) Load

As shown in Table 6, the O₂ concentration in the diesel exhaust varies with load. Since the project objective is to deplete the 21% O₂ in the air ingested by the engine, the proportion of fuel to the engine and catalytic convertor changes with load; however, the total fuel required does not. Since the catalyst is currently limited to a maximum operating temperature of 1260°C (2300°F), the maximum catalytic convertor O₂ depletion is limited to ~10%. For intermediate and low load settings of the engine, a modification of the convertor system is required.

Table 6

Allis Chalmers DES-60 Diesel Exhaust Characterization

Load kW (hp)	Temperature °C (°F)	CO ₂ %	CO %	O ₂ * %	NO _x ppm
0	182 (360)	2.3	0.05	17.66	500
12 (16)	232 (450)	3.2	0.05	16.14	650
24 (32)	299 (570)	4.5	0.05	12.33	>1 000
36 (48)	343 (650)	5.6	0.05	11.19	>1 000
48 (64)	371 (700)	6.2	0.05	9.59	>1 000
60 (80)	393 (740)	6.6	0.05	7.50	>1 000

*Bag sample

There was no effect apparent in catalytic convertor performance as total gas flow was varied. The only effect noticed was in the fuel/air preparation section at the 36-kW (48.3-hp) load, where flashback was observed at a reference velocity ≤ 1.5 to 1.8 m/s (≤ 5 to 6 ft/s) at the catalyst inlet face. This was attributed to hot catalyst radiation baking the uncooled diffuser transition section approaching the catalyst.

At the 60-kW (80.4-hp) load, the O₂ concentration at the catalyst inlet is low enough to allow stoichiometric and fuel-rich operation to be carried out without risk of excessive catalyst temperatures. The results shown in Figures 13 through 15 indicate that both O₂ and NO_x essentially disappear at slightly rich operating conditions. This relationship is indicated by the maximum CO₂ reading at the catalyst exit and can be identified in Figure 19, which is a plot of CO₂ versus the overall fuel/air ratio. The stoichiometric fuel/air ratio for No. 2 diesel fuel is ~0.069 lb/lb.

At the 48-kW (64.3-hp) load, the O₂ level allows stoichiometric operation but is closer to the allowable maximum than the 60-kW (80.4-hp) load. The results are essentially the same in both cases.

Table 7

Test Data at 60-kW (80.4-hp) Load

Reference Velocity m/s (ft/s)	Overall F/A Ratio lb/lb	Engine Exhaust Temperature °C (°F)	Catalyst Inlet Temperature °C (°F)	Emissions				
				%			Vppm	
				CO ₂	CO	O ₂	NO _x	O ₂
1.8 (6)	0.0483	371 (700)		6.4	0.04	8.01	>1 000	
1.8 (6)	0.0574	366 (690)	299 (570)	10.0	0.03		>1 000	
1.8 (6)	0.0620	360 (680)	285 (545)	11.2	0.02		>1 000	>10 000
1.8 (6)	0.0676			13.2	0.05		>1 000	>10 000
1.8 (6)	0.0681	371 (700)	304 (580)	12.0	0.03		>1 000	
1.8 (6)	0.0698	371 (700)	254 (490)		3.0		8.0	≤10
1.8 (6)	0.0711	371 (700)	299 (570)	13.8	7.0		3.5	
1.8 (6)	0.0735	360 (680)	282 (540)	12.2	4.0		6.7	≤10
1.8 (6)	0.0736	377 (710)	260 (500)	12.6	6.5		5.0	≤10
1.8 (6)	0.0778	360 (680)	271 (520)	12.6	6.8		0.3	
1.8 (6)	0.0814	377 (710)	260 (500)	12.0	7.4		11.0	≤10
1.8 (6)	0.0842	371 (700)	288 (550)	11.2	>10.0		0.15	
1.8 (6)	0.0848	360 (680)	277 (530)	10.4	8.2		4.0	≤10
1.8 (6)	0.0877	371 (700)	349 (660)	10.4	8.8		0.15	
1.8 (6)	0.0878	360 (680)	271 (520)	9.6	>10.0		0.6	≤10
1.8 (6)	0.0673	379 (715)	277 (530)		0.05		>1 000	4 110
1.8 (6)	0.0686	377 (710)	279 (535)		1.3		4.0	420

Table 7 (Continued)

Test Data at 60-kW (80.4-hp) Load

Reference Velocity m/s (ft/s)	Overall F/A Ratio lb/lb	Engine Exhaust Temperature °C (°F)	Catalyst Inlet Temperature °C (°F)	Emissions				
				%			Vppm	
				CO ₂	CO	O ₂	NO _x	O ₂
3 (10)	0.0483	371 (700)		6.2	0.02	8.01	>1 000	
3 (10)	0.0532	371 (700)	310 (590)	7.8	0.04		>1 000	
3 (10)	0.0553	377 (710)	304 (580)	10.0	0.03		>1 000	
3 (10)	0.0592	371 (700)	288 (550)	11.0	0.05		>1 000	
3 (10)	0.0593	366 (690)	288 (550)	9.8	0.05		>1 000	
3 (10)	0.0628	354 (670)		11.8	0.05		>1 000	
3 (10)	0.0631	371 (700)	299 (570)	12.5	0.04		>1 000	
3 (10)	0.0634	371 (700)	293 (560)	13.0			>1 000	
3 (10)	0.0704	371 (700)	299 (570)	14.0	1.45		5.4	
3 (10)	0.0706	371 (700)	299 (570)	13.2	2.1		3.2	
3 (10)	0.0708	382 (720)	310 (590)	13.1	3.9		0.1	≤10
3 (10)	0.0712	382 (720)	316 (600)	13.1	4.0		0.1	≤10
3 (10)	0.0716	360 (680)	282 (540)	13.0	3.0		7.4	≤10
3 (10)	0.0725	377 (710)	296 (565)	13.6	4.4		2.0	≤10
3 (10)	0.0771	377 (710)	293 (560)	12.6	7.1		2.0	≤10
3 (10)	0.0750	354 (670)	282 (540)	11.8	6.3		1.4	≤10
4 (13)	0.0579	388 (730)	316 (600)	9.0	0.7		700	
4 (13)	0.0618	388 (730)	316 (600)	11.5	0.55		120	
4 (13)	0.0773	388 (730)	310 (590)	12.2	6.6		0.05	≤10
4 (13)	0.0795	427 (800)	338 (640)	11.3	7.6		0.10	

Table 8

Test Data at 48-kW (64.3-hp) Load

Reference Velocity m/s (ft/s)	Overall F/A Ratio lb/lb	Engine Exhaust Temperature °C (°F)	Catalyst Inlet Temperature °C (°F)	Emissions				
				%		Vppm		
				CO ₂	CO	O ₂	HQ _x	O ₂
2.4 (8)	0.0486	349 (660)	277 (530)	6.3	0.05			
2.4 (8)	0.0552	327 (620)	260 (500)	9.8	0.02			>10 000
2.4 (8)	0.0573	338 (640)	293 (560)	9.8	0.02			
2.4 (8)	0.0581	360 (680)	316 (600)	12.5	0.05		>1 000	
2.4 (8)	0.0581	338 (640)	282 (540)	10.0	0.04		900	
2.4 (8)	0.0703	354 (670)	277 (530)	13.2	1.5		5.0	≤10
2.4 (8)	0.0719	343 (650)	282 (540)	13.1	2.6		8.0	≤10
2.4 (8)	0.0739	354 (670)	282 (540)	12.8	5.1		0.1	≤10
2.4 (8)	0.0739	354 (670)	277 (530)	13.1	5.2		0.07	≤10
2.4 (8)	0.0740	343 (650)	277 (530)	12.6	4.1		17.50	
2.4 (8)	0.0749	343 (650)	282 (540)	13.1	4.4		8.1	≤10
2.4 (8)	0.0756	343 (650)	277 (530)	11.8	5.4		10.0	
2.4 (8)	0.0783	360 (680)	271 (520)	11.7	8.2		0.12	
2.4 (8)	0.0796	343 (650)	282 (540)	10.4	8.2		6.5	≤10
2.4 (8)	0.0801	343 (650)	260 (500)	10.5	8.0		6.5	≤10
2.4 (8)	0.0809	338 (640)	277 (530)	10.4	7.6			
2.4 (8)	0.0821	338 (640)	260 (500)	11.6	7.2			
2.4 (8)	0.0838	338 (640)	266 (510)	10.0	8.4			
2.4 (8)	0.0688	327 (620)	266 (510)	12.6	0.2			1 100
3.7 (12)	0.0562	360 (680)	304 (580)	6.7	0.02		>1 000	≥10 000
3.7 (12)	0.062	360 (680)	293 (560)	13.0	0.05		>1 000	≥10 000
3.7 (12)	0.0789	349 (660)	271 (520)	11.5	8.0			
3.7 (12)	0.0799	360 (680)	277 (530)	11.2	8.6			≤10
3.7 (12)	0.0799	360 (680)	282 (540)	11.3	8.4		0.7	
4.3 (14)	0.0544	399 (750)	343 (650)	8.2	0.75		>1 000	
4.3 (14)	0.0581	399 (750)	371 (700)	10.5	0.2		>1 000	
4.3 (14)	0.0751	399 (750)	427 (800)	12.2	5.0		10.5	
4.3 (14)	0.079	393 (740)	371 (700)	11.6	6.8		3.0	≤10

Table 9

Test Data at 36-kW (48.3-hp) Load

Reference Velocity m/s (ft/s)	Overall F/A Ratio lb/lb	Engine Exhaust Temperature °C (°F)	Catalyst Inlet Temperature °C (°F)	Emissions				
				%			Vppm	
				CO ₂	CO	O ₂	NO _x	O ₂
2 (6.5)	0.0423	316 (600)		5.0	0.05		800	12.09
2 (6.5)	0.0423	304 (580)		4.8	0.03		>1 000	
2 (6.5)	0.0423	338 (640)		5.4	0.05		>1 000	
2 (6.5)	0.0423	327 (620)		5.4	0.05		>1 000	
2 (6.5)	0.0423	327 (620)		5.0	0.02		840	
2 (6.5)	0.0506	321 (610)	266 (510)	9.8	0.05			
2 (6.5)	0.052	321 (610)	266 (510)	9.5	0.05		900	
2 (6.5)	0.0582	299 (570)	254 (490)	12.2	0.02		645	
2 (6.5)	0.0583	327 (620)	266 (510)	12.2	0.05		745	
2 (6.5)	0.0617	299 (570)	243 (470)	13.1	0.05		660	
2 (6.5)	0.0778	321 (610)	321 (610)	10.5	9.5		0.35	<10
2 (6.5)	0.0782	327 (620)	249 (480)	11.7	7.8		1.1	
2 (6.5)	0.0857	299 (570)	243 (470)	9.6	>10.0		0.8	
2 (6.5)	0.0506	321 (610)	266 (510)	8.0	0.05			
2 (6.5)	0.0524	321 (610)	304 (580)	9.3	0.05		880	
2 (6.5)	0.0818	332 (630)	282 (540)	11.3	9.2		0.3	

Figure 19. Converter Exhaust CO₂ versus Fuel/Air Ratio

As shown in Figures 13 through 18, CO levels climb as the stoichiometric condition is approached from the lean side, with the fuel/air ratio at <0.069 lb/lb. At optimum conditions for O_2 and NO_x reduction, with the fuel/air ratio slightly rich at >0.07 lb/lb, CO levels exceed 1 to 3%.

Although detailed specifications for inert gas composition have not been established at this time, consideration should be given to reducing the allowable CO concentration to a few tenths of a percent or lower. This reduction can be accomplished in a number of ways, depending on the number of load settings at which the diesel/convertor system is to be operated. One method for a limited load range is depicted by the schematic in Figure 20. In this system, part of the convertor exhaust is recycled to the engine exhaust/catalytic convertor inlet. This system has two advantages over the once-through system currently used because the recycle system

1. Artificially reduces inlet O_2 levels to permit a wider load range while preventing excess convertor operating temperatures and
2. Supplies some CO for NO_x reduction at the catalyst inlet, initiating reduction reactions at a leaner fuel/air ratio.

A method for an unlimited load range is illustrated by the schematic in Figure 21. In this example, two convertors operate in series, and, depending on the mode of operation, the convertors can accomplish full load-range capability and have the best potential for minimum CO production under the following conditions:

1. Diesel exhaust $O_2 \leq 10.0\%$
  - a. First stage is slightly rich to reduce O_2 and NO_x .
  - b. Second stage eliminates CO by controlled air addition.
2. Diesel exhaust $O_2 > 10.0\%$
  - a. First stage is rich to reduce O_2 and NO_x .
  - b. Second stage eliminates CO by controlled air addition.

In a fixed load operation, both modes of operation may be used; however, automotive exhaust treatment technology, including flow controls, may be used in a modified, two-stage treatment system. Thus, the second stage would be an "emissions abatement convertor" designed to eliminate residual O_2 , CO, NO_x , etc.

Additional factors to be considered in reviewing modified nitrogen generating systems are listed in Table 10. Process steps to be added downstream of the inert gas generator may be H_2O , CO_2 and S removal. Available technology exists to carry this out and will be addressed after more detailed field system gas composition requirements are established. Efforts are continuing to determine the desirability of (1) fixed engine load operation, (2) limited engine load-range operation, or (3) full engine load-range operation and to provide specifications on required inert gas composition by end use requirements.

Vppm = Volume, parts per million

Figure 20. Schematic of Inert Gas Generator Using an Exhaust Gas Recirculation System; Limited Load Range

Vppm = Volume, parts per million

Figure 21. Schematic of Inert Gas Generator Using a Two-Stage Converter System; Unlimited Load Range

Table 10

Alternate System Operating Requirements

<u>Exhaust Gas Recirculation Option</u>	<u>Two-Stage Convertor Option</u>
1. Single-stage burner	Two-stage burner
2. Burner/boiler package	Burner/boiler/superheater package
3. Simpler controls	More complicated controls
4. Enhanced sulphur recovery	Low level sulphur recovery
5. "Existing package boiler" + burner modification for waste heat recovery	New burner/boiler design for waste heat recovery
6. Lower pressure steam	Higher pressure steam
7. Pressure boost required for recycle by compressor by steam ejector	No pressure boost required
8. $H_2O/S/CO_2$ /etc., removal/recovery process steps may be required in both options; hence, some form of pressure enhancement may be incorporated.	

The durability tests are underway and will include

1. 100 hours at 60 kW (80.4 hp) at minimum fuel/air ratio for O_2 and NO_x reduction (near stoichiometric) and
2. 100 hours at 48 kW (64.3 hp) at a fuel-rich setting.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

★

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
FIELD EVALUATION OF HTM-1 MUD SYSTEM MAURER ENGINEERING LABORATORY TESTS FIELD TESTS	As Required Tentative Imperial Valley												

LEGEND:

———— ACTIVITY PERIOD
 - - - - - RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.6 Field Evaluation of HTM-1 Mud System

Contractor: Maurer Engineering, Inc.
Principal Investigator: L. J. Remont (713) 683-8227
Contract Period: 15 November 1979 to 30 June 1980
Contract Number: 07-7068 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to determine the performance of the high temperature mud system (HTM-1) under field conditions. Appropriate laboratory tests will also be conducted in order to monitor the field performance of HTM-1, which is an improved geothermal drilling fluid developed for drilling into hydrothermal reservoirs. HTM-1 can be prepared with conventional equipment using commercially available materials.

Project Status

The project was initiated in the latter part of the previous reporting period. Efforts to locate a suitable well for testing HTM-1 are progressing. Laboratory testing of sample formulations has been conducted and is continuing.

Quarterly Progress

Field interviews with geothermal operators and service companies indicate that McCulloch, Mapco, and Occidental will be drilling geothermal wells that may exceed temperatures of 260°C (500°F) in the Imperial Valley, California, in the first half of 1980. Union Oil Company and Republic Geothermal will be drilling wells with estimated temperatures lower than 260°C (500°F).

Republic Geothermal and Union Oil Company of California plan to drill some step-out wells in the Imperial Valley, but they estimate that these wells will be at lower temperatures than the in-field wells. Republic is also a partner with Mapco in an operation involving several wells which are expected to exceed 260°C (500°F). Mapco, which operates out of Tulsa, Oklahoma, is the operator for the partners. A visit is planned to Mapco to determine the possibility of using HTM-1 on one of the Mapco wells.

Baroid was contacted to discuss the possibility of renting one of its field laboratory trailers. The firm indicated that it would rent the trailer only if it sold the mud materials on the job. Baroid also indicated that Occidental was planning a well which is expected to have a bottomhole temperature in excess of 260°C (500°F). Occidental will be contacted to obtain more details on this well.

