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Geothermal Drilling and Completion Technology Development Program Annual Progress Report

October 1979 - September 1980

Samuel G. Varnado, Editor

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GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
ANNUAL PROGRESS REPORT

October 1979-September 1980

Samuel G. Varnado
Editor
Drilling Technology Division 4741
Sandia National Laboratories
Albuquerque, NM 87185

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ABSTRACT

This report describes the progress, status, and results of ongoing Research and Development (R&D) within the Geothermal Drilling and Completion Technology Development Program. The work reported is sponsored by the Department of Energy/Division of Geothermal Energy (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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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
ANNUAL PROGRESS REPORT

October 1979-September 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 1980 fiscal year.

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2. HIGHLIGHTS

The following highlights set forth the major accomplishments achieved under the Geothermal Drilling and Completion Technology Development Program during the 1980 fiscal year.

Drilling Hardware

- Conducted the third field test of the downhole replaceable chain drill

The third field test of the chain drill confirmed the reliability of downhole cycling of the chain links. In comparison to the success achieved in the first field test, drilling performance was not as good. Investigation of the causes of the degraded drilling performance is underway, including theoretical analyses and controlled laboratory drilling tests.

- Identified seal designs and lubricants for use in sealed geothermal roller-cone bits

Elastomeric and all-metal seals were designed, and lubricants were formulated for use in sealed roller-cone bits under geothermal drilling conditions. The seals, soaked at 288°C (550°F) and tested at 125°C (257°F), and lubricants were successfully laboratory tested and are considered ready for full-scale drilling tests.

- Conducted two field tests with full-scale drag bits, modified to use PDC cutters

The first test of full-scale drag bits using PDC cutters was conducted in the Baca field early in FY80 and demonstrated penetration rates up to 4 times greater than a conventional bit. A second field test with a redesigned bit was attempted late in FY80, but a manufacturing error led to an unsuccessful test. The error has been corrected and more bit tests are planned to establish bit life.

Drilling Fluids

- Completed preliminary screening of surfactants for development of aqueous foam drilling fluids

Surfactant screening at high temperature and in various chemical environments has identified several surfactants that are promising for geothermal applications. Evaluation of selected surfactants is continuing at high temperatures and high pressures.

- Demonstrated a technique of nitrogen generation from diesel engine exhaust using a catalyst

Catalytically supported thermal combustion as a means of generating nitrogen from the exhaust of a diesel engine was successfully demonstrated in laboratory testing. The durability of the catalyst was shown in two 100-hour tests; one at a full engine load and one at a part load. The results indicate an ultimate catalyst life in excess of 1000 hours. Development of a scaled-up, field-size system is under consideration.

- Conducted a successful field test of a high-temperature drilling mud

A field test of the HTM-1 mud system was successfully conducted during the drilling of the McCulloch Mercer 2-28 well in Imperial County, California. No mud solidification, no serious lost circulation, and no corrosion problems were encountered during drilling with the HTM-1 mud. A detailed analysis of the test data is being conducted. The formulation used for HTM-1 mud is now commercially available from a leading mud company.

Completion Technology

- Designed and fabricated a system utilizing cavitation techniques for downhole geothermal well cleaning and scale removal

The motor and cavitating nozzle mechanisms for a downhole descaling unit were fabricated and laboratory tested. Experiments to determine the threshold intensity of erosion of calcium-based scale found in East Mesa wells were completed. A value of 650 W/m^2 (0.42 W/in.^2) was established. A field demonstration of the device is scheduled early in FY81.

- Investigated formation permeability impairment due to drilling mud invasion as a function of varying stagnation times, mud types, temperature, and backflow durations

The evaluation of the laboratory test results for two mud systems indicated that (1) permeability impairment due to formation/drilling fluid interaction is time dependent, with significant impairment occurring within 48 hours residence time, (2) permeability impairment is temperature dependent, with lower temperature, i.e., 100°C (212°F), exposures resulting in greater impairment than higher temperature, i.e., 200°C (392°F), exposures, and (3) both temperature and time dependence vary with drilling fluid chemistry.

Lost Circulation Control Methods

- Completed a study to determine the geological characteristics of lost circulation zones in volcanic sequences

A study of the geological characteristics of lost circulation zones was conducted in an attempt to define one or more parameters that could be utilized to predict with a high degree of accuracy those zones where

circulation might be lost. The study found that detailed quantitative data on the geological characteristics of lost circulation zones do not exist and concluded that experiments should be conducted in drill holes to determine the physical parameters of those zones.

- Acquired an extensive data base concerning rock properties, temperature histories, and lost circulation experience in geothermal wells

A data collection effort was completed to acquire and collate information on rock properties, well temperature histories, and lost circulation experience in geothermal wells. The data will be used for thermal simulation of wells during drilling, production, and injection, using the GEOTEMP code.

- Completed an assessment of lost circulation mapping tools and techniques

Tools and techniques were identified, described, and evaluated concerning their capabilities to map lost circulation zones in geothermal wells. Twenty five tools were examined and ranked on the basis of performance, risk, availability, and cost. The Sound-Temperature Survey received top ranking although the study concluded that multiple tools, usually two, are required to obtain sufficient information in order to map lost circulation zones.

- Initiated a project to design and fabricate a facility for testing lost circulation materials and cementing techniques at simulated geothermal well conditions

The number, availability, and capabilities of existing lost circulation/cementing testing facilities indicate an urgent need for a facility to support development of materials and procedures for lost circulation control and cementing. Design of the facility has been initiated and construction is expected to be completed during FY81.

Supporting Technology

- Fabricated a facility for conducting studies of drill bit hydraulics

Fabrication and assembly of a test facility that will be used in optimizing the design of bit hydraulics for geothermal drill bits were completed. The facility provides the capability to visualize the flow field along the bit face and to measure bottomhole pressure gradients, cutter heat transfer coefficients, and chip removal. Experiments will begin in early FY81.

- Produced an H₂S resistant, silicon-based, dual-phase steel sample for possible drill pipe applications

An experimental quantity of a silicon-based, dual-phase steel was produced and processed for use in corrosion-fatigue tests. Fabrication of

specimens from the steel for heat treatment experiments is underway. A corrosion resistant drill stem material with suitable mechanical properties is expected to result from this effort.

- Expanded the capability of the GEOTEMP code for predicting transient wellbore temperatures during drilling, circulation, injection, and production in geothermal wells

Modifications to the GEOTEMP code were completed to handle deviated holes, variable tubing areas, and multiple fluids separated by interfaces in the wellbore. Work is continuing to develop compressible flow capabilities in the code.

Advanced Drilling Systems

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

A facility for testing a downhole motor bearing and seal package under simulated downhole conditions has been completed. This facility has been used to screen seal designs and lubricants. The Variseal® high-temperature seal achieved a lifetime of 165 hours at temperatures ranging from 82° to 177°C (180° to 350°F) and a pressure drop of 10.3 MPa (1500 psi).

- Demonstrated the feasibility of a downhole pressure-pulsing device for use with cavitating jets in high-pressure, jet drilling systems

Laboratory tests of a tandem-orifice "Pulser" concept indicated the feasibility of developing a downhole pressure-pulsing device for creating cavitation at lower nozzle pressure drop. This development may lead to high cutting rates with reduced surface pressure. Work on optimizing the configuration of the device will be continued in a follow-on program.

- Evaluated percussion drilling devices for use under geothermal conditions

Laboratory tests of conventional percussion drilling equipment were conducted at high temperatures. The percussion equipment drilled up to three times faster than conventional rotary drilling, but high-temperature failure of plastic parts in the air valving mechanisms of the percussion hammers was encountered. Work is continuing to determine modifications required to correct the failures encountered and to compile additional data for an economic analysis of the potential benefits of percussion drilling.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:
——— ACTIVITY PERIOD
○ PLANNED START
▽ PLANNED COMPLETION

- - - - - RESCHEDULED
● STARTED
▼ COMPLETED

3. MANAGEMENT

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.

Advisory Panel

The semi-annual meetings of the Geothermal Drilling and Completion Advisory Panel were held on 11-13 December 1979 in Washington, DC, and on 19-20 June 1980 at Texas Tech University, Lubbock, Texas. The minutes of the meetings were published separately. The members of the advisory panel are listed in Appendix A.

National Research Council

A presentation on material needs for geothermal drilling and completions was made to the National Research Council Materials Advisory Board in Washington, DC, on 17 March 1980. This committee is tasked to identify materials problems presently limiting geothermal development and to formulate recommendations aimed at finding solutions.

Workshop on Geothermal Drilling Fluids

A workshop on Geothermal Drilling Fluids was sponsored by Sandia for DOE/DGE on 9 October 1979 in Houston, Texas. Presentations describing ongoing fluids research sponsored by Sandia/DOE were given by Sandia technical consultants and by the contractors. Presentations by industry on their activities concerning drilling fluids were also made. A separate report of the workshop proceedings has been published.¹

International Conference

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

Systems Analysis

The systems analysis efforts for FY80 were directed primarily at establishing the capability to define the progress that is being made toward reaching the goals of the Geothermal Drilling and Completion Technology Development Program. Emphasis was placed on the evaluation of technological developments in drilling and completion as to their potential for reducing the costs of geothermal wells. Progress was made in the five areas discussed below, and significant work is continuing in the first four. When this work is completed in FY81, it will be possible to define the cost reduction potential of each of the individual program elements with increased confidence.

Development and Use of the Well-Cost Model — Work on IOSYM, the language underlying the well-cost simulation model, was completed in FY80. The User's Manual and the Programmer's Manual will be published early in FY81. The model was discussed in a paper presented to the Joint National Meeting of the Institute of Management Sciences and the Operations Research Society of America.² The well-cost model was used to obtain the results discussed below and in the cost analysis presented at the GRC Annual Meeting in Salt Lake City.³

Emphasis in the modeling effort has shifted to determining networks that realistically represent examples of geothermal drilling and completions and that can be modeled using the IOSYM language.

Characterization of Drilling and Completion Techniques -- The major part of the systems analysis work in FY80 was in the characterization, both technical and economic, of new and existing technologies. In order to evaluate potential cost reductions, it is necessary to determine or estimate the costs and possible performance capabilities of drilling and completion systems. Four areas which required significant effort in FY80 are:

1. Development of a Rig-Rate Algorithm. This effort was concerned with determining the capital and operating costs for conventional geothermal drilling rigs and the rates charged for their use. These rates were determined as functions of (1) the hardware included on, or excluded from, the rigs, (2) the locations of drilling operations, and (3) numerous important economic and company-specific parameters. The resulting functions were programmed in a simple, interactive FORTRAN program. This work provides a baseline for consistent determination of the rig costs associated with new technologies, as well as for realistic analysis of the rig-rate component of geothermal well costs. The work is documented in Reference 4.
2. Well Descaling. This study involved a comparison of the economics, as well as the performance capabilities, of different scale removal and scale inhibitor systems. The results of this study will be presented in a report that is currently undergoing review and will be published in FY81.
3. Fluid Jet Drilling. A year-long study of the nature, costs, and capabilities of various fluid-jet drilling systems has been completed and a report is being prepared. The systems considered

included abrasive-jet drilling systems, cavitating-jet drilling systems, and systems that use high-pressure drilling fluid alone or to augment mechanical cutting. The approach was to gather all possible data from previous and ongoing fluid jet drilling programs, to use these data to define the drilling components necessary and the performance of the different systems, and then to estimate the costs associated with the systems.

4. Percussion Drilling. Data describing percussion drilling systems and estimates of their performance were compiled. An evaluation of the economics of percussion drilling systems is continuing. This characterization is proceeding in conjunction with the testing of percussion hammers and bits. The results of preliminary analyses are discussed in Section 9.6.

As characterizations of technologies are completed, the new technologies and their impacts on drilling and completions costs can be evaluated in the well-cost model. Results, such as those shown in Figure 3-1 for improved bit lubricants, have been derived for a number of new technologies. Figure 3-1 illustrates the projected effect of the new technology on the well costs for four specific and one generic or representative well. To construct the chart, the costs that might have been experienced if the wells had been drilled with bits utilizing improved seals and lubricants were compared with the actual well costs. The major effect of improved lubricants is to increase bit lifetime. The results show that this improvement can have fairly significant impact on the costs of some wells and trivial effects on the costs of others.

The analysis of technologies is continuing.

Documentation of the Costs of Conventional Drilling and Completion —

Two areas of work in well-cost documentation and data collection were pursued in FY80 and are continuing. These are the collection of historic well costs and the development of representative well plans that can be used to predict costs for the major geothermal areas.

Historic well-cost data are being collected on three different levels: (1) total cost, (2) well cost divided into major categories such as site preparation, drilling contractor charges, cement charges, etc., and (3) detailed costs broken down into the costs associated with each operation in the drilling and completion sequence. The total cost is currently known for more than 50 wells; cost by category, for 25; and detailed costs, for 4. The detailed cost data allow sensitivity analysis like that shown in Figure 3-2 to be carried out. The figure illustrates the sensitivity of total well cost to changes in the values of several parameters. The parameters to which well cost is highly sensitive are those on which technology development should focus. As might be expected, the sensitivities vary greatly among geothermal wells, and the relationships illustrated in Figure 3-2 are only one example. In addition, new technologies generally affect the values of more than one parameter. Nonetheless, this sensitivity information is useful in identifying attractive new technologies. Furthermore, it is necessary to have the detailed cost data in order to evaluate their cost reduction potential.

Figure 3-1. Preliminary Cost Impact Results
for Improved Bit Lubricants

Figure 3-2. Well Cost Sensitivity

The development of representative or "generic" geothermal well plans was initiated in the last part of FY80. Well plans that represent drilling in The Geysers steam field and at three sites in the Imperial Valley have been completed, and plans for other sites are being constructed. These well plans provide sufficiently detailed data to allow analysis of the costs of the individual operations at each area. Therefore, these plans will facilitate evaluation of new technologies. In addition, the well plans will eventually be supplemented by data defining the frequencies and costs of drilling and completion troubles in the different areas. Problems that arise during drilling and completion, such as lost circulation, stuck pipe, corrosion, etc., can add significantly to the total well cost. The data that describe the nature of such problems will aid in the statistical modeling of trouble costs and in the evaluation of the cost reduction potential for technologies directed toward solving such problems.

Survey of Future Drilling Requirements -- A projection of the geothermal drilling that will be done during the next 20 years has been completed and the report is under review. The report will be published early in FY81. The projection indicates that The Geysers will continue as the most important area of geothermal drilling for electricity generation for the next 5 years, but that Imperial Valley drilling will dominate other areas after that time period. The survey also indicates the likely locations and nature of future drilling for direct use applications. The purpose of the study was to estimate the relative importance of different types of drilling and different drilling and completion problems. This information will be used to help define where program emphasis should be placed in the future.

Well Cost Impacts on Energy Costs -- The study of the sensitivity of geothermally produced energy costs to well costs was completed late in FY80. Draft reports are being reviewed and the final volumes will be published early in FY81. The results indicate that a 25% reduction in well costs would reduce the costs of geothermally generated electricity 12 to 14%, regardless of whether the reservoir is steam or liquid dominated. Furthermore, the costs may also be reduced, by a few percent, by improved completion techniques. The energy cost savings in direct-use cases are much more sensitive to the overall nature of the project (industrial, district, or single-facility heating) and range from 6 to 12%.

Drilling Hardware

Dyna-Drill Turbodrill -- 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 the Sandia 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 the Sandia program in the development of downhole motors and high-speed bits.

Hot Dry Rock (HDR) Program -- DOE/DGE requested Sandia to provide assistance to Los Alamos Scientific Laboratory (LASL) in the conducting of LASL's HDR program. LASL has a critical need to drill highly accurate directional holes in the HDR program. LASL 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 HDR 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 tested at the Gearhart-Owen facility in Dallas and failed. Two basic problems were identified. The first was 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 was 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.

It appeared unlikely that LASL would be able to use the two turbodrills as originally designed. Sandia provided assistance to LASL in trying to correct some of the problems with the existing turbodrill. As part of this effort, two 13.7-cm (5.375-in.) diameter turbodrills manufactured by Maurer Engineering were tested at the Drilling Research Laboratory (DRL), Salt Lake city, Utah, during the week of 14 April 1980. The tools were to be used for drilling part of the 22.2-cm (8.75-in.) segments of Wells EE-2 and EE-3 at LASL's Fenton Hill site. The drills were tested with tricone bits in Texas pink granite. Although similar tools had previously given substantial problems with speed control, these turbines demonstrated stable operation at moderate speed, 350 to 400 rpm, and good penetration rate, 9.1 to 12.2 m/h (30 to 40 ft/h). The reason for improved operation appeared to be the use of a different bit and a sealed lubricated bearing assembly.

A meeting was held on 24 June 1980 between representatives from SNL and LASL to discuss Sandia's further participation in the HDR project. A decision was made that Sandia would obtain two of the new 17.8-cm (7-in.) geothermal turbodrills fabricated and tested by Dyna-Drill.

Two Dyna-Drill 17.8-cm (7-in.) diameter downhole turbines were tested in the 31.1-cm (12.25-in.) segment of the EE-3 hole being drilled by LASL at Fenton Hill. First, the 7.3-m (24-ft) long directional turbine was run at about 1951-m (6400-ft) depth and demonstrated its capability to drill in this formation using a carbide-button rock bit by drilling about 3.1 metres (10 ft) at a rate of 3.7 m/h (12 ft/h). Drilling was limited to 3.1 metres (10 ft) because the Scientific Drilling Control steering "EYE" tool was not functioning properly. At a depth of 2560 metres (8400 ft), the 14.6-m (48-ft) straight-hole turbine was placed in the hole, and it reamed about 30.5 metres (100 ft) of hole but never actually reached bottom because of tight hole conditions. The stabilizer mounted on the turbine caused the assembly to bind in a tight spot more than 305 metres (1000 ft) from the

bottom. However, the turbine and tachometer operated satisfactorily and provided the driller with a real-time indication of the motor's speed during the entire run. The directional turbine with tachometer will be run at LASL's request at a depth of approximately 3048 metres (10 000 ft). Sandia is providing these turbines for LASL under a lease agreement with Dyna-Drill in order to obtain data on turbine performance.

Drilling Fluids

N. Corrosion Test — Coordination was made with Union Geothermal to delineate specific areas of responsibility for the planned field test of nitrogen as a geothermal drilling fluid. The general experimental configuration was discussed in detail, and agreement was reached on the various responsibilities for the test. Sandia will supply the liquid nitrogen, 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 system 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. The status of the field test is reported in Section 5.2.