In preliminary negotiations, McCulloch showed an interest in using HTM-1 on its proposed deep, hot well in the Imperial Valley in March or April 1980. McCulloch requested that field samples of sepiolite be obtained and tested in laboratory formulations at 288°C (550°F). A sack of GeoGel, which is marketed by Magcobar, was obtained for testing.

HTM-1, prepared with laboratory stock sepiolite, was similar to that prepared with the field sample of sepiolite (Magcobar's GeoGel) in tests conducted immediately after preparation, after hot-rolling 18 hours at 66°C (150°F), and after static aging 24 hours at 288°C (550°F) and 3.5 MPa (500 psi).

The samples were prepared using the formulations shown in Table 11. The samples were stirred 40 minutes at high speed.

Table 11

HTM-1 Sample Formulations

Sample No.	Formulation	
I.	Water	0.16 m ³ (1.0 bbl)
	Thermogel	6.8 kg (15 lb)
	Aquagel	2.3 kg (5 lb)
	Brown coal	9.1 kg (20 lb)
	Cypan	1.1 kg (2.5 lb)
	Naolt	0.91 kg (2 lb)
II.	Water	0.16 m ³ (1.0 bbl)
	Thermogel	6.8 kg (15 lb)
	Aquagel	2.3 kg (5 lb)
	Knife River lignite	9.1 kg (20 lb)
	Cypan	1.1 kg (2.5 lb)
	Naolt	0.91 kg (2 lb)
III.	Water	0.16 m ³ (1.0 bbl)
	GeoGel	6.8 kg (15 lb)
	Aquagel	2.3 kg (5 lb)
	Knife River lignite	9.1 kg (20 lb)
	Cypan	1.1 kg (2.5 lb)
	Naolt	1.1 kg (2.5 lb)

The three mud samples had similar properties when tested immediately after preparation. Sample I differed slightly in that it exhibited a higher 10-minute gel strength. The samples were rolled at 66°C (150°F) for 18 hours and tested again. Sample I became thicker than the other two samples. Sample II remained essentially unchanged, and Sample III became thicker than it had been before rolling.

Samples II and III were static aged at 288°C (550°F) and 3.5 MPa (500 psi) for 24 hours. After this aging, both samples exhibited less viscosity but much higher 10-minute gel strengths. The low shear strengths indicated that the muds had gelled upon exposure to these high temperatures. No indication of mud solidification was noted in these tests. The data recorded on the samples are shown in Table 12.

After rolling, each of the three mud samples was static aged at 288°C and 3.5 MPa (550°F and 500 psi) for 2 weeks (336 hours). At the end of this period, the cell containing Sample III was found to have leaked, and no results were obtainable for this sample. Sample I exhibited a lower plastic viscosity but a greater yield point and greater gel strengths when compared to the mud after hot rolling for 18 hours at 66°C (150°F). Sample II exhibited a similar plastic viscosity but a greater yield point and greater gel strengths after two weeks when compared to the mud after hot rolling. Both mud samples showed no tendency toward solidification. The muds were easily stirred and poured from the container after mixing. At each stage in the testing procedure, the muds foamed when stirred. The foam was effectively reduced by using octyl alcohol defoamer before testing.

Brown coal currently stored at Sandia was sampled. Visual inspection indicated that the material was dry, flows freely, and had a consistent particle size. From a material handling standpoint, the brown coal appeared typical of most drilling mud quality additives. Fifteen samples were obtained from the stock of brown coal and shipped to Maurer for testing. The 15 samples, ranging in weight from 1395 to 1968 grams (3.1 to 4.3 pounds) were obtained from 15 separate pallets of the brown coal. Every third sample was tested to determine the particle size distribution, moisture, ash, pH of a 5% dispersion in distilled water, and the water soluble chemical constituents. The results of these tests are shown in Table 13. A composite coal sample was prepared from all 15 samples. Three portions of this composite, identified as C-1, C-2, and C-3, were tested for the same properties in order to characterize the composite sample. The results of these tests are contained in Table 14.

The composite coal sample was then used to prepare the two HTM-1 formulations shown in Table 15. The samples, designated IV and V, were stirred 40 minutes at high speed and then tested following preparation as indicated in Table 16. The results of the tests are presented in the same table. Sample IV and Sample V exhibited similar properties, with Sample V demonstrating a slightly higher plastic viscosity. Both became slightly thicker after rolling. Static aging tests (24 hours and 2 weeks) are now being conducted on these mud samples.

The experiments with brown coal indicate that this substance is suitable for drilling operations and for preparation of HTM-1 formulations. The particle size distribution is such that the coal would not interfere with normal mud handling equipment in field operations. The calcium ion content is higher than in the brown coal tested previously but lower than regular drilling mud lignite. The magnesium ion content is higher in this coal than in the brown coal tested before and in regular lignite. Other soluble ions are in the range expected for brown coal.

Table 12
Properties of Mud Samples

Conditions/Properties	Sample Number							
	I	I	II	II	II	III	III	III
Rolled at 65.6°C (150°F), hours	0	18	0	18	18	0	18	18
Static aged at 287.7°C (550°F), 3.5 MPa (500 psi), hours	0	0	0	0	24	0	0	24
Plastic viscosity, Pa·s (cp)	0.035 (35)	0.054 (54)	0.030 (30)	0.030 (30)	0.020 (20)	0.026 (26)	0.036 (36)	0.022 (22)
Yield point, Pa (lb/100 ft ²)	12.9 (27)	20.1 (42)	9.6 (20)	11.0 (23)	13.9 (29)	6.2 (13)	17.2 (36)	10.5 (22)
10-second gel, Pa (lb/100 ft ²)	1.9 (4)	3.4 (7)	1.9 (4)	2.4 (5)	2.9 (6)	1.9 (4)	2.9 (6)	2.4 (5)
20-minute gel, Pa (lb/100 ft ²)	7.2 (15)	5.7 (12)	4.3 (9)	3.8 (8)	21.1 (44)	4.3 (9)	4.8 (10)	15.3 (32)
API filtrate, ml (in. ³)	6.0 (0.37)	5.1 (0.31)	6.5 (0.40)	5.3 (0.32)	18 (1.10)	6.6 (0.40)	4.9 (0.30)	19 (1.16)
pH	10.8	9.8	11.0	9.0	7.8	11.2	9.5	8.5
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)		22.8 (1.39)		23.9 (1.46)	36.8 (2.25)		25.2 (1.54)	39.2 (2.39)
Shear strength, Pa (lb/100 ft ²)					9.6 (20)			9.6 (20)

Table 13

Characterization of Brown Coal Samples

Chemical Analysis	Sample Number				
	1	4	7	10	13
Moisture, % by weight	13.2	12.2	10.3	15.0	9.0
Ash, % by weight*	15.5	15.3	16.9	15.9	15.0
pH of 5% dispersion*	4.2	4.1	4.2	4.1	5.2
Soluble Salts*					
Calcium, ppm	3 690	3 640	2 590	3 760	1 320
Magnesium, ppm	2 590	2 560	1 930	2 700	790
Chloride, ppm	495	570	445	590	330
Hydroxide, ppm	0	0	0	0	0
Carbonates, ppm	0	0	0	0	0
Bicarbonates, ppm	425	420	412	435	930
Sulfides, ppm	trace	none	none	trace	trace
Sulfates, ppm	7 630	8 540	6 830	10 300	8 650
<u>Particle Size Distribution</u>					
Cumulative Percent Retained:					
U.S. Standard Sieve No.					
20	5.0	9.2	8.1	3.4	9.3
30	8.1	13.3	12.1	5.2	15.2
50	20.0	28.9	24.8	14.2	32.9
100	34.7	47.5	39.3	29.0	51.8
200	50.9	64.9	55.9	47.8	67.6

*Dry Basis

Table 14

Characterization of Composite Brown Coal Samples

<u>Chemical Analysis</u>	<u>Sample Number</u>		
	<u>C-1</u>	<u>C-2</u>	<u>C-3</u>
Moisture, % by weight	1.1	11.1	11.0
Ash, % by weight*	14.8	14.0	13.8
pH of 5% dispersion*	5.1	4.8	5.1
Soluble salts*			
Calcium, ppm	2 610	2 520	2 610
Magnesium, ppm	1 510	1 510	1 510
Chloride, ppm	340	380	380
Hydroxide, ppm	0	0	0
Carbonates, ppm	0	0	0
Bicarbonates, ppm	765	740	690
Sulfates, ppm	6 975	5 900	6 320
<u>Particle Size Distribution</u>			
Cumulative Percent Retained:			
U.S. Standard Sieve No.			
20	8.8	8.2	8.2
30	13.9	13.3	13.4
50	30.1	29.7	29.6
100	48.7	48.2	47.9
200	66.5	65.8	65.3

*Dry Basis

Table 15

HTM-1 Sample Formulations using Brown Coal

Sample No.	Formulation	
IV	Water	0.16 m ³ (1.0 bbl)
	Thermogel	6.8 kg (15 lb)
	Aquagel	2.3 kg (5 lb)
	Composite Coal Sample	9.1 kg (20 lb)
	Cypan	1.1 kg (2.5 lb)
	NaOH	0.91 kg (2 lb)
V	Water	0.16 m ³ (1.0 bbl)
	GeoGel	6.8 kg (15 lb)
	Aquagel	2.3 kg (5 lb)
	Composite Coal Sample	9.1 kg (20 lb)
	Cypan	1.1 kg (2.5 lb)
	NaOH	0.91 kg (2 lb)

Table 16

Properties of Brown Coal Mud Samples

Conditions/Properties	Sample Number			
	IV	IV	V	V
Rolled at 65.6°C (150°F), hours	0	18	0	18
Static aged at 287.7°C (550°F), 3.5 MPa (500 psi), hours	0	0	0	0
Plastic Viscosity, Pa·s (cp)	0.015 (15)	0.017 (17)	0.018 (18)	0.023 (23)
Yield point, Pa (lb/100 ft ²)	2.4 (5)	3.4 (7)	2.4 (5)	3.8 (8)
10-second gel, Pa (lb/100 ft ²)	1.4 (3)	1.4 (3)	1.4 (3)	1.4 (3)
10-minute gel, Pa (lb/100 ft ²)	1.9 (4)	1.9 (4)	1.9 (4)	1.9 (4)
pH	11.0	9.5	11.0	9.5
API Filtrate, ml (in. ³)	5.1 (0.31)	5.5 (0.34)	5.0 (0.30)	5.2 (0.32)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)		26.0 (1.59)		25.4 (1.55)

The HTM-1 samples prepared with a composite brown coal sample exhibited properties similar to those muds prepared in the initial studies. The HTM-1 formulations exhibit excellent properties for drilling in geothermal operations.

5. 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. The approach to improved completions is to develop design criteria, completion techniques, and/or hardware to extend well life and improve production. Projects are presently underway with the objectives of (1) designing a downhole perforator for use in geothermal well completions, (2) establishing needs and defining requirements for downhole primary cementing tools and for monitoring tools to detect critical failure modes of a geothermal well completion, and (3) designing and demonstrating a system using a controlled cavitation technique for downhole geothermal well cleaning and scale removal. The status and progress of these activities are described within this section.

Completed efforts under this element of the Geothermal Drilling and Completion Technology Development Program have resulted in improvements in geothermal well completion technology and identification of needed technology development. Failure modes and reasons for geothermal well casing failures have been documented and published. Requirements for technology development to reduce the probability of casing failure were also formulated as part of the casing/liner design and cementing study project.

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

A new technique using high-pressure cavitating jets to remove scale from pipes in geothermal power plants was demonstrated. The possibility of using the system to remove scale from the wellbore in a flowing well was also demonstrated, and the parameters needed for design of an operational downhole geothermal well cleaning and scale removal system were established. Development of this system is approaching the field demonstration stage.

The first phase of a project to investigate the effect on rock permeability of drilling mud invasion has been completed. The laboratory test results for two mud systems are being evaluated, and a follow-on project to continue the study of drilling fluid/formation interactions has been established.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>HIGH-TEMPERATURE PERFORATOR</u> STUDY OF OFF-THE-SHELF PERFORATORS HIGH-TEMPERATURE PERFORATOR DESIGN	START DEPENDENT ON STUDY FINDINGS												

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5.1 High-Temperature Perforator

Sandia National Laboratories
Technical Consultant: W. Leslie (505) 844-3267

Project Objective

The objective of this project is to determine the feasibility of designing an explosive perforator that is capable of functioning at and after exposure to a temperature of 250 to 300°C (482 to 572°F) for 45 minutes.

Project Status

A variety of conventional explosive perforators have been purchased from a commercial supplier. Diagnostic techniques for determining the performance of these perforators are presently under investigation. Findings of the ongoing study phase of the project will determine subsequent efforts to design a high-temperature perforator.

Quarterly Progress

Ten different types of commercial perforators, designed to function at ordinary oil-well temperatures, were purchased for testing. Before any perforators can be detonated at elevated temperatures, it will be necessary to first develop diagnostic techniques that will give a measure of the performance of a perforator subjected to each test. Development of these techniques will be the next step in the program.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>COMPLETION TECHNOLOGY CONSULTATION</u> <u>COMPLETION TECHNOLOGY COMPANY</u>													
LONG-RANGE GEOTHERMAL WELL TECHNOLOGY PROGRAM FORMULATION/EXECUTION		●										▽	
CEMENTING TOOLS						●						▽	
MONITORING TOOLS					●							▽	

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5.2 Completion Technology Consultation

Contractor: Completion Technology Company
Principal Investigator: R. E. Snyder (713) 961-5011
Contract Period: 16 November 1979 to 30 September 1980
Contract Number: 46-0173 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The project objective is to provide consulting and engineering services to the Geothermal Drilling and Completion Technology Development Program in the following areas: (1) establishing needs and defining requirements for downhole primary cementing tools; (2) establishing needs and defining requirements for monitoring tools to detect critical failure modes of a geothermal well completion; (3) defining at a state-of-art level, geothermal well completion technology and transferring technology to industry; and (4) formulating and implementing the long-range DOE/Sandia geothermal drilling and completion technology development program.

Project Status

The project was initiated in the latter part of the last quarterly reporting period and continued the consulting services provided under a previous contract concerning other elements of completion technology development. Work on the state-of-the-art study of cementing and monitoring tools has been initiated.

Quarterly Progress

A paper, "Geothermal Well Casing Failure Modes," was prepared and presented to the 1980 ASME Petroleum Division Conference in New Orleans, Louisiana, 6 February 1980.

Materials and required study guides were organized for the Geothermal Resources Council Technical Training Course held in Albuquerque, New Mexico, 24-26 March 1980. The session on geothermal well casing failure analysis and prevention was conducted by CTC.

Preliminary investigations into the state of the art of monitoring methods and equipment were conducted. Several wireline companies were contacted in the data collection effort.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE	
<u>CAVITATION DESCALING DAEDALEAN</u>														
DESIGN PARAMETER IDENTIFICATION TESTS	COMPLETE													
SYSTEM DESIGN AND FABRICATION														
CLEANING HEAD														
TUBING REEL														
LABORATORY TESTS														
FIELD DEMONSTRATION														
CONTRACTING														

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5.3 Cavitation Descaling Technique for Downhole Geothermal Well Cleaning

Contractor: Daedalean Associates, Inc.
Principal Investigators: Dr. A. P. Thiruvengadam (301) 442-2620
Dr. A. A. Hochrein, Jr.
Contract Duration: 14 February 1979 to 15 August 1980
Contract Number: 13-2361 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

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).

Project Status

The design parameters were identified on 29 and 30 March 1979 at the East Mesa (California) geothermal test facility. The design process is now proceeding as a result of the data obtained from this test. The water-powered, hydraulic, cleaning head motor is in the final design stages. The current target date for the completion of the field demonstration is 12 June 1980.

Quarterly Progress

A nozzle rotator (Figure 22) was designed for use when the well is flowing. The central core of the rotator is a section of high-pressure tubing which connects the cleaning head to the rotating seal/coiled tubing adaptor assembly. Attached to the central core are the impeller assemblies, which, after being exposed to the geothermal flow, impart the rotational force to the cleaning head. The rotator assembly is designed to rotate at 60 rpm. Previous experiments demonstrate that this speed allows the four-nozzle cleaning head (Figure 23) to operate most effectively.

The water-powered, hydraulic, cleaning head rotator is in the final design stages. This rotator will incorporate a gerotor-type hydraulic motor that has been modified to operate using water as the working fluid. The metal-to-metal sealing surfaces in the motor are being redesigned, as suggested by the manufacturer, to incorporate a self-lubricating bearing material on both of the sealing faces of the motor.

The feedwater for the modified hydraulic motor will be obtained from the high-pressure supply line that carries the water to the cavitating

Figure 22. Concaver Nozzle Rotator

0 TO 5° TYP

DETAIL "A"

5/8--18 UNF 3A
0.500 DEEP
4 PLACES

NOTE: DIMENSIONS IN INCHES
TOLERANCES
DECIMAL: ± 0.010
ANGULAR: $\pm 5^\circ$

Figure 23. Cleaning Head, Multi-Nozzle Holder

cleaning nozzles. Approximately $6.3 \times 10^{-5} \text{ m}^3/\text{s}$ (1 gpm) will be utilized to supply the motor.

The search for a coiled tubing capable of withstanding the 103-MPa (15 000-psi) operating pressure is continuing. A tubing that will operate at 76 MPa (11 000 psi) has been located. The supplier of this tubing is checking on the possibility of manufacturing a special run of tubing capable of withstanding the 103-MPa (15 000-psi) operating pressure.

The Otis Engineering Company was contacted concerning the availability of a heavy-wall, coiled tubing capable of withstanding the high-pressure requirements of the cavitating cleaning system. Otis indicated that it would be taking delivery in the latter part of March 1980 of a 2.16-mm (0.085-inch) wall thickness tubing with a burst rating of 97 MPa (14 000 psi). The firm agreed to allow the tubing to be operated at 76-MPa (11 000 psi). However, a question has arisen regarding the effects of bending the tubing over the injector head under the 76-MPa (11 000-psi) internal pressure. The additional stresses produced in the tubing due to the bending may cause the tube to rupture. Therefore, a limited test program is being proposed that would allow Otis to burst test the tubing in their laboratory under simulated field conditions to verify the maximum allowable operating pressure.

A meeting was held with Sandia to review the progress in the program and to discuss the tasks which need to be completed during the remaining months of the project. The current target date for the completion of the field demonstration is 12 June 1980.

6. LOST CIRCULATION CONTROL METHODS

A major contributor to the high costs experienced in geothermal well drilling is lost circulation. Drilling fluid loss causes several undesirable drilling conditions, including diminished or terminated cooling of the bit and removal of bottomhole chips. Also, most drilling fluids are expensive, and transportation of additional fluid additives to the drilling site results in costly time delays as well as in increased direct material/services costs. Lost circulation problems, in general, are not well defined nor readily understood, and methods and materials used to control lost circulation problems are even more ill defined. Normal industry practice is to treat each lost circulation situation separately as it occurs. The approach to the development of lost circulation control methods is to (1) characterize and define in detail the operational and technical parameters of the problem, (2) formulate possible solutions, and (3) conduct the indicated research and development required for identifying effective control or prevention methods, materials, and/or equipment. Projects are currently proceeding with the objectives of determining the geological characteristics of lost circulation zones and of collecting, collating, and analyzing industry experience concerning the causes, prevention, and remedy of lost circulation in geothermal environments. The status and progress of these activities are described within this section.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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6.1 Geological Characterization of Lost Circulation Zones

Contractor: Tech. Reps., Inc.
Principal Investigator: R. V. Guzowski (505) 262-2077
Contract Period: 10 December 1979 to 31 May 1980
Contract Number: 46-8886 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project to determine the geological characteristics of lost circulation zones in the volcanic sequences encountered during the drilling of geothermal wells. These characteristics will be compared for consistency within each of several Known Geothermal Resource Areas (KGRA). If specific lithologic properties are related to lost circulation in each area, the results for the various KGRA's will be compared to determine if the properties are of local or regional significance. In addition to rock properties, the effects of various drilling practices will be considered to determine whether lost circulation is naturally occurring or drilling induced.

Project Status

The project was initiated at the end of the last quarterly reporting period. Information on lost circulation experience in geothermal well drilling in the Cove Fort-Sulphurdale, Utah; Raft River, Idaho; and Valles Caldera, New Mexico is included in the data collected. The literature search and data collection efforts have been completed. Analysis of the data and development of a parametric model are continuing.

Quarterly Progress

The primary objective of determining the geological characteristics of lost circulation zones is to define one or more parameters that can be utilized to predict with a high degree of accuracy those zones where circulation will be lost. Because of the differing mechanical behavior of the igneous, volcanic, and sedimentary rock types encountered in the various types of geothermal resource areas, a generalized characterization for all areas probably is not possible. Because of this complexity, the scope of the project was narrowly defined. Volcanic terrains are prime targets for geothermal exploration, and much drilling experience has been amassed. As a result, this project is concentrating on lost circulation zones encountered in volcanic terrains.

The geologic areas under consideration for investigation include Valles Caldera, New Mexico; Jemez Mountain Region, New Mexico; Mt. Lassen, California; Snake River Plain, Idaho; and Long Valley, California. The following agencies and organizations were contacted in an attempt to gather sources for drilling information in the selected areas:

- American Petroleum Institute
- Bureau of Land Management, Santa Fe, New Mexico
- California Division of Mines
- California Division of Oil and Gas
- Department of Energy, Idaho Falls, Idaho
- Idaho Bureau of Mines
- Idaho Department of Water Resources
- Montana Bureau of Mines
- Nevada Bureau of Mines
- New Mexico Bureau of Mines
- Petroleum Information Corporation
- University of Utah Research Institute
- Utah Geological Survey
- Wyoming Geological Survey
- Wyoming Oil and Gas Commission

In addition, government agencies in 11 western states, several state geological societies, the Rocky Mountain Association of Geologists, the American Association of Petroleum Geologists, and the American Petroleum Institute were contacted for lists of publications to determine the available literature on geothermal research, lost circulation studies, regional geology, and local geology. Visits were made to the University of Utah Research Institute in Salt Lake City and to the DOE office in Idaho Falls. Contacts with private organizations involved in geothermal exploration and development have also been made.

Investigations revealed that the University of Utah Research Institute (UURI) in Salt Lake City, Utah, and the DOE office in Idaho Falls, Idaho, have drilled geothermal wells in areas containing volcanic stratigraphic sequences. Because the results from these drillings were immediately available, these two agencies were contacted first in the data collection effort.

At UURI, a thorough library search yielded completion reports and geophysical logs for two of the three wells drilled at the Cove Fort-Sulphurdale KGRA in Utah. This was the only area with records on file at which the stratigraphic sequence is at least in part of volcanic origin. Preliminary analysis of the various logs and drilling records indicated that lost circulation in the volcanic rocks was not correlatable from well to well and that physical properties of the rocks were no indication of where lost circulation would occur. Most zones in which circulation was lost were located where the drill-hole intersected a fault zone. Except for cement, no information was available on the techniques or materials used in attempting to solve lost circulation problems.

In Idaho Falls, DOE, EG&G, Idaho, Inc., and Energy Services, Inc. were contacted. DOE provided information concerning problems encountered in drilling most of the wells at Raft River KGRA, Idaho. The logs for these wells were available at EG&G. Energy Services had worked on the first two Raft River wells and has drilled several other geothermal wells in the Snake River Plain. Energy Services related its experiences with lost circulation zones encountered during drilling through volcanic sequences and agreed to provide a drilling report when that report is completed. The Raft River KGRA probably does not contain enough volcanics to be of use to this project.

Coordination of data-gathering efforts with the project on geothermal well temperature histories and lost circulation being conducted by Eneritech was made in a meeting with Sandia to avoid any duplication or unnecessary multiple interviews. Subsequently, the meeting participants, Tech. Reps., Eneritech, and Sandia, visited the geothermal offices at LANSL and were briefed on the drilling and casing problems encountered during the hot dry rock (HDR) project at Fenton Hill. The briefing was followed by a trip to Fenton Hill, where the drilling history of LANSL's Sigma Mesa Well was reviewed.

The information provided on the Fenton Hill drilling is of marginal use in attempting to characterize the geological aspects of lost circulation zones. However, a review of the completions reports of this drilling may yield some useful data. LANSL agreed to provide a copy of its report on the Sigma Mesa Well when the report is completed. Preliminary analysis of the limited amount of information concerning the Sigma Mesa Well indicates a close correlation between rock type and lost circulation zones.

In order to supplement the information provided by LANSL on the Sigma Mesa Geothermal Well, attempts were made to locate additional drilling data for the geothermal well and drilling records for water wells in the Los Alamos area. A summary of these efforts follows.

- LANSL provided copies of the electric logs, sample descriptions, and notes for the Sigma Mesa Well. LANSL indicated that the depths of lost circulation listed in the notes may not be the depths at which the drilling fluid escaped from the hole. The electric logs showed no notable variations for the lost circulation zones which were listed. Much of the information obtained about the Sigma Mesa Well drilling is of little use in determining the detailed geological characteristics of lost circulation zones.
- LANSL was involved with the drilling of some of the water wells in the Los Alamos area. Because of the age of the drilling data, however, none of the information has been retained.
- Herkenhoff, Gordon, and Associates, Inc., located in Albuquerque, New Mexico, were also involved with the drilling of water wells in the Los Alamos area. The records for the water wells are in storage and not readily accessible. Because of previous commitments, company personnel were not available to locate the records by the end of this reporting period.

Union Oil Company of California has drilled on the Baca property within Valles Caldera, which is located west of Los Alamos, New Mexico. Most of the drilling was through the Bandelier tuff. As a result, almost all of the lost circulation zones were located in this tuff. Union Oil indicated that the lost circulation was primarily the result of fracture zones, although occasional, highly porous pumice beds also caused problems. Copies of the well completion reports, the lithologic logs, and the electric logs were made from those on file at the DOE office in Albuquerque. Major lost circulation problems were reported for only 8 of the 13 wells for which records were kept. Electric logs were available for only four of these eight wells, and only two of the wells had logs which measured the physical properties of the rocks. Based on the analysis of the limited

data available, no correlation was noted between lost circulation zones, minor variations in rock type, or variations in rock properties as recorded by the electric logs.

The manager of Geothermal Exploration, Phillips Petroleum Company has agreed to provide limited data on the lost circulation problems encountered in geothermal areas. An interview will be conducted when he returns from the Philippines.

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FISCAL YEAR 80[illegible]

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6.2 Temperature History and Lost Circulation Experience in Geothermal Wells

Contractor: Enertech Engineering and Research Co.
Principal Investigator: G. Wooley (713) 521-9294
Contract Period: 29 August 1979 to 31 May 1980
Contract Number: 13-8769 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The objective of this project is to provide temperature histories required for geothermal well casing design and to provide a synopsis of causes and preventions of, and remedies to, lost circulation in geothermal environments.

Project Status

Project work was initiated in September 1979. An information survey plan has been developed to acquire and organize the required well thermal history and lost circulation experience data. The review of pertinent literature and the interview of selected companies with appropriate experience is progressing.

Quarterly Progress

Activities in this quarter continued in compiling and reviewing literature on geothermal well temperature histories and lost circulation, refining the project scope, and pursuing the planned interviews with companies and agencies having geothermal well drilling experience.

The project plans, progress, and scope were reviewed in detail with Sandia. As a result of the review, additional or expanded efforts were identified. These efforts include work to review existing experimental equipment for testing lost circulation materials, to expand the petroleum industry interviews to include more operators and service companies, and to focus a literature survey on lost circulation. Some of these efforts were incorporated in planned activities, and the remainder were accommodated by a month extension of the contract period. Coordination with the project on geological aspects of lost circulation was made to avoid any duplication of effort and to assure that companies and agencies interviewed are not subjected to unnecessary multiple interviews.

Many companies have been evaluated regarding their potential for a productive interview concerning geothermal well drilling experience. The companies considered included those recommended by Sandia and Tech. Reps., Inc., the company conducting the project on geological aspects of lost circulation. Additional companies will be considered on a continuing basis, and the interview list will be revised accordingly. The current list of

companies and agencies considered prime information sources include the following:

- Union Geothermal
- Phillips Geothermal
- Los Alamos National Scientific Laboratory
- Department of Energy
- University of Utah
- Terra Services
- Mobil Oil
- Messenger
- Mexican Geothermal
- IMCO
- Baroid
- Haliburton
- Exxon
- Shell

The results of Sandia's literature search on lost circulation have been made available to Enertech and work is underway on sorting through the references and abstracts. As part of the overall assessment of lost circulation in geothermal wells, the literature on lost circulation in both petroleum and geothermal wells will be evaluated and categorized into specific subject areas. Each subject area will be summarized and documented. Such a categorization has not been previously compiled. In this form, the lost circulation literature should be more useful to the present investigation and to future investigations. The documentation by category will serve as a single reference for quick review. Subject categories will include:

1. Lost circulation materials,
2. Detection methods of lost circulation zones,
3. Laboratory tests and testing equipment,
4. Drilling-related causes of lost circulation, and
5. Formation-related causes of lost circulation.

In reviewing Sandia's literature search two key words, lost circulation and thief formation, were used. From examination of references listed in Petroleum Abstracts, four other key words were found to yield a significant number of additional sources. These four key words were:

1. Lost circulation additive,
2. Formation plugging,
3. Plugging agent, and
4. Selective plugging.

The Sandia search was computer-based and considered the literature from 1969 to mid-1979. Enertech has begun to expand on the Sandia search in two ways:

1. By manually searching the six key words in the monthly lists published by Petroleum Abstracts from mid-1979 and continuing into 1980, and
2. By searching the additional four key words from 1975 to 1979.

In this reporting period, interviews were undertaken with Dresser-Magcobar in Houston, Texas, with Union Geothermal in Santa Rosa, California, with Louis Capuano, a consultant in Santa Rosa, California, and with LANSI, New Mexico. The results of these meetings are presented below relative to the temperature history and lost circulation aspects of the project.

•Temperature History

Casing sizes, setting depths, cement intervals, and lithology were provided by LANSI for the EE-1, EE-2, and GT-2 wells. Drilling rate data were also provided for GT-2. An undisturbed geothermal profile for the region was obtained, which shows a bilinear gradient.

Downhole temperature data during circulation in one of the LANSI wells is being measured, and results will be forwarded to EnerTech. Such data will be useful for correlation with GEOTEMP and will serve to estimate soil thermal properties by means of inverse simulation.

With the drilling data on the GT-2 well, thermal simulation with GEOTEMP can be performed to obtain a drilling temperature history. Injection and production temperature histories can also be simulated for the circulation loop formed by EE-1 (injection well) and GT-2 (production well).

Dresser had no data that could be released. Union Geothermal has compiled drilling and production data and well completion information on The Geyser field for forwarding to Sandia. Union requested that copies of the data be obtained from Sandia. The data include two sets each for drilling and production and bound the range of typical histories. Undisturbed geothermal temperature profiles for The Geysers were also provided by Union. They pointed out that the gradients have never been measured directly and that the data supplied by Union are simply the best estimate. It was noted that the typical Geyser geothermal gradient was approximately bilinear, indicating that GEOTEMP can sufficiently simulate the undisturbed conditions.

In addition to the drilling and production data, a request was made that injection data also be supplied. Subsequent to the meeting, injection flow histories and injection temperatures were obtained for two types of injection processes, namely well killing and water reinjection. In both cases, injection follows production and, therefore, GEOTEMP simulation must account for the proper sequence of events. Between production and injection, the wells are "shut-in," i.e., produced slowly. The shut-in period can vary significantly depending on the production history. Union has provided typical shut-in conditions associated with the range of production and injection histories.

Thermal/mechanical rock properties for geothermal formations were discussed with Union. They suggested that Terra Tek be contacted regarding mechanical properties for Geyser formations and that W. Somerton at the University of California at Berkeley and Dr. Ramey at Stanford University be contacted for thermal properties. For the Baca field, Union indicated that thermal property data has been published and is available through DOE.

A literature search has been initiated for thermal/mechanical properties of geothermal rocks. Specific key words identified in Petroleum Abstracts for this purpose are:

1. Geothermal property,
2. Rock property,
3. Thermal property, and
4. Rock mechanics.

The search will span the years 1975-1979 and the first quarter of 1980.

•Lost Circulation

Lost circulation occurrences were discussed in detail with LANSL drilling engineers for the EE-1, EE-2, and GT-2 wells. In these wells, lost circulation in vugular limestone is complicated by shales swelling above the limestone and by unexplained casing failures. Well data, including caliper and cement bond logs, were provided to Enertech. Solution methods were discussed. The present approach for handling the lost circulation is to set casing immediately above and below the thief zone.

Of particular interest are the casing failures, i.e., holes and splits in the casing wall, experienced in the EE-2 well after drilling and cementing were completed. Such failures may be related to the lost circulation problem and will be investigated further by Enertech.

The Sigma Mesa Well near Los Alamos was discussed with personnel at the Fenton Hill site. No documentation was provided, but a well report is being compiled and will be made available. Concentric drill string for control of lost circulation of drilling mud was successfully used in this well.

Dresser's experience with lost circulation in geothermal wells is principally in The Geysers, with some limited experience in Utah. An active research project at Dresser to solve lost circulation in The Geysers is expected to reach completion by April 1980. K. Green of Dresser plans to present results of the project at a GRC meeting in Albuquerque. The research involves sodium silicate as a sealing agent. Due to the confidential nature of the project, Dresser declined to discuss the research at this time. Information and data on the project is expected to be obtained within the time constraints of this contract. Interpretation and evaluation of the Dresser results will be included in the final report.