Completion Technology

Cementing and Lost Circulation Test Facility — A meeting was held with T. Muecke, Supervisor of Completions Research, at Exxon Production Research Company in Houston to discuss the facility that Halliburton has built with Exxon support for determining the effectiveness of mud displacement by cement during oil well completion operations. Exxon has also developed a proprietary computer code that models the non-Newtonian flow characteristics of these fluids. The facility simulates a wellbore, and cement and mud can be pumped through it. Once the cement sets up, the casing and the core that surrounds it can be sectioned to permit investigation of the displacement phenomenon. This test facility has been constructed at the Halliburton research headquarters in Duncan, Oklahoma. Halliburton conducts the tests for Exxon and supplies the data to Exxon for comparison with calculated values from their proprietary code. Since casing design and cementing techniques are extremely important to geothermal operations, a facility of a similar type would be extremely valuable to Sandia's completion technology program. The upper temperature limit on the existing facility is 121°C (250°F). The facility is reserved for use for the next two years by Exxon. Sandia conducted a series of discussions with Exxon and Halliburton to determine the feasibility of constructing a larger diameter, higher temperature facility to do similar work for geothermal

applications. Sandia initiated a project late in FY80 to design and fabricate a facility for testing lost circulation materials and cementing techniques at simulated geothermal well conditions. The status of the project is described in Section 7.4.

Formation Damage — T. Strickland of Republic Geothermal visited Sandia to discuss formation damage from drilling mud invasion with Sandia and Terra Tek personnel. Republic's field development activities have been delayed pending a satisfactory solution to the apparent formation damage problem, i.e., reduction in permeability and thus production, that is occurring in the geothermal wells drilled in the East Mesa of the Imperial Valley. A Sandia-sponsored test at Terra Tek was devised to seek a solution to this problem. The results of this effort are reported in Section 6.4.

Lost Circulation Control Methods

As part of Sandia's activities to develop a program in lost circulation control methods, a visit was made to LASL to discuss drilling and completion problems with personnel involved in the HDR program. One of LASL'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.

W. Holman and D. Reynolds of Milchem, Inc., expressed an interest in the Geothermal Drilling and Completion Technology Program and a willingness to work with Sandia in the program. Two specific items in their product line may be of interest: Mil-Temp, a fluid additive to reduce high-temperature viscosity, and Mil-Squeeze, a silicate-based clay that is used for lost circulation control. Arrangements were made for a demonstration of Mil-Squeeze at Sandia.

Venture Chemicals, Inc., and Poly Plug, Inc., visited Sandia and presented ideas for sealing lost circulation zones in geothermal wells.

Venture Chemicals has developed a dehydrated, pelletized, cellulose material that expands approximately 10 times when mixed with water. Sandia will perform some laboratory tests to quantify the material's properties and its capability to plug formations under geothermal conditions.

Poly Plug, Inc., has developed a two-part mix, polyurethane foam that has been successfully used to stop water flows in water wells. Sandia will furnish Poly Plug with data on the geothermal environment and critique the Poly Plug tests conducted under the conditions presented in the data. Loffland Brothers Drilling Company has agreed to perform a mechanical design of a placement device for this material.

Advanced Drilling Systems

Flexible Drill Pipe — An investigation of the use of ethylene propylene diene (EPDM) compounds to upgrade flexible drill pipe for geothermal drilling applications has been initiated. 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 leak-proof. 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. Progress on this project, which was initiated in the latter part of FY80, is reported in Section 9.8.

Supporting Technology

Drill Pipe Corrosion — Five scientists from the European community visited Sandia on 3 October 1979 to discuss Sandia's geothermal drilling research, geothermal logging, and magma energy program. Representatives from Belgium, France, Holland, and the United Kingdom attended. The Sandia programs and the European geothermal program funded by the Commission of European Communities were discussed. One of the interesting highlights of the European activities was the drilling at Laradarello, Italy. One well is being drilled past 4500 metres (14 765 feet) and temperatures in excess of 380°C (716°F) are being encountered. This environment has caused severe corrosion of the drill pipe and has presented a new suite of problems to be solved in drilling technology.

The primary corrosion problem involves the presence of oxygen and H₂S in the wellbore. The current remedy is to treat the drilling fluid with oxygen and H₂S scavengers. The pipe is being closely monitored to determine the effectiveness of the treatment. Since 1973, the average life of the drill pipe has increased from 3 to 5.3 years. This has resulted in a large cost savings in terms of drill pipe life. Commonly used oxygen scavengers include sodium sulfite and zinc chloride. Treatment costs for these chemicals average approximately \$70/day throughout the U.S. for oil and gas drilling; however, in geothermal drilling in The Geysers the chemical treatment costs are approximately \$500/day with an additional \$300/day in pipe loss cost. The need for drilling fluids with reduced oxygen content and new drill pipe steels that are more resistant to H₂S attack are clearly indicated.

GEOTEMP Code -- S. Sarem, Union Oil Company of California, visited Sandia on 15 May 1980 to discuss Union's use of the GEOTEMP wellbore thermal simulation code. Union has installed this code on its computer and is using GEOTEMP to calculate temperature profiles both in muds and cements used in geothermal wells. Union requested Sandia's assistance in debugging the code. Union also indicated an interest in pursuing joint research programs with Sandia. The first of these activities will involve Union supplying some field data for Sandia to use in code verification runs. Since there are very few sources of such data, this interchange of information is expected to be of mutual benefit to Sandia and Union.

A meeting was held at the Amoco Production Research Center, Tulsa, Oklahoma, between representatives from Sandia and Amoco. Discussions were concerned with drill string dynamics and wellbore temperature prediction capabilities. Amoco is interested in Sandia's activities in these areas and requested a copy of the wellbore temperature prediction code, GEOTEMP. The code is being supplied. Amoco is an industry leader in drilling research, and the company's participation and support should be valuable assets to the geothermal drilling program. Amoco also agreed to critique Sandia's plans for the drill string dynamics study.

Drill String Dynamics -- Sandia visited Amoco Production Company's Research Center on 21 August 1980 for the purpose of discussing drill string dynamics research. Both K. Millheim and R. Huggins at Amoco expressed an interest in working with Sandia in this area. K. Millheim offered Sandia the use of a computer program, developed by Amoco, that is used to correlate the trajectory of a wellbore with the bottomhole assembly configuration and the formation characteristics encountered. This code is used to post-analyze directional wells that have been drilled by Amoco so that the company can improve its ability to predict trajectories in subsequent holes. The use of this code will be of significant value in comparing trajectory predictions from Sandia's drill string dynamics study with actual field data. No other source for these field data is known and this cooperative effort will result in substantial time and cost savings in the study effort.

Elastomer Coatings -- Sandia 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 0.37-mm (0.0015-in.) thick film of Parylene C was deposited onto elastomers by Union Carbide's vapor phase, pyrolytic method, while a

0.038-mm (0.0015-in.) 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.

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

Geothermal Information Exchange with New Zealand

S. Varnado visited New Zealand in support of a recently signed International Cooperative Agreement between the U.S. Department of Energy and the New Zealand government. The Wairakei Geothermal Project in Wairakei, New Zealand, was visited on 14-16 April 1980 for discussions with personnel from the New Zealand Ministry of Works. In addition, technical discussions were held on 18 April 1980 with the geothermal staff of Kingston, Reynolds, Thom, and Allardice (KRTA), geothermal consultants in the Philippines. KRTA is located in Auckland, New Zealand. Key personnel at the Wairakei project were B. Denton, Geothermal Project Engineer, and L. Fooks, Investigations Engineer. At KRTA, the primary contact was T. Dobbie, Associate for Chemical Engineering.

The purpose of this trip was to discuss geothermal drilling and completion practices that are currently being used in New Zealand and in the Philippines and to present an overview of the DOE/DGE program in geothermal drilling and completion technology development. A summary of the discussions and observations concerning geothermal projects in New Zealand and the Philippines follows.

New Zealand — The problems experienced in New Zealand are different from those encountered in The Geysers and other U.S. resources. The New Zealand Ministry of Works is willing to participate in a joint research program to test new bit designs in their wells. Because they have a significant amount of experience in formations different from those so far encountered in the U.S., it would be in the interest of the U.S. to participate in such a joint program. They are also interested in testing some of the new high-temperature logging tools recently developed by DOE.

Interest was expressed in two other downhole tools. First, the need for a high-temperature, open-hole packer for staged cementing was clearly expressed by the New Zealanders. In this application, the packer would have to tolerate a high temperature for about 2 hours. Second, there exists a need for a casing inspection tool that could be used in old wells to evaluate the effects of corrosion on the casing. This tool is needed to answer the question of the integrity of the casing after the well has been in operation for a period of 20 or more years.

The Philippines -- The basic problems encountered in drilling geothermal wells in the Philippines are lost circulation control and drill string dynamics. Materials for controlling lost circulation under high-temperature conditions are needed. In addition, the development of an understanding of drill string dynamics and of the design of shock subs to mitigate the vibrations induced while drilling fractured formations is needed. This same technology would be useful in designing the bottomhole assembly to provide a straight-hole trajectory.

Currently used completion procedures have proven to be reasonably successful in field operations; however, it is clear that there is a significant lack of understanding of the displacement of mud by cement and of the flow of cement in highly fractured formations. Experimental work to enhance the level of understanding of the cementing process would be beneficial to the U.S. geothermal operators as well as overseas operators.

Reports and Presentations

A list of significant presentations made and reports published during FY80 is compiled in Appendix B.

References

1. Maurer Engineering, Inc., Proceedings of Workshop on Geothermal Drilling Fluids, SAND79-2395 (Albuquerque: Sandia National Laboratories, October 1979).
2. J. Polito and D. Smith, IOSYM: A Network Simulator Language for Continuous Systems, SAND79-0567C (Albuquerque: Sandia National Laboratories, October 1979).
3. C. C. Carson and Y. T. Lin, "Geothermal Well Cost Sensitivity Analysis: Current Status," Transactions, Volume 4 (Geothermal Resources Council, September 1980) pp 277-280.
4. Scientific Applications, Inc., Economic Evaluation of Geothermal Drilling Equipment, Final Report, Sandia Contract No. 13-8724 (Tulsa, OK: January 1980).