The main mud system offered by Dresser for geothermal drilling is water base mud with lignite for filtration control. Lost circulation materials are generally not used. Lignosulfonates are not permitted by the Environmental Protection Agency (EPA).

Cements and "gunk" squeezes were also discussed. Dresser stated that cement systems are generally designed for assumed downhole temperatures of about 193°C (380°F), which is based on twice the flowline temperature of 88°C (190°F). Dresser believes that these assumed downhole temperatures are much higher than actual and that too much retarder is used. High interest in GEOTEMP for cementing in geothermal wells was expressed by Dresser.

Bentonite-diesel-cement squeezes are regarded by Dresser as having high potential for control of total lost circulation, but these systems must be properly designed and implemented to be successful. However, the diesel component is not acceptable for environmental reasons. With some research, it may be possible to replace the diesel with another constituent that is environmentally acceptable.

Dresser is not presently involved with any research or development projects on lost circulation for geothermal wells other than the sodium silicate system mentioned previously. No equipment has been designed or is being used for testing lost circulation materials. A list of commercial lost circulation materials offered by Dresser was provided. Although spinner surveys have been used on occasion, Dresser does not use any down-hole devices on a routine basis for detection of lost circulation zones.

Operations in Utah, in The Geysers, and in the Baca field were discussed with Union Geothermal. Union no longer operates in Utah because maximum reservoir temperatures are only 177°C (350°F). Lost circulation was a severe problem in Utah, accounting for nearly 30% of well costs, and was complicated by H₂S gas which was difficult to control without circulation.

In the Baca area, lost circulation is a problem in fractured rock of the Bandalier tuff, causing water flows from above in the Caldera fill because of pressure underbalance. The water influx into the wellbore is accompanied by hole caving and sloughing, generating additional drilling problems. If lost circulation results in partial loss of returns, then use of lost circulation material in the drilling mud is normally tried. If the loss is total, then cement spotting and squeezing is used.

In the steam dominated Geyser field, reservoir pressure is low, compared to the higher pressures of the water dominated reservoirs in Utah and Baca. Union suggested that this can magnify the lost circulation problem because of drilling-induced pressure-parting of the rock formations. Union is uncertain whether lost circulation in The Geysers is governed principally by pressure-parting or by natural fractures and vugs and to what extent the two mechanisms interact and contribute to the problem.

The present solution for lost circulation control involves cement and sodium silicate. If the loss is partial, then lost circulation additives, usually mica or walnut hulls, and/or straight cement are used. Total loss is controlled with cement preceded by sodium silicate gel. Gunk squeezes are not used because of environmental factors and because of the difficulty in determining mixture ratios for the squeeze. Without annulus fluid levels, the balanced plug method for designing a gunk squeeze cannot be used to calculate proper mixture ratios.

Open hole logs are not generally run in The Geysers. Logs, however, are available for the Baca field.

Borehole detection devices such as spinner surveys and borehole televiewers are not used by Union. Presently, Union cannot specifically identify and accurately locate individual lost circulation zones and intervals in open hole. In cased holes, the cement bond log is run, but is not dependable for locating lost cement zones or voids behind pipe.

Concentric drill string has been tried by Union with foam drilling fluids, but it did not perform well. Seals were not effective at the higher temperatures, and the additional running time caused the system to be uneconomical.

Union is not actively involved in lost circulation research at the present time for the following reasons:

1. Union is no longer operating in Utah where the most severe problems occurred,
2. Sodium silicate works sufficiently well for most applications, and
3. Lost circulation is less of a problem for them because of past experience.

Union acknowledged interest in further research because of the high potential for economic benefit. One area that was briefly discussed was the need for a laboratory facility to test new materials and equipment before going to the field.

As an independent consultant, formerly with Thermogenics, Louis Capuano has worldwide experience in geothermal drilling, including Hawaii, Costa Rica, and Indonesia. He serves operating companies in the capacity of the drilling engineer.

As a general rule, Capuano has found that geothermal formations around the world are fractured and/or vugular rock with low pressure. Lost circulation problems are common to the geothermal areas, but the procedure for controlling lost circulation varies from field to field. To combat total loss, bridging material, perlite and/or sand, is used in the cement system and, if not successful, sodium silicate is used. A common cement system consists of one-to-one mixture of perlite and cement with 40% silica flour.

In The Geysers, Thermogenics uses precooling and no retarder to avoid the risk of cement plugs not setting in the lost circulation zone. The cooling is provided by using a 31- to 61-metre (100- to 200-foot) water pad that precedes the cement.

For improved cementing of casing opposite lost circulation zones, Capuano recommends that a liner and tieback string always be used because of the following benefits:

1. Lost circulation zones can be squeezed with cement from the top of the liner,
2. A good cement job between tieback string and casing is ensured because the interval opposite the liner has previously been cemented, indicating that the lost circulation zone below will not effect the cement placement in the casing-casing annulus which eliminates voids and/or pockets of water between casing strings, and

3. The tieback system provides a new wellhead valve and production casing string that is undamaged from drilling.

Further interviews with service and producing companies are planned. The literature search for both lost circulation and thermal/mechanical rock properties will include review of paper abstracts for final selection of papers to be retrieved.

GEOTEMP simulation of drilling and production for the LANSI Hot Dry Rock project will be initiated along with a simulation for The Geysers.

7. SUPPORTING TECHNOLOGY

The proper design of improved and new 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 technology is to acquire and provide the information necessary to develop improved and new designs, techniques, and/or materials. The approach to providing the required analytical and experimental data includes the development of appropriate computer codes, construction or modification of test facilities, and research into the performance of materials. Currently, projects are underway to expand capabilities to predict transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells; to determine optimal number, size, and placement of nozzles used for bit cooling and cleaning purposes; 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; to study the metallurgical composition of conventional drill stem and 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; and to extend capabilities for high-speed/high-torque bit testing. The status and progress of these activities are described within this section.

A computer model for calculating the stress induced in drag-type cutters and for modeling the tool/rock interaction has been developed and applied to the use of steel cutters in sandstone. The model is a finite element code called TOODY, which has been used extensively in predicting shock wave propagation. Use of the code is continuing for calculating stresses in the PCD cutter/rock interaction studies.

A computer model for predicting the temperatures of borehole fluids and downhole equipment under real-time, flowing conditions has been 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 and gas and geothermal wells. The model is being modified to predict single-phase, compressible flow, transient wellbore temperatures.

Development of an operations-based model for analyzing the effects of improved technology on well costs has been 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 by use of the model.

A laboratory facility for use in optimizing drill bit hydraulics has been designed and fabricated.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

7.1 Bit Hydraulics Studies

Sandia National Laboratories
Technical Consultant: D. Glowka (505) 844-3601

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 position, size, and placement of nozzles used for cooling and cleaning purposes. A bit hydraulics laboratory will be built in order to visualize the flow field along the bit face.

Project Status

Design of the test facility has been completed. An internal R&D report has been issued with recommended designs for the test apparatus. A technical investigation procedure for the study has been updated. Design and detailed stress analysis of special-order items for the test stand have been completed. Fabrication of the test stand is in an advanced stage. Proof testing of the test stand is expected to be completed in April 1980.

Quarterly Progress

During this reporting period, all machined parts for the bit hydraulics test stand were received from suppliers. However, some of the parts did not meet the required specifications. Hence, some parts were returned to the suppliers for modification, while some were modified by Sandia.

Additional problems in assembling the test stand were encountered. Some of the off-the-shelf items ordered for the test stand did not meet the specifications quoted in the suppliers' catalogs. However, these items required only minor modifications to either the delivered items or to the test stand.

Assembly of the test stand has proceeded throughout this reporting period, but the modifications reported above have resulted in the project slipping approximately 1-1/2 months behind schedule. Review of the remaining work to complete the test facility resulted in the conclusion that proof testing of the facility will not require 1-1/2 months as originally estimated. The project schedule has been revised accordingly.

The Safe Operating Procedures for the test facility have been written and are undergoing Sandia review for approval.

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 ● STARTED

▽ PLANNED COMPLETION
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7.2 Drill Stem Corrosion

Sandia National Laboratories
Technical Consultant: R. Salzbrenner (505) 844-5041

Project Objective

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

Project Status

An Internal R&D research report has been issued. The test facility design has been completed, and the facility will be built by the time test specimens are ready for testing. Compositional changes to the drill stem material have been defined, and conventional drill stem material suitable for the corrosion fatigue study has been identified. Unavoidable delays in the delivery of the steel for test specimens delayed the test program start. However, the dual-phase steel alloys have now been made, and the conventional drill stem material delivered. General corrosion tests have been initiated. Processing of the dual-phase alloys is continuing and heat treatment experiments are proceeding.

Quarterly Progress

The initial metallography on the heat treated ingot material was completed. A representative selection of micrographs is shown in Figures 24, 25, and 26. In Figure 24, the microstructures are shown for steel alloy samples of Fe-2.0Si-0.1C-0.1V which were austenitized at various temperatures and water quenched. These micrographs show that a larger fraction of the alloy is transformed to martensite as the austenitizing temperature is raised. This transformation is most likely caused by an increased amount of carbon being dissolved at the higher austenitizing temperature; a higher level of carbon in solution allows the alloy to transform to martensite more readily. These results are consistent with the hardness results reported in the last quarterly progress report; the alloy which is austenitized at the highest temperature exhibits the highest hardness due to an increased amount of martensite. Figure 25 shows microstructures of this same alloy upon tempering after quenching. Figure 26 shows microstructures of the alloy upon intercritical annealing and quenching after austenitization and quenching. Figure 25 also shows the tempered microstructure which contains areas of ferrite (white phase near prior austenitic grain boundaries) and areas of tempered martensite (acicular microstructure with dark etched carbides). The carbides lie along both the martensite boundaries and the prior austenite grain boundaries. The "dual phase" structure (i.e., after an intercritical anneal and quench), shown in Figure 26, is comprised of areas of proeutectoid ferrite (relatively large,

Figure 24. Steel Alloy, Fe Plus (by weight percent) 2.0Si-0.1C-0.1V, Austenitized and Water Quenched; Austenitized at (a) 1000°C (1832°F), (b) 1100°C (2012°F), and (c) 1200°C (2192°F). The micrographs are magnified 100 and 500X. The samples were etched in 2% Nital

100x

500x

Figure 25. Steel Alloy, Fe Plus (by weight percent) 2.0Si-0.1C-0.1V, Austenitized at 1200°C (2192°F), Water Quenched, and Tempered 1 hour at 550°C (1022°F). The micrographs are magnified 100 and 500X. The sample was etched in 2% Nital

Figure 26. Steel Alloy, Fe Plus (by weight percent) 2.0Si-0.1C-0.1V, Austenitized at 1200°C (2192°F), Water Quenched, and Intercritically Annealed at 925°C (1697°F) for 20 Minutes and Water Quenched. The micrographs are magnified 100 and 500X. The sample was etched in 2% Nital

regular, white areas), martensite (irregularly shaped, white to gray areas) and acicular ferrite (fine, irregular, white to gray areas). The absence of carbides along boundaries and the martensite surrounded by ferrite (either acicular or proeutectoid) can be seen. This morphology is expected to result in very good ductility and toughness properties in comparison with the quenched, or quenched and tempered microstructures. The distinction between the various constituents in the microstructures, particularly in Figure 26, is not clear-cut after the sample's surface has been etched in 2% Nital. Alternate etching procedures are being pursued to allow the various phases to be clearly distinguished from each other.

A modified, dual-phase heat treatment has been developed for the high-silicon, low-alloy steels made at Sandia. The dual-phase heat treatment as developed by the G. Thomas group at Berkeley is shown in Figure 27. This heat treatment involved quenching from the austenitizing temperature, then reheating to the intercritical annealing temperature, and finally quenching. The microstructure obtained on the Fe plus (by weight percent) 2.0Si-0.1C-0.1V alloy through this heat treatment is shown in Figure 28. The modification to this heat treatment is schematically depicted in Figure 29. Rather than first being quenched to room temperature and then reheated, the alloy is austenitized and taken directly to the intercritical annealing treatment and held for 20 minutes before quenching. The microstructure (Figure 30) obtained from this modified heat treatment shows a dramatic difference from the microstructure obtained from standard heat treatment, (Figure 28). This alternate heat treatment may impart some important properties to the steel. The partitioning of the substitutional solutes of vanadium and silicon should be decreased as a result of this modified heat treatment. Reduced partitioning will improve the general corrosion resistance of the steel and will allow the formation of stable vanadium carbides during tempering of the as-quenched, dual-phase substructure. Both of these improvements should further enhance the resistance of the dual-phase steel to hydrogen sulfide. Additionally, the microstructure produced in the modified, dual-phase substructure will play an important role in the mechanical properties of the alloy. For example, the toughness of the alloy may be improved because of the larger areas of continuous ferrite (the dark, etched area in Figure 30) which are present.

Investigations were continued on the significance of the modified heat treatment on the properties of the alloy. The hardness of the specimens as a function of intercritical annealing temperature is shown in Figure 31. The modified, dual-phase heat treatment produced samples with a higher hardness than the standard dual-phase heat treatment. The high hardness is probably due to kinetic factors. The standard heat treat samples should be held at the annealing temperature for longer than 20 minutes to attain the equilibrium amount of martensite because hardness increases with an increased fraction of martensite. The modified heat treatment allows the samples to form the equilibrium amount of martensite within 20 minutes. The reasons for the different length of time at temperature needed to reach equilibrium for these two heat treatments are being investigated.

Initial studies on the effect of tempering after the dual-phase heat treatment are also on-going. Hardness as a function of annealing temperature after tempering at 540°C (1004°F) for 1 hour is shown in Figure 32. The tempering treatment decreases the hardness of the samples which underwent the modified heat treatment more than it decreases the hardness of the

(a)

(b)

Figure 27. Standard Duplex Ferritic-Martensitic Heat Treatment of an Iron-Carbon-Silicon Alloy; (a) Phase Diagram and (b) Heat Treatment Schematic

Figure 28. Microstructure of Steel Alloy, Fe Plus (by weight percent) 2.0Si-0.1C-0.1V, Formed by the Standard, Dual-Phase Heat Treatment; (a) Mag: 250X and (b) Mag: 500X

(a)

(b)

Figure 29. Modified Duplex Ferritic-Martensitic Heat Treatment of an Iron-Carbon-Silicon Alloy; (a) Phase Diagram and (b) Heat Treatment Schematic

Figure 30. Microstructure of Steel Alloy, Fe Plus (by weight percent) 2.0Si-0.1C-0.1V, Formed by the Modified Dual-Phase Heat Treatment; (a) Mag: 250X and (b) Mag: 500X

Figure 31. Hardness versus Intercritical Annealing Temperature (at Temperature for 20 min) for Dual-Phase Heat Treatments (Standard and Modified)

Figure 32. Hardness versus Intercritical Annealing Temperature (at Temperature for 20 min) for Dual-Phase Heat Treatments (Standard and Modified) after Tempering 1 hour at 540°C (1004°F)

samples heat treated by the standard dual-phase heat treatment. The decrease in hardness is probably due to the fact that the standard heat treat samples have less martensite and will thus lose a smaller fraction of their hardness when the martensite is tempered. The tests thus far have shown the probable success of tempering the dual-phase heat treated material. Tempering should improve the resistance of low-alloy steels to a hydrogen-containing environment. Metallographic studies of these samples are proceeding.

The as-cast ingots underwent vacuum arc remelting. Then, the remelted ingots were homogenized by heating them to 1150°C (2102°F) in argon for 16 hours. The homogenized ingots have been scheduled for hot forging and rolling at Rocky Flats during the early part of April 1980.

Metallurgists at the Climax Molybdenum Research Center, Ann Arbor, Michigan, have developed a modified 4lxx* steel alloy for enhanced resistance to hydrogen-sulfide-containing environments. Extensive testing of this alloy has been performed at Case Western Reserve under the direction of Professors Hehemann and Troiano and at Armco Steel by J. Peterson. A major portion of this testing has been in the area of static stress corrosion in an H₂S-containing solution, and the steel has shown an enhanced resistance to cracking under a static load. As there are important differences between static stress corrosion and corrosion fatigue, the steel should be tested in corrosion fatigue to determine the suitability of the alloy for use as drill stem. J. Strattmenn of the Pittsburgh office of Climax was contacted in an effort to obtain some of the modified 4lxx steel for Sandia's testing program. He subsequently arranged to have a small heat of material made for inclusion in Sandia's corrosion fatigue testing program. The 4lxx alloy is being made and will be shipped as soon as it is available.

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*xx denotes the carbon content, which can range from 0.20 to 0.45 weight percent.

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>ROCK MECHANICS</u>													
CALCULATIONS													
TOOL													
STRESSES													
FRICTIONAL FORCES													
HEAT INPUT													
WEAR													
THERMAL ANALYSIS													
FLUID STUDIES													
EXPERIMENTS													
CHIP FORMATION													
FORCE DETERMINATION													
TEMPERATURE MEASUREMENTS													
FRICTION MEASUREMENTS													

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▽ PLANNED COMPLETION
 ▼ COMPLETED

7.3 Rock Mechanics for Polycrystalline Diamond Compact Cutters

Sandia National Laboratories
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The project objective is to conduct research and testing of the chip formation process of rock cutting tools utilizing polycrystalline diamond compact (PDC) cutters in order to optimize the design of bits using these cutters.

Project Status

A study of the procedures necessary for conducting chip formation testing has been initiated. Modeling of the rock/tool interface has begun. Calculations of tool stresses and frictional forces have been completed. Calculations of heat input have been completed and wear calculations are continuing. A thermal analysis is being conducted.

Quarterly Progress

During the past quarter, TOODY was used to model the drag tool/rock interaction for a drag tool with a -20° rake angle. Calculations indicate the crack formation process is strongly dependent on the location assumed for the rock boundaries in the problem and on the initial geometry of the drag bit/rock interface.

The rock boundaries influence the crack formation process by influencing the stress fields inside the rock. The influence of the boundaries was determined by performing a series of calculations in which the size of the rock was varied. It appears that it is necessary to model a piece of rock approximately 8 cm (3.15 inches) square to negate the effects of the boundaries. For rocks of this size, it has been found that one or two cracks run downward from the bottom of the bit; two cracks, when initiated, ultimately combine to form a single crack. This unexpected calculational result suggests that rock samples from experiments be cross sectioned and examined for the presence of the vertical crack. During the final stages of this crack formation, another single crack forms, runs ahead of the bit, and produces a chip similar in shape to chips observed in cutting experiments.

An analysis of the stress field ahead of the bit indicates that the chip formation process may be strongly dependent on the amount of the bit initially in contact with the rock. This implies that the tool forces may be a strong function of the initial geometry of the drag bit/rock interface. A preliminary calculation substantiates this hypothesis, but additional calculations and analysis are required to determine the influence of the initial geometry of the chip formation process.

Future work will investigate (1) the influence of the drag bit/rock interfaces initial geometry on the chip formation process and on tool forces, (2) the stress state in the tool and the efficiency of rock removal for various rake angles, and (3) the modification of TOODY to treat the effects of confining and in situ pressure.

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7.4 Modification and Extension of Testing Capabilities

Contractor: Drilling Research Laboratory, Inc.
Principal Investigator: A. D. Black (801) 582-2220
Contract Period: 12 September 1979 to 12 May 1980
Contract Number: 13-8785 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to modify and extend testing capabilities in the following areas:

1. Selection and acquisition of pertinent rock samples and specifications,
2. Torque and rpm availability for testing high-speed/high-torque bits,
3. Bit dynamic data acquisition, and
4. High-pressure/jet-drilling testing capability.

Project Status

All project tasks have been initiated. Rock specification data are being compiled and potential sources of rock specimens have been identified. Design of the high-speed/high-torque facility is continuing. Some components have been purchased or placed on order. A high-rate, data acquisition, computer program has been completed. Conceptual ideas for the high-pressure facility were evaluated, and design of the facility is underway.

Quarterly Progress

Rock Specifications and Acquisitions -- During this reporting period, some additional data on the properties of rocks in major geothermal areas were obtained, but emphasis was placed on locating surface outcroppings of medium to hard sandstone and andesite. Three sandstone formations were located and some basic rock properties determined. Two of the sandstones are Nugget sandstone from two different quarries in Utah. The third sandstone was located in the form of boulders in Spanish Fork Canyon in Utah. Samples of these sandstones and the data on rock properties were sent to Sandia for evaluation for possible use in upcoming Stratapax™ tests. The density, unconfined compressive strength, and axial strain at failure are summarized in Table 17. The unconfined compressive strength versus axial strain is plotted in Figure 33.

Figure 33. Unconfined Compressive Strength of Sandstone versus Axial Strain

Table 17

Properties of Sandstone Samples

Rock	Density kg/m ³ (lb/ft ³)	Unconfined Compressive Strength MPa (psi)	Axial Strain at Failure %
Nugget sandstone (Heber City)	2 220 (138.6)	121.3 (17 600)	0.58
Nugget sandstone (Park City)	2 230 (139.2)	133.1 (19 300)	0.65
Sandstone (Spanish Fork Canyon)	2 480 (154.8)	165.5 (24 000)	0.94

Large, intact blocks of medium-hard nugget sandstone were located and obtained for two Sandia drilling hardware projects. A 3-foot by 4-foot by 3-foot block of nugget sandstone was secured for the Stratapax™ drilling test in the high-temperature, air, test facility at DRL, and smaller blocks were obtained for the Stratapax™ single cutter tests. Obtaining large blocks of rock for laboratory testing will be difficult unless special arrangements can be made with quarry operators to look for and take special care to excavate large blocks in addition to their normal operations. Should this rock prove useful in the two current Sandia drilling projects, DRL is recommending that Sandia authorize DRL to make the necessary arrangements with the local quarry operators to obtain large blocks of nugget sandstone as the blocks become available.

Potential sites to obtain andesite for laboratory drilling tests were also investigated. The andesite would simulate formations at the Baca, New Mexico geothermal site. Two andesite formations were located in Utah and hand samples obtained for evaluation. Physical and mechanical properties of the andesite samples are being determined and will be compared to the existing property data from the Baca formations. Andesite from the two sites in Utah can be obtained in the form of large boulders or cores from rock outcrops.

High-Speed/High-Torque Capabilities -- The bearings, sheeves, belts, couplings and transmission mounting plates were received for the 0-500-rpm drive system. The detailed design and assembly of the mounting frame was completed. The second 125-hp, d.c. motor was removed from the small DRL pump, inspected, and readied for installation in the new high-speed/high-torque transmission system. A stock transmission was located and delivered to the DRL. All other parts to the system have been received and assembly of the system is proceeding.

Detailed design of the 500-1000-rpm drive system was delayed until arrangements for the use of a high-speed turbine could be made. LANSI was contacted, and the possibility of using one of LANSI's turbine sections in

the high-speed bit test set up at the DRL was pursued. The proposed test set up is shown in Figure 34. As soon as arrangements are made with LANSL and detailed information on the turbine end connections and performance are received, the detailed design of the test set up will be started. If LANSL cannot provide the equipment, industry turbine manufactureres will be contacted immediately. Sandia is also considering the purchase of a high-speed/high-torque turbine that can be used to drive the high-speed bits in the laboratory.

Bit Dynamic Data Acquisition -- The high-rate, data acquisition, computer program and data reduction and plotting software are completed and debugged. Figures 35 and 36 show plots of load and torque versus frequency for an actual drilling test. The program was used successfully for analysis of the dynamic characteristics of various downhole hammers as part of the Sandia project to evaluate downhole hammers for geothermal application. It is anticipated that minor changes and adjustments may be necessary as experience is gained in using this data acquisition and analysis system.

High-Pressure Capabilities -- As previously reported, a decision was made to relocate the DRL 1600-hp mud pump to allow access by a forklift to the pump fluid end for easier installation and removal of the standard and high-pressure fluid ends. During this reporting period, the small DRL mud pump was removed, and the 1600-hp Continental Emsco mud pump was rotated 90°. Photographs of the mud pump location before and after are shown in Figure 37. Access to the fluid end section of the pump by the DRL forklift can be seen in the figure. The pump has been brought back into operation. Fluid end lifting brackets will be designed in the next reporting period. Also, design of the skid mounted suction and discharge piping for the high-pressure fluid ends will be completed.

The preliminary design of the high-pressure choke system was completed. A schematic (Figure 38) shows the basic features of the system, including a high-pressure-cutting catch vessel, two nozzle subs, two fluid impact and wear subs, two high-pressure fluid bypass lines to reduce "cavitation" and "water hammering" on the downstream side of the nozzle, a variable choke being supplied by DRL, and low-pressure return and bypass lines that are tied to the present fluid return lines.

Selection of the final design of the high-pressure-pulsation damping system is proceeding. In addition, Mobile R&D supplied DRL with information on an in-line pulsation dampener. Although the current models are rated for only 3000 psi, the use of the in-line concept for higher pressure is being pursued.

Figure 34. Proposed Test Set Up for Pressure Drilling at Rotary Speeds Greater Than 500 rpm

***DRLPLT - "FREQ." FILE PLOT
 FROM FREQ.FILE: NSF2.FFT
 DATA TYPE:"QUICK" CREATED:12/21/79 TIME:09:40:42
 TESTID: NSF ANISOTR. HOLE2 12/21/79
 ***FREQ. DOMAIN PLOT - X-SCALE: FREQ-HZ XCOL# = 2
 1 Y COL(S) PLOTTED...#'S 10
 FOR THIS PLOT X-RANGE = 0.0000E-01 TO 9.9989E+01
 Y-RANGE = 1.1943E+01 TO 3.2824E+05

Figure 35. Example of Load versus Frequency Plot

***ORLPLT - "FREQ." FILE PLOT
 FROM FREQ.FILE: NSF2.FFT
 DATA TYPE:"QUICK" CREATED:12/21/79 TIME:09:40:42
 TESTID: NSF ANISOTR. HOLE2 12/21/79
 ***FREQ. DOMAIN PLOT - X-SCALE: FREQ-HZ XCOL# = 2
 1 Y COL(S) PLOTTED...#'S 10
 FOR THIS PLOT X-RANGE = 0.0000E-01 TO 9.9989E+01
 Y-RANGE = 4.5610E-02 TO 3.1521E+03

Figure 36. Example of Torque versus Frequency Plot

BEFORE RELOCATION

Figure 37. Relocation of DRL 1600-hp Mud Pump

AFTER RELOCATION

Figure 37 (Continued). Relocation of DRL 1600-hp Mud Pump

Figure 38. Schematic of High-Pressure Choke System; Maximum Pressure--103.4 MPa (15 000 psi), Flow Rate--0.01 m³/s (180 gal/min), Fluid--Mud and Drilled Cuttings

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7.5 Development of an Advanced Wellbore Thermal Code

Contractor: Enertech Engineering and Research Co.
Principal Investigator: G. R. Wooley (713) 521-9294
Contract Period: 25 January 1980 to 30 April 1981
Contract Number: 46-5670 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to develop an advanced computer code for predicting transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells. The development of the code will encompass

1. Modification of the existing, single-phase fluid code to allow
  - a. A variable-tubing flow area,
  - b. Separated, multiple fluids in the wellbore,
  - c. Provision for a deviated wellbore, and
2. Advanced code development providing for
  - a. Formulation of single-component, compressible flow in a wellbore,
  - b. Formulation of multicomponent, compressible flow in a wellbore, and
  - c. Reconstruction of the existing code to include compressible, multicomponent flow.

Project Status

The project was initiated during this quarterly reporting period. Effort is underway to modify the existing GEOTEMP code to handle deviated holes, and work has been started on formulating two-component flow with continuum mixture theory.

Quarterly Progress

A meeting was held with Sandia to discuss initiation of the project. New ideas for formulation of two-component flow were introduced, and plans for the work effort were discussed.

Some literature on two-component flow has been collected and reviewed. Traditional two-component flow formulations for pipeline and wellbore flow are being reviewed, and techniques employed in two-component reservoir flow modeling are being evaluated.

Technical effort has been directed at the following two tasks:

1. Modifying the existing GEOTEMP code to handle deviated holes and
2. Formulating two-component flow with continuum mixture theory.

Compared to vertical wells, deviated holes extend both the travel time and distance of fluid in a well. Therefore, flowing fluids are more sensitive to surrounding temperatures in deviated holes than in vertical holes. Figure 39 shows the geometry of a deviated well, which is defined by the following three variables:

1. True vertical depth to bottomhole,
2. Measured depth to bottomhole, and
3. Depth to deviation.

The assumption is made that the well is vertical to the deviation depth, which defines the angle of inclination θ , where

$$\theta = \cos^{-1} \left(\frac{D_m - D_d}{D_v - D_d} \right)$$

The variables in the equation are defined in Figure 39. Having defined the angle of inclination, a deviated hole can be modeled with the same formulation as a vertical well, except for the following two changes:

1. Replace the vertical depth with measured depth in grid generation and
2. Convert the undisturbed temperature gradient to measured depth.

First, vertical grid spacing is defined to the total measured depth, rather than to the vertical depth. Existing formulation of the code then properly accounts for the change in grid. Second, the undisturbed temperature distribution, which is defined in terms of the true vertical depth, is adjusted to measured depth. These temperatures have an important impact since they act as both initial and boundary conditions.

As a first step in the development of a multicomponent, compressible flow wellbore simulator, the balance laws and formulation of continuum mixture theories are being reviewed. There are two main applications of this study. First, mixture theory may provide a theoretical framework within which existing multicomponent models can be understood and criticized. For example, Fick's Laws of diffusion can be seen to result from specific assumptions about component velocities and accelerations and from assumptions of a Stokes form integration between components. An imperfection in the classical laws of diffusion is the prediction of an infinite velocity of propagation of the diffusion front. In the context of mixture theory, this prediction can be seen to result naturally from the neglect of inertial forces, and the appropriate formulation with finite speed of propagation can be developed in a fairly obvious way.

A second application of mixture theory is the solution of the multicomponent flow problem. Preliminary analysis indicates that solution of the equations of mass and momentum conservation for each component, with

change of phase from one component to the other, may not be as difficult to analyze as the classical formulation of this problem. When a clearer picture of the difficulty of this approach is developed, Enertech will make a specific recommendation as to the approach favored.

Future efforts will include coding and testing of the deviated hole formulations presented above. In addition, the effort in applying mixture theory to two-component flow, specifically, development of the balance equations, will be continued. Formulation of compressible single-phase fluid flow will also continue.

Figure 39. Geometry of Deviated Well

8. ADVANCED DRILLING SYSTEMS

Advanced and innovative drilling systems are required in order to meet the 1987 well cost reduction goal of 50%. The approach to the development of advanced systems involves investigations of high-pressure water-jet erosion drilling systems, cavitating jets, improved downhole motors, and percussion drills. The investigations include laboratory testing and field demonstration of full-scale devices. Projects are presently underway to design, fabricate, and laboratory test a water-jet erosion drilling under-reamer, a pressure-pulsing device for use with cavitating jets, and improved downhole motor bearings and seals. Projects to evaluate the potential of percussion drilling devices for use in the geothermal environment and to assess the performance potential and economics of erosion drilling systems are also proceeding. The objective of these projects is to develop and demonstrate hardware incorporating these design techniques so that increased rates of penetration and longer downhole drilling periods may be achieved. The status and progress of these activities are described within this section.

Field tests of a hybrid, high-pressure water-jet/roller-cone bit have been completed. 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 after a threshold pressure of 82.7 MPa (12 000 psi) had been reached. The final report on the field tests is in preparation.

Experiments to establish a standard for testing rock resistance to cavitation attack have been completed. Samples of granite, marble, sandstone, and dolomite were subjected to cavitation attack, and the mean and cumulative depths of erosion over a 7-hour period were recorded. The data are being used in an attempt to correlate rock response to cavitation/water-jet action. The experiments are being evaluated and a final report prepared.

Laboratory tests were completed to establish the design parameters for a cavitating-type jet nozzle using drilling mud as an erosion medium. The experimental program established the feasibility of utilizing cavitating jets to drill deep holes for geothermal and petroleum extraction. The results indicated 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. It was further shown that the use of drilling mud imposes no adverse effects upon jet performance. These results led 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. A follow-on project to optimize cavitating-jet nozzle design was initiated during this reporting period.

A facility for testing downhole motor bearing and seal packages under simulated downhole conditions has been completed. The facility permits the 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 facility is currently in use in the project to improve downhole motor bearings and seals.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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LEGEND:

ACTIVITY PERIOD

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PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

8.1 Characterization of High-Pressure Jet Drilling Systems

Contractor: Foster-Miller Associates, Inc.
Principal Investigator: J. Harding (617) 890-3200
Contract Period: 1 August 1979 to 31 July 1980
Contract Number: 13-8728 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

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 objective of this project is 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 lifetime,
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.

Project Status

Project activities were initiated in August 1979. The state-of-the-art assessment has been completed. Coordination has been made to assure a proper interface between the study output and the Sandia Wellcost Simulation Model. An erosion drilling information computer search has been made and data on the Gulf Oil Company abrasive-jet drilling program obtained. Assessment of the data is progressing.