4. DRILLING HARDWARE

In order to reduce well drilling costs, improved drilling hardware that has a longer life and that drills at an increased rate of penetration is required. The approach to achieving the needed improvements 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 rock-fracture/cutter wear mechanisms. Projects are presently under way to 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. A project to design and develop high-temperature seals and lubricants for sealed bits was completed during the 1980 fiscal year. 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 experimental bits were evaluated in a geothermal well at The Geysers, along with seven conventional bits. The material improvements allowed the experimental 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, bits using the new materials would save 2 to 4% of the total cost of wells drilled in The Geysers.

Experiments with high-temperature seal designs, materials, and lubricants for sealed-bearing bits, completed this fiscal year, 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 was corrected, and a third field test at NTS was completed in June 1980. No problems were encountered in cycling the chain downhole; however, the bit wore out quickly in the hard granite formation. The development of the diamond matrix version of the prototype chain link has been suspended until data analysis is completed. A parallel effort to develop an all-PDC chain link for the drill was initiated this fiscal year and is continuing.

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 in October 1979 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. Because these tests were limited to approximately 15.2 metres (50 feet) each, bit lifetime could not be established. Additional field testing was attempted near the end of this reporting period, and the test data and problems encountered were being analyzed as the fiscal year ended. Details of these field tests will be reported in the next quarterly progress report.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

4.1 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 and to obtain industrial participation in the development of the hardware.

Project Status

The Prototype II, Mod 2, continuous chain drill bit field tests were conducted at NTS during the period 5-20 June 1979 (field test I). The results were included in the April-September 1979 Semi-Annual Report (see Reference 1). A follow-up field test at NTS was initiated in mid-September 1979 (field test II). Unexpectedly rapid wear of the chain link cutting surfaces was experienced, and the tests were terminated after the determination that field repair of the drills could not be made. A 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.

The redesigning and fabrication of two Mod 4 chain drills were completed, and a third field test was conducted in June 1980 (field test III). The analysis of the data is in progress. A parallel effort to develop an all-PDC chain link is continuing.

FY80 Progress

Field Tests — One of the objectives of the June 1980 field tests was to determine whether the cause of the failure of the two Prototype II, Mod 3 chain bits that occurred during the September 1979 tests at NTS had been corrected. An analysis of the two chain bits after the September 1979 tests revealed that the mud flow channel in both bit bodies had ruptured (see Figures 4-1 and 4-2). This failure was believed to have occurred during surface cycling tests prior to drilling operations. The resultant internal leakage of drilling mud was a contributing factor that caused each of the four cutting surfaces to fail prematurely because of water starvation. The evaluation showed that the weld joint structural strength was marginal. This condition, coupled with stress concentration and fatigue, caused the joints to rupture.

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 tests. The method selected uses a 1.91-mm (0.075-in.) thick cover plate with an improved weld joint. This rework procedure was considered adequate to allow the drill to survive the anticipated downhole environment expected in the June 1980 field test.

Figure 4-1. Ruptured Mud Flow Channel in Continuous Chain Bit Body

Figure 4-2. Close-Up View of Ruptured Mud Flow Channel

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 were established.

Final phases of preparation for the third chain bit field test at NTS began on 12 June 1980. The established procedure was to ream the hole and core 0.9 metres (3 feet) and then drill with the Christensen MD 24 diamond bit, which was used for comparison with the chain bit. This procedure would allow the hole to be opened to gage, a core to be taken, the drill pipe to be washed out, and the drilling instrumentation to be checked out before drilling began with the chain bit.

Downhole problems were experienced during the initial coring at a hole depth of 250 metres (819 feet), where formation sloughed into the hole. The core bit became stuck and then the pipe twisted off. The bit was fished and recovered. However, approximately 48 cm (19 in.) of cut core was left in the hole. The first attempt to drill the unretrieved core with the MD 24 bit resulted in extremely rough drilling and damage to the throat of the bit. The second trip into the hole with a core bit retrieved a small piece of core with a large loose rock on it. This core bit was damaged and could no longer be used. After the drill pipe was tripped out of the hole, the hole was filled with cement to a depth of 116 metres (380 feet) from the surface and squeezed to force cement into washed out zones. The cement was then drilled out, and the hole was deepened 2.7 metres (9 feet) using a carbide-insert tricone bit. This bit was severely damaged when used to drill the additional 2.7 metres (9 feet). The cones were pinched, carbide inserts were broken, and the bit was under gage. Later it was determined that the 2.7 metres (9 feet) of hole was "corkscrewed," apparently because the bit had been overweighted.

Preparations were started on 25 June 1980 for drilling with the first chain bit, unit No. 1. Several mud pump efficiency flow tests were made. The pump was about 90 to 96% efficient, pumping mud at 0.01 m³/s (160 gpm) with unrestricted flow. There was no equipment available onsite to choke the flow to obtain the desired back pressure. The drilling instrumentation was checked out and calibrated. The following drilling data were recorded and/or displayed:

1. Penetration rate,
2. Bit weight,
3. Weight on crown block,
4. Mud flow rate,
5. Rpm,
6. Damped and undamped swivel pressure,
7. Pressure drop across the surface mud filters,
8. Time, and
9. Mud pit level.

The stiff bottomhole assembly that was run with chain bit No. 1 consisted of the following:

1. Chain bit,
2. Near bit stabilizer,

3. Shock sub,
4. Spiral stabilizer,
5. 2.4-metre (8-foot) drill collar with inline filter,
6. Spiral stabilizer,
7. 9.1-metre (30-foot) drill collar, and
8. Spiral stabilizer.

The mud system had two surface, inline filters between the mud pump discharge and the swivel. The return flow passed through a shale shake, a desander, settling tanks, and a screen before entering the drill stem. Liquid polymer was used with water to obtain the Marsh funnel viscosity of 29 to 32 seconds. The polymer reduced the flow friction and provided the required viscosity for good bottomhole cleaning and chip removal.

Chain bit No. 1 with nine new chain link sets for drilling and one high-pressure link set for furnishing a signal to the surface in order to index the chain was run in the hole. The bit was in the extended position, with link No. 22 in the drilling position. It was necessary to ream the hole for the last 9.1 metres (30 feet) because of the corkscrewed condition and the stiff bottomhole assembly. The reaming operation severely damaged link sets No. 22 and No. 24, and the chain bit gage diamonds on the head and body were almost worn away. The damage was undesirable but necessary if drilling was to continue in the hole. On reaching bottom at approximately 260 metres (853 feet), the chain bit was cycled three times, bringing link set No. 23 into drilling position. The hole was first shaped to contour, and then a pump-off test was run to find the hydraulic force that opposed the weight on bit. This value was recorded as 1497 kg (3300 lb).

The drilling time for testing link set 23 was 24 minutes. The drill stem was rotated at 100 rpm. The bit started drilling at a rate of penetration (ROP) of 0.9 m/h (3 ft/h) with a bit weight of 2722 kg (6000 lb). The performance of link set 23 was similar to the performances of four link sets tested in field test II. The ROP was established at 1.2 m/h (4.0 ft/h); then the mud pressure quickly began to increase and the ROP began to decrease. The bit weight was increased until the mud pressure reached a maximum of 10.7 to 11.0 MPa (1550 to 1600 psi), which is the limit of the National duplex pump. After 24 minutes, the ROP was down to 0.6 m/h (2 ft/h), at which time drilling was stopped. The chain bit was cycled 11 times to bring link set 25 into position; then drilling was resumed. Drilling again was stopped after an additional 0.18 metre (0.6 foot) was drilled.

Chain bit No. 2 was prepared and run in the hole. Testing was carried out on link sets 22 (modified), 27, and 29, with only 0.76 metre (2.5 feet) being drilled. The cycling mechanism worked without flaw, as was the case in field test II. A comparison of drilling results for all three field tests is shown in Table 4-1.

After drilling with the five different link sets and changing from polymer mud to water on the last link set, the testing was stopped. The reasons for the poor drilling results were not readily apparent. However, it was obvious that some major change had taken place in the drill bit or in the downhole environment.

Table 4-1

Chain Bit Field Test Results

<u>Test No.</u>	<u>Link Set No.</u>	<u>Depth Drilled</u> <u>Metres (feet)</u>	<u>Average ROP</u> <u>m/h (ft/h)</u>	<u>Rock Strength</u> <u>MPa (psi)</u>
I	12	8.69 (28.5)	1.07 (3.5)	
	13	13.62 (44.7)	1.31 (4.3)	3.4 (5 000)
	14	8.78 (28.8)	1.01 (3.3)	to
	15	9.42 (30.9)	1.07 (3.5)	22.0 (32 000)
	16	23.62 (77.5)	1.46 (4.8)	
	18	9.14 (30.0)	1.43 (4.7)	
II	17	0.67 (2.2)	0.79 (2.6)	22.0 (32 000)
	19	0.37 (1.2)	0.58 (1.9)	to
	20	0.61 (2.0)	0.61 (2.0)	
	21	0.61 (2.0)	0.40 (1.3)	25.0 (36 000)
III	23	0.46 (1.5)	1.01 (3.3)	
	25	0.18 (0.6)	0.55 (1.8)	Estimated
	22*	0.27 (0.9)	0.67 (2.2)	to be
	27	0.18 (0.6)	0.46 (1.5)	25.0 (36 000)
	29	0.27 (0.9)	0.88 (2.9)	

* Modified

Post-Field Test Analysis — After field test III, an investigation of the poor drilling performance of the chain drill was initiated. The two chain bits were first pressure tested, and no internal leakage was found. The chain was removed for inspection of the cutting surfaces.