Quarterly Progress

Investigation of the Gulf Oil Company abrasive-jet drilling work was continued. Almost all of the material had been reviewed at least once by the start of this reporting period. The emphasis of the review has been on understanding the technical aspects of what was done. The results of the review were briefed to Sandia in early January 1980. Work continued on the Gulf data with an updating of all raw costs in the Gulf study to 1980 dollars. This effort will permit better understanding and evaluation of the Gulf approach to abrasive jet drilling.

A list of questions was prepared for use in obtaining technical information pertaining to Shell's jet drilling program. The list was provided Sandia who is assisting Foster-Miller in obtaining the Shell data.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DOWNHOLE MOTOR SEALS AND BEARINGS</u> <u>TERRA TEK</u>	CONTINUING AS REQUIRED												
SEAL TESTING													
BEARING/ SEAL PACKAGE TESTING													
FULL-SCALE MOTOR TESTING													

LEGEND: ————— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

8.2 Improvement of Downhole Drilling-Motor Bearings and Seals

Contractor: Terra Tek, Inc.
Principal Investigator: G. Tibbitts (801) 582-2220, ext. 187
Contract Period: 1 November 1979 to 31 October 1980
Contract Number: 46-3053 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

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 that operate at a 121°C (250°F) circulation temperature.

Project Status

Facilities have been developed to test seals and bearing/seal packages at geothermal downhole conditions: 300°C (572°F) and 34.5 MPa (5000 psi). Selected standard seals have been tested to determine baseline performance. New seals have been designed in cooperation with the seal industry and tested in the laboratory. New bearing seals for downhole motors have been designed and will be laboratory tested in the bearing/seal package test facility. The bearing/seal test facility is now completed, and full-scale testing has begun. The present lubricant screening program test results have been completed and published. The lubricant test facility remains available for check-testing as required. Seal testing and evaluation are continuing.

Quarterly Progress

Project Review Meeting -- The project objectives and developments were reviewed in a meeting with Sandia and supporting contractors. The program goal to develop a seal that will have pressure drop capabilities of 6.9 MPa (1000 psi) was discussed. Although the pumping capacity presently on drill rigs is not able to meet such high-pressure demands, there are field developments suggesting potential pumping pressure in the 27.6- to 34.5-MPa (4000- to 5000-psi) range; this could produce a 6 to 9 MPa (870 to 1305 psi) pressure drop at the seal.

Two of the Maurer turbines with the bearing packages (Grafoil® seals, PLX-014 lubricant, and no cooling modification) developed under this project will be run in Canada. The data from these runs will be made available to this project.

The different, zero clearance, seal backup systems were also discussed in the meeting. The first seal tests of the flexing leaves concept will

use seals having three leaves of 0.79-mm (0.03-inch) thick phosphor-bronze, with Grafoil® as the seal material.

The canted seal concept was discussed with the following results and conclusions:

- The canted seal concept still has merit and warrants testing.
- The shaft finish for the canted seal and all other elastomers should be 0.20 to 0.31 μm (8 to 12 $\mu\text{in.}$) rms.
- The canted seal should be made into a cartridge seal, but the 12.7-mm (0.5-in.) cross section is too small.
- For the 12.7-mm (0.5-in.) cross section, modify the seal lips into a 'plow share' configuration for better installation into the seal tester.
- At least three candidate materials should be used for the test program.

Coupons of elastomeric seal material will be supplied to Maurer Engineering by Utex Industries for temperature soak tests, which will run for 24 hours at 260°C (500°F) and 34.5 MPa (5000 psi); one test may be run in Pacer PLX- 014 and another in water.

The hybrid seal concept was discussed, and the following points were made:

- A hybrid seal assembly should be tested early in the 1980 program. The seal would consist of a high-temperature elastomer flanked on both sides with non-elastomer seals.
- New geometry of molds would be needed to fabricate the non-elastomer.
- A hybrid seal constructed of different materials as a unit seal should be designed and tested.

The question was raised as to why face seals have not been examined in the project. Two face seal companies, Gits Brothers and Sealol, were contacted about the project. After talking to representatives of these companies, they decided not to become involved due to other industry commitments. A suggestion was made that letters be written to companies that may have experience with face seals including NL Petroleum Services, Dyna-Drill, and G.E. Electro Drill.

The possible effects of Grafoil® orientation on heat transfer were discussed. These points were made:

- A set of seals made from flat rings of Grafoil® should be tested, although they are expensive--\$335.00 per seal.

- Because graphite-type seals are not as temperature sensitive as elastomers, a non-laminar product such as pelletized graphite or Grafoil® should be investigated.
- Union Carbide should be contacted to find out if the properties of slug or pellet Grafoil® are an average of the directional properties of the ribbon Grafoil®.

The failure of the metal/Teflon seal backup system number 2 was discussed. The Teflon portion of the backup failed during the test, apparently due to creep which caused the metal ring to seize the shaft. It was suggested that the Teflon portion of the system be replaced by Ryton, an elastomer that has good resistance to creep failures.

The present redundant seal parts and design were reviewed. The first redundant seal tests will use a manually set secondary seal. Hardware for automatic actuation of redundant seals will be provided for subsequent tests.

The interconnecting parts for testing the bearing/seal pack with industry motors have been fabricated. The motor supplier's shops will machine the motor interface threads on the parts.

Seal Testing and Evaluation -- The new seal tester main shaft was completed, delivered to Terra Tek, and sent to a Salt Lake City company to be flash nickel plated for corrosion resistance. The tapered roller bearings for the new shaft were received at Terra Tek and were installed on the shaft.

Seals for the beginning of Phase IV tests - canted seals, hybrid seals, Grafoil® seals with flat laminations, and standard Grafoil® seals - have been ordered, and several kinds have been received.

Test DMT-034 was completed during this reporting period. This was the first test of the zero clearance backup system III (flexing leaves) with a non-elastomer seal. This system is shown in Figure 40 and details are found in the report "Deflections in Rotary Seal Back-Up Rings" by D. Dareing, Terra Tek Technical Report No. TR78-34.

DMT-034 used three Grafoil®-phosphor-bronze seals with three 0.79-mm (0.031-inch) thick phosphor-bronze rings and a bottom backup ring with a radial clearance of 2.154 mm (0.0848 inch) between the ring and the shaft surface. The three phosphor-bronze rings have a nominal interference fit on the shaft when pressurized, giving a near zero clearance under test conditions. The total duration of the test was 4 hours. The following is a brief description of the test:

1. 0 to 0.83 hours; $\Delta P = 10.3 \text{ MPa}$ (1500 psi)
The test seal was leaking substantially, and the dummy seal had a small leak. At 0.83 hours, the ΔP was increased to 12.1 MPa (1750 psi) to see if this had any effect on the test seal leak rate.
2. 0.83 to 2.75 hours; $\Delta P = 12.1 \text{ MPa}$ (1750 psi)
During this period, the test seal leak rate dropped off significantly. One possible explanation for this is that the three

0.79-mm (0.031-inch) thick rings were too stiff to create a zero clearance at 10.3 MPa (1500 psi). At 2.75 hours, the test was stopped to replace an "O" ring in the vessel.

3. 2.75 hours to 4.0 hours; $\Delta P = 10.3 \text{ MPa (1500 psi)}$
The test was resumed and run until one gallon of lubricant had leaked past the test seal.

Figure 40. Flexing Seal Backup Rings

Inspection of the seals after DMT-034 showed a loss of seal material from the Grafoil® seals.

Based on the experience from DMT-034, the stiffness of the flexing leaves will be reduced by making them from 0.4-mm (0.016-in.) material. All other conditions will be the same (see Table 18).

Bearing/Seal Package Testing and Evaluation -- New strain gages for the load and torque cells were installed on the dynamic actuator. After installation, the gages were coated with M-Coat A, made by the strain gage manufacturer, Micro-Measurements. The coating is designed to protect the gage against water and oil.

The calibration of the new load and torque cells was completed. Also, an isolation transformer was added to the control console to prevent the electronic equipment in the control console from being affected by any

other power source in the building. This should make the downhole motor instrumentation more reliable.

A spare seal sleeve (part number 78-416) for the bearing/seal package was ordered from Maurer Engineering. Delivery was expected in the latter part of the reporting period.

Maurer Engineering assisted in the changing of the bearing/seal package from wire mesh springs to Belleville springs which will provide more even loading of the bearings by the Belleville springs.

Parts for the redundant seal assembly were received from Maurer Engineering. Material for the modified bearing make-up sub for the redundant seal assembly was ordered. The sub will be manufactured in a Salt Lake City-area machine shop.

Lubricant Testing and Evaluation -- Pacer Lubricants is formulating a heavier, more viscous version of PLX-014 lubricant. A sample will be provided for testing as soon as it becomes available.

Table 18
Seal Test Conditions

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	ΔP MPa (psi)	rpm	Duration h	Chrome Shaft Coating Finish (rms) μm ($\mu in.$)	Diametral Clearance: Shaft to Backup Rings mm (in.)
034	Grafoil®- phosphor- bronze	3	Backup III w/3 0.79-mm (0.031-in.) leaves	12.1/ 10.3 (1 750/ 1 500)	412	4.0	0.1-0.2 (4-8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.170)
035	Grafoil®- phosphor- bronze	3	Backup III w/4 0.4-mm (0.016-in.) leaves	10.3 (1 500)	412		0.1-0.2 (4-8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.170)

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>SUPPORT OF SEAL AND BEARING RESEARCH</u> <u>MAURER ENGINEERING</u> FABRICATION AND DESIGN													OCT 1980

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

8.3 Design and Fabrication Support of Bearing/Seal Research

Contractor: Maurer Engineering, Inc.
Principal Investigator: J. Barnwell (713) 683-8227
Contract Period: 1 November 1979 to 31 October 1980
Contract Number: 46-3054 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to provide the required design, manufacturing, and post-test component analysis support for the development of downhole drilling-motor bearings and seals.

Project Status

Maurer Engineering has been providing support services to the bearing/seal research under a subcontract with Terra Tek, Inc. Since November 1979, the required support services have been furnished under a separate contract with Sandia. Design of redundant seals and of the areas interfacing with the bearing/seal package is continuing.

Quarterly Progress

Motor Interface Parts -- Manufacture of the Dyna-Drill and Eastman Whipstock motor interface parts were completed up to the point of threading the adapters. The adapter parts were sent to the respective motor manufacturers for threading. Dyna-Drill completed the threading and delivered its part to Terra Tek. Eastman Whipstock was ready to forward their threaded adapter near the end of the reporting period.

Improved Floating Piston -- Several alternate designs for improved floating pistons were developed. The details of the proposed designs are nearly complete. The decision on which design to use will be made in conjunction with Terra Tek. The descriptions of the basic design concepts follow; these designs are for a piston which does not rotate with the shaft, so the inside diameter is the rotating seal and the outside diameter only slides in the housing.

Type I--a single-piece piston which utilizes elastomer O-rings on both the i.d. and o.d. seal surfaces. Any compensation for misalignment of the seal surfaces occurs in the elastomer.

Type II--a multi-piece piston which utilizes a set of Grafoil® rings to seal the i.d. A set of O-rings seals on the o.d. surface. Out-of-roundness is again absorbed by the elastomer.

Type III--a multi-piece piston. Seals are either elastomer or Grafoil®. The basic characteristic of this type of piston is that, radially, the o.d. and i.d. are independent of one

another. However, the seals are fixed so as to rotate together. This requires another seal at a central interface but allows for complete compensation for radial eccentricities in both shaft and housing.

Both Grafoil® and elastomer seals have been suggested for the inside diameter. So far the elastomer seals have been self-destructive. As the rotary speed rises, the frictional heat buildup in the elastomer causes it to shrink, further increasing the friction. This eventually causes the O-ring to seize on the shaft and fail. To avoid seizure, the manufacturer's recommendations concerning contact surface, tensile force in the O-ring, and percent squeeze should be closely followed. Contact surface (i.e. O-ring size) is a function of rotary speed. Tension should be avoided, and percent squeeze should fall below a set maximum. Results from Terra Tek's geothermal bit program are being used in selecting a suitable elastomer.

Grafoil® is unaffected by temperatures present in the bearing/seal package, but these seals provide little or no compensation for radial eccentricities. Also, the "set" in a conventional Grafoil® seal is vital to the performance, because a certain compressive force is necessary if the Grafoil® is to cause a load on the shaft. Due to the position of the floating piston in the housing, it is impossible to apply this force when it is seated on both i.d. and o.d. surfaces. Thus, the designs given earlier rely on elastomer seals on the o.d. These o.d. seals also have a large contact surface which ensures that the floating piston is rotationally fixed with respect to the outer housing. Then, if a Grafoil® seal is desired on the i.d. surface, the seal can be set before installation is complete.

Improved Redundant Seals -- Manufacture of the first improved redundant seal was completed, and the seal was delivered to Terra Tek. One backup ring, PN 79-453, was damaged in shipment. Another backup ring was fabricated and shipped to Terra Tek. A second redundant seal is currently being manufactured.

Other Activities -- Maurer assisted Terra Tek in refitting the bearing/seal package with a preload system using Belleville springs. The evaluation of the test results from the seal tester and the LANSI geothermal turbodrills is continuing.

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>WATER-JET DRILLING</u> <u>UNIV. OF MO-ROLLA</u> HYDRO MECHANICAL BIT (18 000 psi TEST) UNDER-REAMER CAVITATION TEST STANDARD IN ROCK													

LEGEND: ——— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

8.4 Development of Geothermal Erosion Drilling Hardware

Contractor: University of Missouri-Rolla
Principal Investigator: D. A. Summers (314) 341-4311
Contract Period: 6 February 1979 to 31 March 1980
Contract Number: 13-2346 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

The objective of this project is to continue work in erosion drilling for geothermal applications through investigations into the design, fabrication, and demonstration of hardware useful for geothermal 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.

Project Status

Modifications to the triaxial test chamber were made and the test chamber was used to demonstrate the capability of a water-jet under-reamer to cut rock at the ambient and confining pressures specified. Additional tests of a redesigned water-jet under-reamer were postponed because of delays in parts delivery, and the extension of the scheduled test period was required. Because the tests are performed outdoors, severe weather caused further delays, and completion of the tests within the extension period was uncertain at the close of this reporting period.

Initial results of field tests of the hydromechanical drill in drilling dolomite indicated that a jet pressure of 68.9 MPa (10 000 psi) must be exceeded before a jet assist improves performance. Above 82.7 MPa (12 000 psi), improvements of approximately 100% or better in drilling rate can be achieved using a single jet directed axially along the drill. Other jet orientations have achieved even higher rates. The field tests were concluded during October 1979. While an improvement in drilling rate was achieved where high-pressure water jets were directed across a quadracone bit (the hydromechanical bit), the practical problems of running the present bit design in a hole were such that it was recommended that this particular design not be further developed.

Work on evaluation of the cavitation resistance of various rock types has been completed, and a final report is being prepared.

Quarterly Progress

In response to a questioning of the cavitation results obtained using the Lichtarowicz cell, the data obtained were reassessed. Specifically, a challenge was made that other research had shown that damage varies as $(D_N)^{1.7}$ * rather than a variation as $(D_N)^5$ as determined in the experiments. A suggestion was made that the indicated error was due to experimental design.

Reassessment of the data did not change the results previously reported; however, a review of the experiments, and other studies, suggests that the challenge erroneously equated damage with depth of cut. From this research effort and from other data examined from an independent source, depth of cut varies as approximately $(D_N)^{1.7}$. For a conventional jet, cutting damage varies as $(D_N)^3$. However, for the cavitating tests carried out in this project, there was, as previously reported, exceptional damage to the sides of the excavation. The damage was much larger than could normally be anticipated without cavitation. Since cavitation was induced on the outer surface of the jet and is a function of $(D_N)^2$, as opposed to the internally generated cavitation of the CaviJet® system, which is not a function of nozzle diameter, the increase in damage is explicable. The relationship can be obtained by multiplying the effect of a standard jet, $(D_N)^3$, and cavitation, $(D_N)^2$, to generate the experimentally obtained relationship $(D_N)^5$.

Despite this verification of previous conclusions, the possibility is accepted that use of a partial fractional design could conceivably have led to some question of the results obtained. Accordingly, a limited, full factorial experiment is being carried out to verify the earlier reported conclusions.

A review of the research performed on the use of water jets to enlarge deep submerged cavities is presented in the abridged report, Appendix C. The report indicates that difficulty may be encountered in the use of an external cavitation nozzle at depths below 308 metres (1000 feet).

After an approximately 2-month delay, the parts for the reaming unit were received and the unit constructed. A modification to the original design was necessary to achieve the required nozzle angle; a conventional nozzle holder could not be made to fit at the required angle because the radius through which the high-pressure tubing could be bent was limited. The problem was solved by threading the nozzle inside the high-pressure tubing. A preliminary test of the system indicated that the angled jet was cutting too wide a slot. Further modification to the nozzle angle is under consideration. Because the tests are performed outdoors, severe weather has been delaying test activities, and completion of all tests within the extended test period remains uncertain.

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* (D_N) = Nozzle diameter

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LEGEND:

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○ PLANNED START

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▽ PLANNED COMPLETION

▼ COMPLETED

8.5 Feasibility and Design Study of a Downhole Pressure-Pulsing Device

Contractor: Hydronautics, Inc.
Principal Investigator: V. Johnson, Jr. (301) 776-7454
Contract Period: 1 August 1979 to 31 July 1980
Contract Number: 13-5111 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

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. The technique should greatly increase the effectiveness of cavitation erosion, inasmuch as tests have shown that rock cutting rates with Hydronautics' Cavijet® nozzles increase as the third power of nozzle pressure drops.

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. The passage will be sized so as to resonate at the vortex-shedding frequency, thereby amplifying the small pressure pulses created by the vortex-shedding phenomenon.

Project Status

Preliminary design studies have been completed, along with a review of past research and literature on shear and oscillatory flows. Three nozzle concepts have been selected, designed, and fabricated. Laboratory testing of the nozzles is proceeding.

Quarterly Progress

A meeting was held with J. Buoyoucos of Hydroacoustics, Inc. The purpose of the meeting was to obtain his advice relative to the theoretical feasibility of the resonator concepts being studied and to possibly retain him for additional services on the program. In general, he agreed in principle with the potential of the resonator concept. However, he was unable to commit himself to participating further in the program because of related proprietary work in which he was involved. This related work involved hydrodynamic oscillation at low frequencies (less than 100 Hz), and the system under consideration had mechanical moving parts. He suggested that Hydronautics contact the Harry Diamond Laboratories to determine their current or past activity related to fluid amplifier, hydrodynamic oscillators.

Experiments in the test apparatus at the University of California at San Diego (UCSD) were started in December 1979. Initial tests with a 6.35-mm (0.25-inch) diameter plain Cavijet® tested at low jet speeds of 30.5 to 61.0 m/s (100 to 200 ft/s) and excited with a modulation pressure of only a few percent of the steady dynamic pressure indicate a near-doubling of the incipient cavitation number in the Strouhal number range of 0.4. Tests to determine the incipient cavitation number over a range of Reynolds and Strouhal numbers were also initiated.

The test apparatus at UCSD was modified so as to correct certain initial instrumentation and undesirable system vibration. Consistent data are now being obtained on the effect of small-amplitude modulation of the supply pressure on cavitation inception using a plain submerged Cavijet®. Preliminary data definitely indicate a near-doubling of the incipient cavitation with only a few percent modulation at a Strouhal number of approximately 0.4. This amplification is not extremely frequency dependent and can be achieved over a range of approximately $\pm 15\%$ of the resonant value. A more complete characterization of the phenomena was undertaken for a range of modulation amplitudes and Reynolds numbers.

Hydronautics observed Dr. Ellis' experiments in the test apparatus at the University of California. Earlier experiments which demonstrated the effect of excitation near a Strouhal number of 0.3 in increasing the incipient cavitation number were repeated. Considerable effort was expended to verify this effect at higher Reynolds numbers, i.e., higher jet speeds, without success. This failure was attributed to the response of the exciter, which was not capable of producing a significant amplitude at the higher frequencies required at the higher jet speeds.

Dr. Ellis will modify the exciter so as to obtain higher amplitudes at higher frequencies. The tests of the nozzle with the supply pipe length tuned to a frequency corresponding to a Strouhal number of 0.3 have begun.

During January, tests on a Helmholtz, tuned-inline-resonant-cavity Cavijet® nozzle were started in the Hydronautics high-pressure test loop used in previous Cavijet® experiments. The nozzle is provided with inserts for varying the cavity volume. Volume removal and penetration rate in Berea sandstone, as influenced by cavitation number and nozzle resonant frequency, were observed. These tests will be followed by a disc-centerbody nozzle having a disc-sting, axial, natural frequency nearly equal to the jet-vortex frequency. Initial tests of such a nozzle have shown marked improvement over other types of Cavijet® nozzles tested. The tests using Berea sandstone revealed increased erosion rates as the cavity volume was changed so as to resonate nearer to a frequency corresponding to a Strouhal number of 0.3. These tests were discontinued while the facility is being modified to allow visual observations.

A test loop using air was put into operation in February. This loop discharges air from promising nozzle concepts against a solid wall located at a variable standoff distance. A hot-film anemometer located in the jet discharge is used to measure the properties of the jet modulation. When combined with cavitation data obtained in water, these tests will provide valuable information as to the feasibility of the various concepts under study.

The design of a small, recirculating test loop which uses the existing 6.9-MPa (1000-psi) Cavijet® demonstration pump and storage system is nearing completion. This small loop, which will utilize an existing, transparent test section, will be used to screen a number of small-diameter, tuned-resonator Cavijet® concepts. In this small facility, the jet can be easily observed and photographed, and the changes in incipient cavitation number caused by system resonance can be detected.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PERCUSSION DRILLING</u> <u>HAMMER AND BITS</u> <u>DRL</u> LABORATORY TESTS													

LEGEND: ACTIVITY PERIOD
              RESCHEDULED

PLANNED START
 STARTED

PLANNED COMPLETION
 COMPLETED

8.6 Testing of Percussion Drilling Hammers and Bits

Contractor: Drilling Research Laboratory, Inc.
Principal Investigator: A. Black (801) 583-4111
Contract Period: 15 December 1979 to 31 March 1980
Contract Number: 46-3173 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to evaluate percussion drilling devices which offer the potential advantages of high penetration rate and achievement of straight holes when drilling with low-density fluids in brittle rock.

Project Status

The project, currently limited to laboratory testing of penetration rate and high-temperature hammer performance of commercially available equipment, was initiated in the last quarter of 1979. The laboratory tests were completed this quarter. The test results are being evaluated with a view toward quantification of the potential economic benefits of percussion drilling operations. The findings of the evaluation will determine what additional efforts will be made to improve percussion drilling devices for geothermal well drilling.

Quarterly Progress

Laboratory tests to evaluate percussion drilling equipment were completed at DRL this quarter. Preparations for a typical test are shown in Figure 41. The tests measured penetration rate, hammer pulses, and hammer life at high temperatures of 177°C (350°F). The penetration tests were conducted in Sierra white granite. The tests compared a conventional tricone insert bit without hammer, two "oil field" hammers with the same tricone bit, and three different "industrial" hammers with solid bits. The oil field hammers drilled faster than the conventional rotary equipment, particularly at low bit weights, and the hammers with solid bits drilled 21.3 m/h (70 ft/h), much faster than conventional rotary equipment operating at realistic loads (see Figure 42).

Limited data were obtained about the hammer pulse characteristics because the accelerometers and load cells used to instrument the tests were destroyed by the hammer blows.

The industrial hammers were run at 177°C (350°F) and did not survive an hour of drilling at this temperature. The failure modes involved plastic parts in the hammers' air valving mechanisms (see Figures 43 and 44), but these parts could be redesigned in metal or other high temperature material.

Work is underway to use the penetration rate data to quantify the potential economic benefits of percussion drilling. In consonance with the above test results and the economic analysis, additional efforts will be undertaken to investigate materials, develop designs, and fabricate and test hardware to improve percussion drilling technology for use in geothermal environments.

Figure 41. EPLEY D-2 Hammer Being Set Up to Drill Granite Sample in Penetration Rate Tests

Figure 42. Comparison of Rate of Penetration of Drilling Hammers and Rotary Equipment

Figure 43. DELRIN Air Feed Tube in Top of the Bit Shank of the MISSION A63-15 Hammer

Figure 44. Pieces of DELRIN Feed Tube Following Failure after Four Minutes of Operation at 177°C (350°F)

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>IMPROVED CAVIJET®</u> <u>NOZZLES</u> <u>HYDRONAUTICS</u> NOZZLE DESIGN LABORATORY ROCK- CUTTING TESTS HARD ROCK, BASELINE DATA CUTTING RATES VERSUS VARIOUS DESIGNS FULL SCALE, HARD ROCK NOZZLE SIZE VERSUS ROCK TYPE CONVENTIONAL BIT COMPARISON	 FINAL SCHEDULE UNDER DEVELOPMENT												

LEGEND: **ACTIVITY PERIOD**
                     RESCHEDULED

PLANNED START
STARTED

PLANNED COMPLETION
COMPLETED

8.7 Development of Improved Cavijet® Nozzles

Contractor: Hydronautics, Inc.
Principal Investigator: A. F. Conn (301) 776-7454
Contract Period: 18 February 1980 to 17 February 1981
Contract Number: 13-5129 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

The objective of this project is to increase knowledge of Cavijet® nozzle design principles and to develop Cavijet® nozzles which achieve increased incipient and optimum cavitation numbers.

Project Status

The project was initiated this quarter. Project startup activities include modification of test facilities and equipment. Establishment of test schedules is proceeding.

Quarterly Progress

Arrangements for conducting hard-rock-cutting tests at DRL are being established. The four-nozzle tool is being reworked by NL/Hycalog to permit operation at higher values of nozzle pressure drop. Several tentative periods available for test operations have been obtained from DRL. Plans for these tests were being finalized during the latter part of the reporting period.

The design effort to provide viewing ports for the Hydronautics high pressure cell (HPC) was begun. Three ports will be provided, each having a circular viewing area 3.8 cm (1.5 inches) in diameter. Two of these ports will be opposite one another, on a line passing through the center of the jet flow. A third port, to provide flexibility in lighting, will be situated at 90° to the aforementioned line between the other two ports. The glass for these ports will be mounted so as to withstand an internal operating pressure of up to 20.7 MPa (3000 psi), the current pressure capability of the HPC.

To permit detailed viewing of the cavitation phenomena produced by various Cavijet® cavitating-jet configurations, an existing binocular telescope/microscope unit is being modified. A new objective lens, having a 20.3-cm (8-inch) focal length, has been ordered. Magnifications varying from 5 to 20X will then be attainable to facilitate cavitation inception observations. Various audio methods for detecting cavitation inception are also being examined.

A means for in situ determination of eroded hole volumes is now in the early stages of design. If successful, this will increase the number of rock-cutting tests which can be run per day by eliminating several openings and closings of the HPC.

References

1. J. Polito and D. M. Smith, "A Simulator for Sensitivity Analysis of Geothermal Well Cost--Recent Results," Transactions Volume 3 (Geothermal Resources Council, September 1979).

APPENDIX A

Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Bit Hydraulics Research Program, SAND79-2433A, by D. Glowka, to Geothermal Drilling and Completion Advisory Panel Meeting, Washington, D.C., 11-13 December 1979.

Development of Percussion Drilling Systems for Geothermal Applications, SAND79-2140A, by J. Finger, to Drilling and Completion Advisory Panel Meeting, Washington, D.C., 11-13 December 1979.

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Wellbore and Soil Thermal Simulation for Geothermal Wells: Comparison of GEOTEMP Predictions to Field Data and Evaluation of Flow Variables, Part II Report, Report No. SAND79-7116, G. Wooley, Enertech Engineering and Research Company, Houston, Texas, Sandia Contract No. 13-0212, January 1980.

Recent Developments in Polycrystalline Diamond Compact Drill Bit Design, SAND79-1592A, by C. Huff and S. Varnado, to 1980 Energy-Sources Technology Conference of the Petroleum Division of the American Society of Mechanical Engineers, New Orleans, Louisiana, 3-7 February 1980.

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APPENDIX B

Proposed Test Plan
for
Continuous Chain Bit Field Test
at
Nevada Test Site

PROPOSED TEST PLAN FOR CONTINUOUS CHAIN BIT FIELD TEST

Test Requirements, Equipment, and Agreements

1. Tentative test date is mid-June 1980.
2. Sequence of drilling and estimated depth.
  - a. Ream hole and core 0.9 metre (3 feet) using drill pipe.
  - b. Life test Christensen MD-24 bit at 12.2 to 21.3 metres (40 to 70 feet).
  - c. Ream hole and core 0.9 metre (3 feet).
  - d. Life test chain bit, drilling with nine cutting surfaces; estimated depth of 82.3 to 137.2 metres (270 to 450 feet).
  - e. Ream hole and core 0.9 metre (3 feet).
  - f. Run hole deviation and caliper survey.
3. Mud equipment.
  - a. Pump capacity of 0.008 to 0.011 m³/s (120 to 180 gpm) at 11 MPa (16 000 psi) pressure.
  - b. Strainer in suction line with 3.18-mm (0.125-inch) mesh.
  - c. Two mud tanks, one for settling and one for suction.
  - d. Shale shaker with 40-mesh screens.
  - e. Desander.
4. Drill rig--Longyear 44 with hoisting capability of 18 144 kg (40 000 lbs) minimum.
5. Mud program will consist of using good grade of polymer such as supplied by NALCO Chemical Company or Drispac as sold by Baroid. Mud will be tested every 4 hours for the following:
  - a. Weight (lb/ft³),
  - b. Marsh funnel viscosity (seconds),
  - c. Plastic viscosity (centipoise),
  - d. Yield point (lb/100 ft²), and
  - e. Solids content (percent by volume).
6. Drilling instrumentation by EG&G and Sandia shall be installed no later than 12 May 1980 and checked out during drilling of first core and reaming hole. General requirements are as follows:
  - a. Recording equipment with variable chart speed such as 2.54 cm/min (1 in./min) and 0.254 cm/min (0.1 in./min).

- b. Record the following data:
    - (1) Revolutions per minute (rpm) 50 to 200 $\pm$ 5%,
    - (2) Swivel pressure 0 to 13.8 MPa (0 to 2000 psi) $\pm$ 5%,
    - (3) Mud flow rate 0 to 0.013 m³/s (0 to 200 gpm) $\pm$ 5%,
    - (4) Weight on bit 0 to 88 964 N (0 to 20 000 lbf) $\pm$ 5%,
    - (5) Rate of penetration 0.03 to 3.05 m/h (1 to 10 ft/h) $\pm$ 10%,
and
    - (6) Level of mud suction tank in inches $\pm$ 5%.
  - c. Continuous digital or analog display or readout for the following:
    - (1) Rate of penetration,
    - (2) Swivel pressure,
    - (3) Weight on bit, and
    - (4) Revolutions per minute.
  - d. Additional requirements are listed in Table B-1.
7. Core requirements.
- a. Three cores, each approximately 0.9 metre (3 feet) long.
  - b. Core analysis of dry compressive strength, specific gravity, and statement of competency of rock.
  - c. New core bit and reamer shell required with gage of $120.9 \pm \begin{matrix} 0.000 \\ 0.127 \end{matrix}$ mm
 $(4.760 \pm \begin{matrix} 0.000 \\ 0.005 \end{matrix}$ inches)
8. Downhole shock absorber should be provided. Suggested source is Mustang Tool Company, based on market survey. Spring preload should be approximately 26 689 N (6000 lbf).
9. Drilling should be on 24-hour basis unless interrupted by equipment failure or NTS testing. In the event drilling must be stopped, drill should be left in the well after being raised a safe distance off bottom.
10. Bottomhole assembly will be as follows:
- a. With shock sub--
    - (1) Bit,
    - (2) Near bit stabilizer,
    - (3) Shock sub,
    - (4) Spiral stabilizer,
    - (5) 9.1-metre (30-foot) drill collar,
    - (6) Spiral stabilizer, and
  - b. Without shock sub, use a 2.44-metre (8-foot) drill collar for Item a.3 above.
11. Sandia Albuquerque will furnish the following:
- a. Test bits--
    - (1) Two chain bits,
    - (2) Two Christensen MD-24 bits,
  - b. Skid-mounted straining system to remove solids greater than 1.27 mm (0.050 inch). System will be located between mud pump and swivel and will have capability of being back flushed,

- c. Pulsation dampeners for use on the K 280, duplex mud pump, discharge and suction side,
  - d. Bottomhole assembly less shock sub,
  - e. Downhole strainer for 2.44-metre (8-foot) drill collar, and
  - f. Cycling fixture for surface testing chain bits.
12. REECO will furnish material, equipment, and personnel for the following:
- a. Site preparation and cleanup,
  - b. Drill rig,
  - c. Drill collars and drill pipe to drill a minimum of 396 metres (1300 feet) and to apply a bit weight of 66 723 N (15 000 lbf) without hydraulic pull down,
  - d. Core bit and reamer shell to open hole to 12.09-cm (4.760-inch) diameter,
  - e. Rental or purchase of shock sub,
  - f. Core bit to drill cores per Item 7.c,
  - g. Mud equipment such as pumps, tanks, shale shaker, desander, hose, and piping,
  - h. Mud testing and control,
  - i. Provision for circulating mud in tanks and for venting drilling line during cycling,
  - j. Capability of operating mud pumps from driller's station and of observing mud pump pressure, and
  - k. One copy of the driller's log and mud test records.
13. EG&G will furnish rig instrumentation, operation personnel, and trailer for housing instrumentation.
14. Drilling procedure for chain bit and Christensen bits will follow previous test procedure unless downhole problems cause deviation. Procedures are as follows:
- a. Circulate hole for minimum of 10 minutes before starting to drill after shut down over 1/2 hour; otherwise, circulate only 5 minutes. Circulate 5 minutes when coming off bottom after drilling, except for Item 14.b,
  - b. Lift off bottom and circulate hole for 1 minute each time quill is adjusted for new stroke, and
  - c. Maintain drilling rate of 1.22 m/h (4 ft/h) or minimum bit weight of 17 793 N (4000 lbf). Increase bit weight to maximum of 66 723 N (15 000 lbf) force as necessary to maintain 1.22 m/h (4 ft/h). Then, maintain weight and let bit drill off. Rotation should normally be 100 rpm except when starting to drill or when vibration exists.
  - d. Normally, cycling of chain and pulling bits will be directed by a Sandia representative, who will work closely with REECO supervisor or driller.
- NOTE: The driller should stop drilling if for any reason he believes serious problems exist that could cause damage to equipment or endanger personnel.
15. Sandia NTS personnel are requested to coordinate and assist in carrying out this test.