All of the link sets used for drilling in the three field tests were photographed, and enlarged prints were made. Transparent overlays were used to plot the diamond pattern for each link; these patterns were compared with various selected link sets. It was determined that Christensen set the diamonds well, and the patterns are repeatable. The wear pattern on link sets that were successfully tested in field test I showed that the diamonds had little flattening and that wear was uniform except in areas of heavy matrix ringing. Link sets used in field test II and III, particularly the sets used when drilling was stopped early, showed a flattening of diamonds in small areas, such as at the trailing edge of links 2 and 4. However, most of the diamonds showed very little wear, and, in many cases, the diamonds were still covered with a carbide matrix. The tungsten carbide inserts, which function as fluid flow nozzles in the chain links, were

in some instances not machined flush with the mating surface. This flaw could allow the link to rock on the bit head or allow excessive leakage of drilling fluid if the insert is recessed.

A theoretical analysis was made of the relationship between diamond wear and pressure drop across the chain links (see Figure 4-3). The figure shows that the pressure drop across the bit head is very sensitive to diamond wear. A uniform wear of only 0.127 mm (0.005 in.) on the diamond will increase the pressure drop from 550 to 1030 kPa (800 to 1500 psi). The increase in pressure drop can be prevented to some extent by the design of water courses in the chain links, but this approach is a long-term development effort. In order to determine the cause of the poor drilling performance of the chain bit in field tests II and III, a series of controlled laboratory drilling tests at the Drilling Research Laboratory (DRL) were planned.

Chain drill No. 1 was tested at DRL 11-15 August 1980. The primary objective of the test was to determine whether or not the chain bit drilling system had degraded since prior laboratory testing in April 1979. The secondary objective of the test was to conduct mud flow tests to establish mud pump efficiency and to obtain mud flow data in support of analytical calculations for the evaluation of the bit hydraulics. To meet these objectives, link set 28 was tested and the results were compared to those obtained with link set 10 April 1979. Link set 10 drilled a total distance of 8.23 metres (27 feet) in Sierra white granite.

The only changes in the status of chain drill No. 1 since the April 1979 tests were as follows:

1. Drill bit No. 1 has been subjected to three field tests and reworked after each test. The bit was in good condition for the August 1980 test.
2. The rubber seals on the back side of the link sets used for directing the mud flow were replaced with tungsten carbide inserts.
3. Link set 28, used in the August 1980 tests, was from a different production lot than link set 10, used in the April 1979 tests.
4. The internal body of the bit was reworked to repair the mud flow channels; some flow restriction was a possible result.
5. The gage diamonds on the drill bit head were replaced with larger diamonds.

The unrestricted flow tests through the bit showed the bit to have no increased flow restriction. The mud pump hydraulic efficiency at 0.01 m³/s and 1030 kPa (160 gpm and 1500 psi) was 98%.

The laboratory drilling test of link set 28 was terminated after approximately 12 feet of drilling because of excessive torque. A piece of the upper trailing edge of link set 4 had broken off because of high forces

Figure 4-3. Theoretical Analysis of the Relationship between Diamond Bit Wear and the Mud Pressure Drop (ΔP) across the Chain Links

caused by the matrix dragging on the rock after the diamonds were worn flat. The key parameters of link set 28 are compared to link set 10 in Table 4-2.

The results of this test showed strong evidence that the chain bit drilling performance had degraded. The same problems experienced in the field were evident from this laboratory test, such as the swivel mud pressure increasing rapidly while bit life was significantly reduced. However, the DRL mud pump has greater capability than the pump used in the field tests II and III, and the downhole environment is much less severe in the laboratory; consequently, the bit life was extended in the laboratory drilling.

Link set 10, tested in the April 1979 laboratory tests, drilled 27 feet with only a minimum of wear noted on the diamonds; no wear was seen after drilling the first three holes. After drilling the first hole in the August 1980 tests, link set 28 showed significant nonuniform wear on links 2 and 4. This wear became progressively worse, until matrix failure occurred on the third hole.

Additional laboratory tests at DRL are being scheduled, and the results will be reported in subsequent progress reports.

The data reviewed to date concerning the poor drilling performance of chain bit during field tests II and III lead to the following preliminary conclusions:

1. Chain links may be moving on the bit head because of the clearance between mating parts and the failure of parts to conform to drawing tolerance. This movement could cause nonuniform diamond wear on the chain links. The pressure drop across the bit would then be increased and the ROP reduced. These conditions could cause a severe reduction in drilling life.
2. The tungsten carbide inserts may not be efficiently replacing the previously used rubber O-ring seals in the chain links. An excessive leakage of drilling fluid is possible when links rock and move on the bit head.
3. The diamonds may not be accurately located on the hemispherical surface. Inaccurate placement of the diamonds could lead to rapid, uneven wear. Dimensional tolerances are currently being checked.

All-PDC Chain Link Design — The 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 two-piece investment casting using PH 17-4 stainless steel. This design will require increased clearance between the Stratapax™ cutting surface and the bit face to allow

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

Table 4-2

Comparison of Link Set 10 with
Link Set 28 During Drilling

Parameter	Hole 1		Hole 2		Hole 3	
Link Set Number	10	28	10	28	10	28
Test Date	Apr 79	Aug 80	Apr 79	Aug 80	Apr 79	Aug 80
Mud Pressure						
Start MPa	7.58	6.21	7.93	9.31	9.38	10.55
(psi)	(1 100)	(900)	(1 150)	(1 350)	(1 360)	(1 530)
End MPa	8.27	10.07	9.24	11.10	9.51	10.89
(psi)	(1 200)	(1 460)	(1 340)	(1 610)	(1 380)	(1 580)
Bit Weight						
Start kg	2 268	2 268	3 639	5 602	6 151	6 876
(lb)	(5 000)	(5 000)	(8 020)	(12 350)	(13 560)	(15 160)
End kg	3 674	5 806	4 853	6 922	6 577	6 895
(lb)	(8 100)	(12 800)	(10 700)	(15 260)	(14 500)	(15 200)
Torque						
Start N·m	339	298	518	536	740	461
(lb·ft)	(250)	(220)	(382)	(395)	(546)	(340)
End N·m	434	630	583	515	712	441
(lb·ft)	(320)	(465)	(430)	(380)	(525)	(325)
Rate of Penetration						
Start m/h	1.2	1.3	1.2	1.2	1.2	0.7
(ft/h)	(4.0)	(4.2)	(4.1)	(3.9)	(4.0)	(2.3)
End m/h	1.2	1.2	1.2	1.0	1.2	0.6
(ft/h)	(4.0)	(3.9)	(3.9)	(3.2)	(3.8)	(2.1)
Swivel Pressure, off bottom						
MPa	3.0	2.4	2.3	2.4	2.8	2.4
(psi)	(440)	(350)	(340)	(350)	(400)	(350)
Depth Drilled						
cm	91	122	122	127	122	99
(in.)	(36)	(48)	(48)	(50)	(48)	(39)

drilling fluid velocity to be reduced. The design also 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.

A computer optimization code is being used to locate each Stratapax™ cutter as part of a computerized graphics drafting program. The final chain link design is expected to have a tungsten carbide or a PH 17-4 stainless steel pad for holding the Stratapax™ cutters. The pad will be brazed to an investment-cast base link.

The purchase quotation for building the full PDC chain links was sent to the five major diamond bit manufacturers; however, this purchase requisition was cancelled because no quotations were received. The failure to quote occurred in part because of the difficulty of casting or machining the recesses that hold the individual diamond cutters in the matrix pad. The schedule for building the PDC chain link is being extended. Sandia will modify the design so that the pad that holds the cutters can be made out of cast PH 17-4 stainless steel. The pads can then be procured from almost any investment casting company. The recesses will be machined by the EDM process. The final assembly will be accomplished by Sandia or by an outside specialty manufacturer. The parts needed for modifying the Prototype II chain bit in order to test the PDC chain links were received. The machining modification of the bit body has begun at Sandia.

Diamond Set Analysis — The current work included having Christensen, Inc., Salt Lake City, Utah, evaluate the effect on drilling when the diamond-set chain is misaligned. This evaluation involved the use of Christensen's proprietary computer program and a special computer program developed previously for Sandia under another project. Sandia has developed a computer program for obtaining new diamond coordinates when the chain is displaced off-center with respect to the bit body. Christensen used information from the computer program in their analysis.

Christensen completed the study of the effect of chain link misalignment on the bit head during drilling. The theoretical diamond locations for each of four shifted positions were supplied by Sandia. These positions were ± 0.381 mm and ± 1.016 mm (± 0.015 inch and ± 0.040 inch). The Christensen Diamond Bit Performance and Life Analysis Computer Program was used to analyze the drilling performance of each of four shifted data sets. Because of the lower average number of diamonds per ring in the shifted position and the resulting increase in load and work rates, a shorter life span per diamond is expected. The load per diamond increased up to 2.2 times and the work rate increased up to 4.0 times compared with the load and work rate for the most worn diamonds in the normally aligned position.

Investment Casting Chain Link Base — 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. As now machined, the unit cost of the chain link base has varied between \$100 and \$200. The unit cost for production quantities of an investment casting is estimated to be about \$5. 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.

References

1. Samuel G. Varnado, ed, Geothermal Drilling and Completion Technology Development Program Semi-Annual Progress Report, April-September 1979, SAND79-2397 (Albuquerque: Sandia National Laboratories, May 1980).

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.2 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 was to design and develop improved tri-cone roller bits for geothermal applications. The project had 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 demonstrated less wear than production bits in the simulated downhole environment. Third-generation unsealed bits were field tested successfully, and this new technology is being considered for commercialization by a leading bit manufacturer.

A seal tester and a lubricant tester were fabricated to simulate in-use conditions: 300°C (572°F), 34.5 MPa (5000 psi), translation, rotation, and eccentricity. Nonelastomeric seals and coated-elastomer seals were designed and tested. Life tests were run on coated-elastomer seals, and results compared favorably with previous, successful, Viton seal tests. Spring-loaded face seals underwent preliminary tests, and the elastomeric side-seal system was perfected.

Lubricant screening tests, while eliminating several products from further consideration, established the exceptional high-temperature performance of Pacer PLX-014 oil. A grease based on this oil also was compounded and is ready for field evaluation. An oil (PLX-022), not compatible with elastomers, was 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. Elastomeric seals of EPDM (ethylene propylene diene) compounds and Utex Industries' proprietary elastomeric seals were tested. Only the EPDM seal, 267-II-35, supplied by L'Garde, Inc., and the Utex HTCR seal did well. New candidate seals and lubricants were tested, and a final report was published separately.

FY80 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. A sketch of the metal bellows face seal is shown in

Figure 4-4. 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.

Figure 4-4. Metal Bellows Face Seal

The third test was run with approximately 300 newtons (68 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 steps were taken in designing the second-generation, all-metal seals:

1. Observation of warp versus temperature with a 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 were returned to Bel-Flex Products, Inc., for replacement of the bellows. The bellows had been crushed by excessive differential pressure 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 the leak-down rate. The failure detection system was 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 were returned to Bel-Flex Products for replacement of the bellows through the use of an improved welding technique.

The fifth and sixth seal assemblies were received, and four tests were run to determine the wear and leakage rates that occur during the use of abrasives and in the presence of mechanical eccentricities. Leakage rates tended to increase with temperature and became excessive above 200°C (392°F). Two life tests were run at temperature using Geysers abrasives. The first test was run at 200°C (392°F) for 82 hours; the second test was run for 99 hours at 250°C (482°F). Both tests caused excessive wearing of the CBS-600 carburized steel "lug" surface: approximately 0.5 mm (0.019 in.) and 0.9 mm (0.035 in.), respectively. In both cases, the chrome oxide plasma coating on the seal rings was undamaged. A more wear-resistant surface material is required to protect the "lug" sealing surface. The 99-hour test utilized an initial 2-hour soak at 350°C (660°F). No damage to the springs, bellows, or seal ring was observed.

Face Seal with Elastomeric Side Seal -- Although no further work is planned with this system, the results from the all-metal seal tests gave insight into the probable cause of leakage for the elastomeric type. Most likely, these seals leaked at the face, as did the all-metal type, and the elastomeric side seal was not at fault. This system may 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. A sketch of the face seal with elastomeric side seal is shown in Figure 4-5.

Elastomeric Seals -- An EPDM candidate supplied by L'Garde, Inc., did exceptionally well in a trip-in simulation seal test. The seal survived the 2-hour soak at a temperature of 288°C (550°F), after which it was run at 90 rpm for 104 hours. The trip-in simulation test cycle is illustrated in Figure 4-6. The proprietary compound was created for static seal applications in geothermal well logging tools. The base polymer is DuPont

Figure 4-5. Face Seal with Elastomeric Side Seal

Nordel EPDM, molded in the 2-329 O-ring configuration (see Figure 4-7). The seal experienced little chemical degradation from the Pacer PLX-014 grease, which utilizes a synthetic, hydrocarbon oil, as evidenced by a durometer shift from 91 to 85, Shore A. This result was considered significant, because EPDM compounds are generally incompatible with hydrocarbons.

An identical test was run on a Parker EPDM seal (Reed oval configuration) to compare the effect of the PLX-014 grease. The seal failed by ripping at the seal interface after 9-1/2 hours, indicating poor elastomer surface lubricity. The durometer shifted from 72 to 66, indicating that the PLX-014 does not readily attack EPDMs.

The L'Garde EPDM seal survived the highest soak temperature to date, surpassing Parker 4205 Viton's 260°C (500°F) limit by 28°C (50°F). Additional tests were required to confirm the EPDM test; unfortunately, no additional seals were available. L'Garde believes the compound could be further optimized for the rock bit seal application.

Figure 4-6. Trip-In Simulation Test

INNER DIAMETERS:

REED OVAL	53.49 mm	(2.106 in.)
2-329 O-RING	50.17 mm	(1.975 in.)
3-932 O-RING	59.36 mm	(2.337 in.)
2-141 O-RING	58.42 mm	(2.300 in.)

Figure 4-7. Elastomer Seal Cross Sections

These tests indicate that seals are now available to drill the vast majority of the hydrothermal reservoirs, including most of the Imperial Valley known geothermal resource areas (KGRAs).

Utex Industries supplied two new proprietary grades of elastomeric seals in the oval configuration, designated RD-217 and RD-231. Two of the RD-231s were subjected to the same 288°C (550°F) trip-in simulation test described above (Figure 4-6). Seal lives were 1-1/2 and 4 hours, with failures occurring due to abrasives intrusion and tearing of the sealing surface. Compression-set was also evident.

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 contacted L'Garde, Inc., and Utex Industries to obtain EPDM and HTCR seals for coating. L'Garde, Inc., agreed to supply at least four seals in the No. 2-329 configuration.

Testing was completed on a series of four proprietary grades of elastomeric seals provided by Utex Industries, Inc. The design goal for these seals was 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 4-3.

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

These results were 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 represented a significant improvement in the temperature capabilities of elastomeric seals for geothermal rock bits. Both provided a soak temperature 28°C (50°F) higher than the temperature provided by the best previous candidate, Parker 4205 Viton.

Utex Industries, Inc., developed a new, high-temperature elastomer that 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 was the second commercial product developed under the program; Pacer Geobond grease was the first.

Table 4-3

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 (550)	2	1.5	Very little grease loss
229	RD-231	8.8	288 (550)	2	1.5	Cuttings found under sealing surface
230	RD-217	7.5	288 (550)	2	0	Long strips of material were torn from the i.d.
231	RD-217	7.5	288 (550)	2	0.5	Severe damage to seal i.d.
236	RD-226	9.4	288 (550)	3	0	Severe abrasive damage to seal i.d.
237	RD-226	8.9	288 (550)	2	0	Very smooth wear on seal i.d. No cuttings found under seal
238	RD-231	10.2	288 (550)	2	92+	Seal i.d. smooth
239	RD-227	10.9	288 (550)	2	52	Seal i.d. abraded near top
240	RD-227	10.7	288 (550)	2	94+	--

Trip-in simulation seal tests were run on eight Utex HTCR seals received from Utex Industries, Inc. One seal survived a 2-hour soak at 288°C (550°F), followed by 120 hours of rotation at 90 rpm at 150°C (302°F), and with abrasives and mechanical eccentricities present. The soak temperature was increased to 302°C (575°F) for the second test, and the seal failed after 5 hours of rotation. The soak temperature limit therefore lies between 288° and 302°C (550° and 575°F). The performance of HTCR is equivalent to L'Garde, Inc., 267-II-35 EPDM, Utex Industries, Inc., RD-227 and RD-231, and Sandia Teflon-coated Viton seals.

L'Garde, Inc., supplied a new batch of EPDM seals that differed in composition from the original batch known as 267-II-35. The designation of the new batch was changed to Z-267. The first test attempted with this seal was terminated due to equipment malfunction. Subsequently, a trip-in simulation seal test was run using a 288°C (550°F), 2-hour soak, followed by rotation at 150°C (302°F). Failure occurred after 33 hours of rotation. This performance compared unfavorably with the previous L'Garde 267-II-35 seal, which ran for 104 hours. The Z-267 was essentially unaffected by the temperature, pressure, or lubricant. The durometer dropped only 3 points, 95 to 92, Shore A, and the surface was free of cracks and discoloration. The seal failed due to abrasive wear on the i.d., and also seized to the shaft, causing abrasive damage to the top.

Radial Lip Seal — Previous seal-life tests conducted in the seal test facility indicated that the Fluorocarbon, Inc., first-generation, radial lip seal (Figure 4-8) had excellent resistance to abrasive damage but that it tended to leak due to shrinkage. Fluorocarbon, Inc., 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 was sent to Terra Tek with revised recommendations for shaft diameter and gland depth.

Figure 4-8. Fluorocarbon, Inc., Radial Lip Seal, Style RP; Seal Lies in the Horizontal Plane

Three tests were run on the second-generation seals from Fluorocarbon, Inc., using soak temperatures of 250° to 288°C (482° to 550°F). The second-generation seals were identical to the first-generation but were preshrunk. In all tests, the seals held pressure at ambient temperature but not at test temperature. Upon examination, it was found that the two seals that soaked at 288°C (550°F) had lost nearly all compression; the one seal soaked at 250°C (482°F) retained 70% of its original compression. Two of the tests were continued for approximately 10 hours in order to evaluate cuttings damage; none was observed. Further development was not recommended for this seal. Although the exact failure mode was not determined for all cases, the dimensional stability of the plastic seal body limited the maximum soak temperature to less than 250°C (482°F).

Lubricant Development — Pacer PLX-030 and PLX-031 were candidate oils for all-metal (nonelastomeric) sealing systems and were similar to PLX-022 oil. PLX-030 and -031 contain additives to improve lubrication below 135°C (275°F). Both caused the lubricant test machine to seize. Tests were terminated, with no further testing planned.

The ability of PLX-014 to accommodate water was evaluated by adding 10 drops to a standard 316°C (601°F) test. The resulting wear scar was 4.34 mm (0.171 in.), which compares unfavorably with typical 1.27- to 1.91-mm (0.050- to 0.075-in.) scars. Pacer was consulted to determine what can be done to rectify this situation.

Geobond 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 4-4, 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.