Table B-1

Additional Field Test Instrumentation Requirements

1. Record drilling torque delivered to drill stem in the range of 0 to 1085 N·m (0 to 800 lbf·ft) $\pm$ 10% with visual display of real time data and chart recording.
2. Record penetration rate of drill in the range of 0 to 3.1 m/h (0 to 10 ft/h) $\pm$ 5% with visual display of real time data and chart recording.
3. Install pressure transducer on cycling fixture hydraulic system for measuring bit weight during surface cycling.
4. Install pressure transducer at cycling fixture for measuring mud pressure during surface cycling.
5. Monitor and record undamped mud pressure pulses of short duration on real time bases.
6. Provide string weight on sand line by strain gages or other means.
7. Operate two multi-channel chart recorders during chain bit cycling at surface and downhole.
  - a. Fast recorder should run at 60 mm/min (2.4 in./min) and 30 mm/min (1.2 in./min) for the surface and downhole cycling, respectively.
  - b. The slow recorder should run at 3 mm/min (0.12 in./min) for all cycling.
8. Record the following test parameters during surface and downhold cycling:
  - a. Mud flow rate,
  - b. Mud pressure,* and
  - c. Bit weight.**
9. Enter real time (day, hour, and minute) and scale for each test parameter on chart each time chart is started or stopped; every hour on slow recorder and every 15 minutes on fast recorder; entries made by operator.
10. Run slow recorder at all times unless delay is longer than one hour; reason for stopping recorder should be noted on chart by the operator.

*Record mud pressure at swivel and at fixture during surface cycling.

**Record weight on sand line for downhole cycling.

APPENDIX C

Considerations in the Use of Water Jets to
Enlarge Deep, Submerged Cavities

D. A. Summers and Z. Sebastian
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CONSIDERATIONS IN THE USE OF WATER JETS TO ENLARGE DEEP, SUBMERGED CAVITIES

Introduction

Within the last few years, there has been an increasingly wide examination of alternate energy sources for the United States as domestic and foreign supplies of oil become less available. One major area of interest, particularly in the West and South, is centered around the use of the earth's heat as a means of providing energy. In general, this heat source is available from subterranean waters which have, during the passage of time, acquired the heat of the surrounding rock. The water can be tapped and brought to the surface and the heat extracted. Unfortunately, during the time the water is in contact with the earth at depth, the water dissolves out some of the constituents of the surrounding rock and becomes an environmentally unacceptable solution. Hence, the water must be disposed of after the heat has been extracted. This disposal normally requires that the geothermal fluid be reinjected underground after use.

Under conventional technologies, the reinjection of the geothermal fluid requires that wells be sunk to the required depth and that the fluid then be pressure-injected into the ground. Many problems can arise during the latter process. For example, the fluid may deposit some of its constituents as it penetrates the rock. The deposited solutes restrict the passage of the fluid and make the system less efficient. Consequently, the hole may require further stimulation.

In order to facilitate the use of reinjection wells and to lower their cost, a project was initiated in the spring of 1979 to determine the practicality of reaming a single well from its normal 22.5-cm (8.86-inch) diameter to a diameter of approximately 2 metres (6.56 feet) over an increment of 70 metres (230 feet) at a depth of 2000 metres (6562 feet). Under such conditions, it should be possible to generate with a single well a capacity sufficient for coping with flow rates which would otherwise require that a dozen wells be emplaced at a high cost.

Program Plan

The program for this development was built around information acquired in previous tests in which high-pressure water jets were used to drill through rock. The tests proved the capability of drilling through rock which is under the well pressures predicated for this program.¹ In particular, borehole fluid back pressures of approximately 18 MPa (2611 psi) could be anticipated, and confining pressures on the rock due to the depth stipulated could be expected to reach approximately 42 MPa (6092 psi).

Concurrently, in a comparison program, a second development has led to a system whereby water jets can drill from a vertical well into a horizontal plane.² If a cavity approximately 1 metre (3.3 feet) in diameter is generated at the bottom of the well, the drilling system can drill more than 15 metres (49 feet) horizontally from the cavity into the flat rock formation. With this technique, the underground cavity can be enlarged beyond the 2-metre (6.56-foot) reaming requirement. Tests of this system to date have centered around surface drilling in coal.

Test Results

Earlier drilling tests had shown that drilling through rock with a water jet was a practical technology. However, a question remained as to the water jet's effectiveness in cutting rock where some standoff distance would be needed between the nozzle and rock surface and where relatively large areal increments must be removed.

To obtain some measure of the water-jet cutting effectiveness at the depth proposed, an initial set of experiments was set up. In order to simulate the required hole conditions, a standard, triaxial cell was modified to accept a water-jet drilling lance. In this cell, samples of Berea sandstone 15 cm (5.9 inches) in diameter were placed inside a rubber jacket. Oil surrounding the sample could be pressurized to generate a confining pressure equal to that likely to be encountered in the underground cavity. A 5-cm (2-inch) central core was drilled out of the test sample to provide central access for the nozzle assembly. This bore was terminated 7 cm (2.8 inches) from the base of the sample to leave support for the sample.

Table C-1 shows that, in all circumstances, the large-diameter nozzle could adequately cut ahead of itself under all the conditions anticipated for the borehole. However, the penetration ability of the smaller diameter jets became insufficient when a confining pressure exceeding approximately 10 MPa (1450 psi) was imposed within the test chamber. The results were verified by applying a confining pressure to the rock and repeating the test experiments with the largest diameter jet (Table C-2). These results verified that, under the required test conditions, the depth of cut which the jet would achieve would suffice to cut the rock surface.

Use of Cavitation

It is pertinent at this point to comment on the use of cavitation. The research that was carried out included examination of the potential for using cavitating nozzles under conditions similar to those used in the tests. It should be emphasized that this discussion is not concerned with the inception of cavitation which results from the nozzle systems used in the tests but rather with the distance from the nozzle over which cavitation continues. This research indicated that, where cavitating jets operate in a pressurized environment, such as that at the bottom of a borehole, the life span of the cavitation bubble is extremely sensitive to the surrounding atmosphere. The bubble is particularly sensitive when cavitation is generated on the outside of the jets rather than on the inside of the

Table C-1

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

Nozzle Diameter mm (in.)	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 (in.)					
0.75 (0.03)	28.58 (1.13)	15.88 (0.63)	15.88 (0.63)	7.94 (0.31)	--	--
1.00 (0.04)	47.62 (1.87)	22.23 (0.88)	22.23 (0.88)	11.11 (0.44)	--	--
1.60 (0.06)	69.85 (2.75)	--	31.75 (1.25)	23.81 (0.94)	20.63 (0.81)	17.46 (0.69)

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

Table C-2

**Effect of Borehole Confinement and Borehole Back
Pressure on Fluid Cutting Capability**

Rock Confining Pressure MPa (psi)	Depth of Cut mm (in.)	Hole Pressure MPa (psi)
0	63.5* (2.5)	0
13.8 (2 000)	11.11 (0.44)	17.25 (2 500)
27.6 (4 000)	8.73 (0.34)	17.25 (2 500)
41.4 (6 000)	6.35 (0.25)	17.25 (2 500)

Note: Jet pressure 69 MPa (10 000 psi)
Nozzle diameter 1.6 mm (0.06 in.)
Target Berea sandstone Standoff distance
6.35 mm (0.25 in.)

*Jet pressure 60.7 MPa (8 800 psi) for this cut

jet, as with the Cavijet® system.* In the latter case, the fluid flow of the jet itself may tend to protect the short-lived bubbles from the rapid collapse which might otherwise occur on the outside of the jet system.

The comparative life span of the bubbles is emphasized because the test results showed that, even at much lower chamber pressures, the cavitating-jet length is extremely sensitive to the surrounding fluid pressure, generally recognized in the "cavitation number" of the system. The damage which the jets induce also appears to vary strongly with the nozzle diameter at power levels up to 5. This sensitivity is illustrated by two photographs (Figures C-1 and C-2) which show that relatively small changes in back pressure reduce the effective length of the cavitating zone. (The pressure in the triaxial chamber, 18 MPa (2611 psi), was larger than that noted in the figures). Although cavitation inception must occur, the length of the cavitation zone is the important factor in cutting because, to be effective, the jet must cut at least 6 mm (0.24 inch) deep at a standoff distance of some 6 mm (0.24 inch). Based on experimental results, an adequate bubble life cannot normally be anticipated with external, i.e., peripheral, cavitation-jet systems at the depths which are under consideration in the reaming project.

Use of Polymers

A projection of the results previously discussed reveals what the data indicated--that the jet's cutting ability, while adequate to the project purpose, corresponded to a 10- to 20-day reaming time for a single hole, a length of time which is excessive from a practical viewpoint. Therefore, the system was reevaluated. Nozzle design had previously been optimized, and it was believed that no additional benefit could be achieved by improving this system. Pressure drop had also been standardized, and, within the confines of the hole geometry, it appeared that not much could be gained by increasing jet pressure. However, earlier work had demonstrated that the addition of long-chain polymers could substantially improve the penetration ability of water jets with distance.³ Accordingly, an experiment was designed to determine if long-chain polymers would improve the cutting capability of the water jet in this circumstance. The test program was partially repeated using a NALCO Corporation polymer, NALCO 625. This polymer was added to the jet fluid in varying concentrations, and tests showed that the jet containing the polymer cut more effectively than did the jet without the polymer (Table C-3). The effectiveness of the cutting jets could now be anticipated to be such that a water-jet reamer could satisfactorily ream the chamber from the original 22.5-cm (8.86-inch) to the 2-metre (6.56-foot) ultimate diameter.

Based on the results of the experiments, it was determined that a 200-ppm concentration of the NALCO chemical would prove sufficient for the experiments to be undertaken.

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* Cavijet® is a trademark of Hydronautics, Inc.

Figure C-1. Cavitation Cloud Length with a Chamber Pressure of 0.14 MPa (20.3 psi)

Figure C-2. Cavitation Cloud Length with a Chamber Pressure of 0.49 MPa (71.1 psi)

Table C-3

Effect of Adding Polymer on the Effective
Jet Cutting Distance

Polymer Concentration ppm	Hole Back Pressure MPa (psi)	Cutting Distance mm (in.)
100	17.25 (2 500)	34.92 (1.37)
100	17.25 (2 500)	34.92 (1.37)
200	17.25 (2 500)	47.62 (1.87)
300	17.25 (2 500)	47.62 (1.87)
300	17.25 (2 500)	28.57 (1.12)
300	10.35 (1 500)	31.75 (1.25)
300	3.45 (500)	36.51 (1.44)

Note: Jet pressure was 69 MPa (10 000 psi), and nozzle diameter was 1.60 mm (0.06 inch).

The results of the tests have been confirmed to a degree by results reported by G. Howells of the Berkeley Chemical Research, Inc. Using a chemical marketed under the trade name "Super Water," Howells was able to clean the clogged slots of oil well liners.⁴ A Superwater solution of 0.3% polymer was able to clean these liners at a standoff distance of 11.75 cm (4.63 inches), the maximum achievable distance within the wellbore. On the other hand, normally unpolymerized water jets could not clean the liners at standoff distances greater than 10 times the nozzle diameter, between 0.38 and 0.76 mm (0.015 and 0.030 inch).

The following procedure was adopted to test the jet cutting capability. First, a small metal cup was inserted at the bottom of the central borehole. Then, the confining pressure on the rock was raised to the required level, at which point the high-pressure water-jet system was turned on. The jet was directed within the metal retaining cup at the bottom of the drilled hole until the pressure in the water-jet system had been stabilized at the required 69 MPa (10 000 psi). At this point, the flow of fluid out of the cell was restricted until the required back pressure of 18 MPa (2611 psi) was achieved in the borehole. Then, the nozzle was rotated and the chamber slowly lowered so that the cutting jet would describe a spiral cut in the wall of the cavity.

An initial experiment with this arrangement, under borehole conditions, indicated that the jet had not noticeably damaged the side walls of the specimen. This result was not expected because the nozzles which had been used in this program were capable of cutting a sandstone target some 1.8 metres (6 feet) from the nozzle orifice in air. It was concluded that the failure to cut was due to the fact that the nozzle was at a considerable standoff distance from the rock surface and that the capability of the water jet to penetrate through pressurized water was very rapidly diminished with an increase in fluid pressure. Accordingly, a series of experiments was carried out at reduced pressure to verify that, under normal situations, the water jet would be capable of cutting through the rock.

Fluid Pressure Effects Testing

The experiments showed that, at lower pressures, the jets cut through the rock. Hence, it was concluded that the increasing back pressure caused the jet performance to decay.

This effect is not the same as that which would occur due to a change in the pressure drop across the nozzle. Earlier experiments have investigated the fluid pressure effect (see Reference 1) and verified that this phenomenon is not strictly related to the pressure drop itself but rather to the inability of the jets to satisfactorily penetrate the water.

In order to better understand the parameters controlling this effect, a simple experiment was set up examining the effects of pressurizing the fluid within the hole. Concurrently, variation in nozzle diameter was included in the experimental design to determine how this would affect the ability of the water jets to cut through the fluid to the rock.

For this series of experiments, the rock specimens were prepared in a different manner. Because the experiments were concerned with the ability of the jet to cut through the fluid to the rock rather than with the confining pressure on the rock, tests were carried out with the entire chamber brought up to the necessary back pressure without other confinement on the rock. The samples were prepared so that the upper surface of each sloped downward across three-quarters of its area (Figure C-3). The nozzle mounting tube was bent to cause the jet to sweep a circular path over the sample. The sample was inserted in the chamber and the cell reassembled. The nozzle was initially located over the highest point on the sample. The chamber was raised until the sample contacted the nozzle. Then, the chamber was lowered 6.25 mm (0.25 inch). The nozzle was rotated until it was at the most distant point from the rock. As in previous tests, the jet was brought up to pressure and the flow restricted to generate the required back pressure. The nozzle was then rotated through one revolution and the system shut down. During the revolution, the distance between the nozzle and the rock surface varied from approximately 5 cm (1.97 inches) down to 6.35 mm (0.25 inch). The minimum distance of 6.35 mm (0.25 inch) was established in order to minimize erosion of the nozzle body by the rebounding fluid and the rock sample material as the jet operated. During the course of the revolution, the nozzle body moved through a circle in which the standoff distance first decreased and then increased as the nozzle returned to its original position. This procedure produced two readings

Figure C-3. Sample Shape and Nozzle Arrangement for Standoff Effect Tests

which could be averaged to give the distance from the nozzle over which the jet effectively cut the rock (Figure C-4). The results of these tests are shown in Table C-1. The nozzles used in this test program were the electroformed nozzles, described in earlier work,⁵ that have such a high-quality surface finish that their cutting ability is unquestioned.

Figure C-4. Representative Sample Showing Slot Cut in Rock Surface

Conclusions

The addition of a polymer to erosion jet fluids to facilitate the enlargement of deep, submerged caverns appears to be a viable concept for improving the excavating capability of the water jet. However, when considering the use of cavitation methods, the tendency of long-chain polymers to inhibit the ability of a water jet to cavitate should be included in the analysis of such methods.

These experiments demonstrated that water jets, particularly when mixed with polymeric additive, are capable of cutting sandstone under the conditions likely to be found at about 2000 metres (6562 feet) down a well.

As a result of this work, a preliminary design for a reaming head has been developed, and a model of the system is currently under test (Figure C-5).

Figure C-5. Start of a 43.2-cm (17-inch) Diameter Hole Being Reamed by a Single Water-Jet Cutter

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