Table 4-4

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., provided five new candidate geothermal bit lubricants for evaluation, all based on high-viscosity, high-molecular-weight, synthetic, hydrocarbon oils. Four of the five contained 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 were compatible with elastomers. The five new candidate lubricants were

1. PLX-042: Similar to PLX-014 oil but with an additional extreme-pressure (EP) additive. PLX-042 and PLX-014 contain suspended graphite.
2. PLX-043: Contains no solids and is a blend of two oils having different viscosities.
3. PLX-044: Contains no solids and uses one base oil having a viscosity similar to PLX-043.
4. PLX-045 and PLX-046: Contain no solids, and both use very-high-viscosity base oils.

The PLX-40 series was designed for the evaluation of the effect of molecular weight and suspended solids on the load-bearing ability of very-high-viscosity, synthetic, hydrocarbon oils. These five PLX-40 grades were evaluated and compared with the best lubricant previously tested, Pacer Geobond (see Table 4-5).

Table 4-5

Load-Carrying Capacity of Five Elastomer-Compatible Oils
for Geothermal Journal-Type Rock Bits, at 316°C (600°F)

<u>Designation</u>	<u>Viscosity</u> [*]		<u>Solids</u>	<u>Load Capacity</u>	
	<u>SUS</u>	<u>(CST)</u>		<u>MPa</u>	<u>(ksi)</u>
Geobond oil	190	(40.4)	Yes	73	(10.6)
PLX-042	180	(38.3)	Yes	64	(9.3)
PLX-043	290	(62.1)	No	63	(9.1)
PLX-044	280	(60.0)	No	66	(9.5)
PLX-045	313	(67.5)	No	69	(10.0)
PLX-046	466	(100)	No	21	(3.0)

* Saybolt universal seconds (SUS) at 99°C (210°F), or centistokes (CST) at 100°C (212°F).

The following observations were made from these tests and the results shown in Table 4-5:

1. Suspended solids are not necessary,
2. Higher molecular weight has a slight beneficial effect,
3. Performance of the 40 series, except for PLX-046, exceeds the design requirement of 30 MPa (4.3 ksi) by more than 100%, and

4. Full-scale geothermal drilling tests should be run on at least two of the high-viscosity oils, as well as on Geobond oil and Geobond grease.

Note: PLX-046 was formulated with a very-high-viscosity, high-molecular-weight base oil.

The most successful lubricants developed by Pacer during this project are listed in Table 4-6, along with the performance criteria established by tests on a conventional bit lubricant. Full-scale drilling tests were recommended for any of the six Pacer products in Table 4-6.

The seal design and testing phase and the lubricant testing phase of the project were completed, and a final report was published separately.

Table 4-6

Lubricants Recommended for Field Testing

<u>Designation</u>	<u>Type</u>	Viscosity ^{**} <u>SUS (CST)</u> <u>or Weight</u>	Elastomer Compatibility <u>at Temperature</u>	<u>Suspended</u> <u>Solids</u>	<u>Test</u> <u>Temperature</u>		<u>Load</u> <u>Capacity</u>		<u>Number</u> <u>of</u> <u>Tests</u>
					<u>°C</u>	<u>(°F)</u>	<u>MPa</u>	<u>(ksi)</u>	
Conventional bit lubricant	Grease	NLGI No. 1	No	Yes	30	(86)	30	(4.3)	4
PLX - 014	Oil	190 (40.4)	Yes	Yes	316	(600)	73	(10.6)	15
PLX - 014	Grease*	NLGI No. 2	Yes	Yes	316	(600)	62	(9.0)	10
PLX - 022	Oil	180 (38.3)	No	Yes	316	(600)	81	(11.7)	12
PLX - 024	Oil	286 (61.4)	Yes	Yes	316	(600)	69	(10.0)	3
PLX - 043	Oil	290 (62.1)	Yes	No	316	(600)	63	(9.1)	2
PLX - 045	Oil	313 (67.5)	Yes	No	316	(600)	69	(10.0)	2

* Available commercially as Geobond grease.

** Saybolt universal seconds at 99°C (210°F), or centistokes at 100°C (212°F).

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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

4.3 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 30 November 1980
Contract Number: DE-AC04-76ET27142
Technical Consultant: D. Wesenberg (505) 844-0129

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, 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 was established for the performance of full-scale bits. This capability was demonstrated with laboratory testing of full bits. Single-cutter tests were run at simulated downhole conditions, and the data were analyzed. The redesign and fabrication of the S-1, modified, bit, necessitated by the catastrophic failure during the November 1978 field test, was 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. Third generation bits, S-2A and S-2B, were designed for additional field testing. The S-2A bits were fabricated and tested in the Baca field using aerated water as the drilling fluid. The S-2B bits are being fabricated for drilling in air in The Geysers, California.

FY80 Progress

Baca Field Tests of Second-Generation Bits — Both the C-1 hard-matrix and the S-1, modified, steel-bodied PDC bits were tested at a location in the Baca field in New Mexico in October 1979. Testing was in andesite, the basement formation for the geothermal wells being drilled by the Union Geothermal Company of New Mexico. Testing was at a depth 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.

One PDC cutter was lost, and most of the remaining wear was on the gage of the bit. Some stud chipping was experienced, but there was no catastrophic failure like that which occurred when the original S-1 bit was tested in 1978.

Bit Performance — Both experimental geothermal PDC bits were returned to GE (CRD), Schenectady, New York, following the October field tests. A detailed wear examination was carried out to assist in the redesign for the two bits fabricated and tested in the final phase of this project. Only six cutters on bit S-1, modified, showed significant wear. One Stratapax™ blank, lost due to a fracture that 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.

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 was refined by the bit manufacturer after 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 was 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 was to identify the penetration rate/bit-life target for the third-generation field test. The analysis indicated 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 drilling economic analysis will be expanded by utilizing the computer-based, geothermal well, cost-simulation technique developed by Sandia. Work on this phase of the project is being coordinated with Sandia.

A firm agreement was reached with Union Oil Company to run the third 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 was 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 was provided.

The bit performance results obtained during drilling in the Baca field, New Mexico, indicated 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 would 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.

The 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 a Sandia project at Terra Tek, Salt Lake City, Utah. These full-scale laboratory drilling tests at Terra Tek in a parallel project provided valuable Stratapax™ drill blank wear and cutter geometry information pertinent to the design of the third-generation geothermal bits. 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 that 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, using 260°C (500°F) air at 25.3 m³/min (1000 ft³/min),

produced diamond layer spalling and severe wear for all the -7° -back-rake gage cutters. Four holes drilled under the same conditions produced no apparent wear of the -25° -back-rake cutters on the S-1, modified, steel-bodied, stud-type bit.

Design Modifications -- Based on these experimental results, the designs for the third-generation bits targeted for the Baca field, New Mexico, and The Geysers, California, were 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 had a surplus of these studs and furnished one hundred at cost. Sandia also supplied an additional 20.

Purchase orders were placed with SII Smith Tool, Irvine, California, for four steel-body, stud-type, geothermal, Stratapax™ bits that were utilized in the field tests of the final phase of this program. The four steel-body, stud-type, Stratapax™ bits incorporated eight changes to the S-1, modified, design, aimed at reducing cutter and gage wear but retaining the basic cutting structure that performed well in the Baca field test in October 1979. The eight changes were as follows:

1. Twenty-six cutters, Nos. 13 through 38, were attached to -25° -back-rake, -25° -end-clearance, cemented, tungsten carbide studs, replacing the -20° -back-rake, 5° -end-clearance studs used previously. Figure 4-9 identifies cutter locations and Figures 4-10 and 4-11 give the stud specifications.
2. The positions of cutters Nos. 31 through 34 were moved slightly, both radially and vertically, to obtain better bottomhole coverage and eliminate the tracking configuration used originally. Figure 4-12 shows the original cutter profile.
3. The eight No. 2399 Stratapax™ blanks that were mounted flush with the bit side-ribs to serve as wear pads have been increased to 16 blanks per bit, mounted in groups of four. In addition, four No. 2399 Stratapax™ blanks per bit were pressed into the junk slot walls so that the diamond layers extend past the bit body outside surface. These were ground flush with the bit body to act as trimmers to maintain the hole gage.
4. Four larger, No. 2532, stud-mounted Stratapax™ gage trimmers, shown in Figure 4-13, were press-fitted into the sides of each bit.
5. The bit body corners behind cutters Nos. 35 through 38 were relieved, and additional junk slots were provided to improve the cooling of these diamond compact cutters.
6. The maximum cutter stand-off, i.e., the height above the bit body, was reduced from 13.20 mm to 8.89 mm (0.520 in. to 0.350 in.), using Smith Tool's eccentric counter-bore technique.* This change

*William Baker, "Design Considerations for Stud-Type Stratapax™ Blank Bits," SII Smith Tool, Irvine, CA, presented at the Energy-Sources Technology Conference and Exhibition, 3-7 February 1980, New Orleans, LA.

CUTTERS No. 1-12 : -20° BACK RAKE, 5° END CLEARANCE
 CUTTERS No. 13-38: -25° BACK RAKE, -25° END CLEARANCE

Figure 4-9. New Type No. S-2. Modification B, Stratapax™ Bit Design

MATERIAL: CARBOLOY GRADE 55B

Figure 4-10. Cutter Stud Specifications; -25° Back Rake, -25° End Clearance

MATERIAL: CARBOLOY GRADE 55B

Figure 4-11. Cutter Stud Specification; -20° Back Rake, 5° End Clearance

Figure 4-12. Cross Section of Half of Bit S-1 Showing Original Profile of Cutter Envelope. Four cutters, 31 through 34, were repositioned in the S-2 design to obtain improved coverage and eliminate "tracking."

Figure 4-13. No. 2532 Stratapax™ Blank Trimmer and Stud

increased the stud support and reduced the chance of stud breakage without significantly reducing the maximum theoretical bit penetration rate.

7. Nozzle attachment was improved to assure that no nozzles can become detached during drilling.
8. For two of the four bits, cutters Nos. 35 through 38 were located so that the edge of the Stratapax™ diamond layer is tangent to the outside diameter of the bit. These bits were designated Type No. S-2, modification A. On the remaining two bits, cutters Nos. 35 through 38 were located so that the edge of the Stratapax™ diamond layer extends at least 1.27 mm (0.050 in.) beyond the outside diameter of the cutter press fitting. These cutters were then ground so that the flat edge that is generated was on gage. These bits were designated Type No. S-2, modification B.

The two No. S-2A bits were fabricated for testing in the Baca field, New Mexico, and the two No. S-2B bits were designated for field tests in air at The Geysers, California. One additional modification was made to both bit types; one more Stratapax™ blank cutter with a -25° rake was added to the primary cutting structure in order to maintain a uniform bottomhole cutting profile while the bit is increased to 22.2 cm (8.75 in.) diameter.

The additional funding necessary to fabricate two more bits than were originally planned for this program was made available. Christensen, Inc., fabricated the two 22.2-cm (8.75-in.) Stratapax™ bits of matrix design. Christensen made design modifications to their basic JD-26, 10-wing-bit design; the modifications included extending the Stratapax™ blanks down the gage and enlarging the total nozzle area to reduce the bit pressure drop to the low values required for air and aerated-water drilling. These bits were constructed to give a direct comparison between the stud-mounted design and the matrix-mounted design.

The field tests in the Baca field, New Mexico, were originally scheduled for July by Union Geothermal Company of New Mexico. Due to unavoidable delays, however, the project schedule had to be extended. Because experimental tasks other than the final field testing phase were completed, preparation of a draft final report was initiated.

At the request of Smith Tool, Irvine, California, assistance and instruction on interference fitting of the -25°-back-rake, -25°-end-clearance Stratapax™ cutter/cemented carbide stud assembly into steel bit bodies was provided. The 5°-end-clearance stud, which has a flat tip, causes no press fitting problem for Smith Tool, but the additional 20° of end clearance plus the rounded tip on SNL's stud design requires some special tooling and the pressing technique developed at SNL. These methods were developed by Sandia and used by Smith Tool on 26 June 1980.

No significant difficulties were encountered during the pressing of the -25°-back-rake cutter/stud assemblies into the bit body, even with the higher diametrical interference required for a geothermal bit as compared to that needed for an oil/gas bit that would operate at considerably lower bottomhole temperatures. The S-2A bit design incorporates the Smith Tool

eccentric counterbore design to reduce cutter standoff; this feature causes the carbide stud to be unequally loaded when pressing is initiated, resulting in a tendency for the stud to tip forward. A technique to correct this was quickly developed, and 22 of the 25 -25°-back-rake cutter assemblies were pressed into the bit without difficulty and without any apparent damage to the PDCs or the carbide studs. Three cutters were not attached, because it was thought that there might be errors in hole positioning. A subsequent check at Smith Tool showed this was not the case.

The two 8-3/4 in.-diameter, S-2A, Stratapax™ geothermal bits targeted for testing in the Baca field, New Mexico, were completed by Smith Tool and, with their special bit breaker, were delivered to Union Geothermal Company of New Mexico. The fabrication of the two S-2B Stratapax™ bits to be used in The Geysers California for testing in air, was nearing completion. The bits will be sent to Union Geothermal, Santa Rosa, California.

Field Tests of Third-Generation Bits — The field test of the third-generation bit, S-2A, was attempted in the Baca field, New Mexico, in August 1980. However, the drilling performance was unsatisfactory, and the testing was terminated. Investigations are under way, to include laboratory tests at DRL to determine the reasons for the drilling problems encountered. The results of these investigations will be reported in the next progress report. The field tests in The Geysers KGRA are being rescheduled so that the findings of the on-going investigations may be utilized, if applicable, prior to the S-2B bit tests.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	★												END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>PDC WEAR MECHANISMS</u> <u>TEST SUPPORT</u> <u>GENERAL ELECTRIC</u> EFFECTS OF DRILLING FLUIDS ROCK FRACTURE/CUTTER WEAR CONSULTATION FINAL REPORT	<p>The chart displays the following activity periods and completion status:</p> <ul style="list-style-type: none"> PDC WEAR MECHANISMS TEST SUPPORT GENERAL ELECTRIC: Activity period from October 1980 to August 1981. Started in November 1980. Completed in August 1981. EFFECTS OF DRILLING FLUIDS: Activity period from November 1980 to August 1981. Started in November 1980. Completed in August 1981. ROCK FRACTURE/CUTTER WEAR CONSULTATION: Activity period from November 1980 to August 1981. Started in November 1980. Completed in August 1981. FINAL REPORT: Activity period from November 1980 to August 1981. Started in November 1980. Completed in August 1981. 												JAN 81

LEGEND:

ACTIVITY PERIOD
RESCHEDULED

○ PLANNED START
● STARTED

▽ PLANNED COMPLETION
▼ COMPLETED

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

Contractor: General Electric Company, CRD
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: D. Wesenberg (505) 844-0129

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 was completed. Preparation of the test facilities and equipment was completed, and the single-cutter experiments were initiated. Procurement of three rock types for use in the PDC cutter tests was completed.

FY80 Progress

Air Drilling Experiments — 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-in.) diameter Stratapax™ steel-bodied, stud-type bit, designated S-1, modified, which was designed, fabricated, and successfully tested in the field, was used for full-scale laboratory drilling. This bit, together with three spare Stratapax™ cutter/stud assemblies, was shipped to Sandia, where several worn cutters on the bit were replaced.

Full-scale drilling tests using preheated air as the drilling fluid to simulate The Geysers, California, conditions were conducted in February 1980 at the DRL, Terra Tek, Inc., Salt Lake City, Utah. The test data were analyzed, wear characteristics studied, and recommendations developed for improving Stratapax™ geothermal bit design.

Two 21.6-cm (8.5-in.) diameter Stratapax™ bits were tested. The first was a hard-matrix bit provided by the Diamond Technology Center, Christensen, Inc., Salt Lake City, Utah. The bit was a five-wing Christensen, type JD 23-P, that is designed for use with a downhole motor

to drill relatively soft, plastic formations such as shale. The back rake for the diamond compact cutters was -7° . Natural diamond stones, 2 stones/carats, were mounted on the gage. The bit face had nine fluid ports with a total nozzle area of $6.5 \times 10^{-4} \text{ m}^2$ (1 in.²).

The second bit tested was the S-1, modified, steel-body, stud-type, Stratapax™ bit fabricated by Smith Tool, Irvine, California, and successfully tested in October 1979 in the Baca field, New Mexico. This bit was rebuilt at SNL. Seven worn Stratapax™ cutters were removed and replaced with new Stratapax™/stud assemblies, which included two -25° -back-rake steel studs with diffusion-bonded cutters. The assemblies included three -25° -back-rake tungsten carbide studs with LS* (brazed) bonded cutters and two of the older style -20° -back-rake tungsten carbide studs with LS* (brazed) bonded cutters. This latter stud design and cutter attachment was the one used initially for this bit; hence, the cutting structure of the rebuilt bit consisted of 33 -20° -back-rake brazed cutters, 3 -25° -back-rake brazed cutters, and 2 -25° -back-rake diffusion-bonded cutters. Figure 4-14 shows the cutting structure of the bit with the locations of the cutters installed by Sandia. Figures 4-10 and 4-11 in Section 4.3 illustrate the stud designs used.

The air for the drilling experiments was obtained from a compressor provided by the Western Air Drilling Service Co., Grand Junction, Colorado. An air flow of $0.94 \text{ m}^3/\text{s}$ (2000 ft³/min) was desired to fully simulate The Geysers drilling conditions. However, the pressure in the system had to be kept at 1.7 MPa (250 psi) or less in order to avoid damaging the gas heat exchanger and the drilling swivel. Therefore, the air flow was a maximum of $0.46 \text{ m}^3/\text{s}$ (983 ft³/min), with most tests being run at $0.43 \text{ m}^3/\text{s}$ (916 ft³/min). A maximum input air temperature of 263°C (505°F) was obtained, which is near The Geysers' bottomhole temperature.

Three rock types were used: Carthage marble, Nugget sandstone, and Sierra white granite. The principal rock of interest was the sandstone, because of its abrasiveness and its moderately high strength and ultimate compressive strength of approximately 124 MPa (18 000 psi). The granite was used to test the stud-type bit to destruction after the sandstone experiments were completed.

* Christensen JD 23-P Bit Tests

The JD 23-P bit was tested in marble first and, subsequently, in Nugget sandstone. Three levels of speed and weight on bit were used. The results of these experiments are summarized in Table 4-7. The penetration rate-weight on bit relationships are shown in Figure 4-15. The bit performed well in both rocks and, in the sandstone, attained a maximum drilling rate of 26.1 m/h (85.7 ft/h) at 50 rpm and a weight on bit of 44.5 kN (10 000 lb). However, severe damage was done to the five-gage Stratapax™ cutters after the drilling of a single hole approximately 0.9 metre (3 feet) deep in the sandstone. These cutters were badly spalled in the

* LS bonding is a brazing process that incorporates cooling of the Stratapax™ compacts as the compacts are induction-brazed to the tungsten carbide studs.

WC = TUNGSTEN CARBIDE

LS BRAZE = SEE FOOTNOTE PAGE 86

Figure 4-14. S-1, Modified, Stratapax™ Bit Showing Cutter and Nozzle Locations and Identifying the Cutters and Studs Replaced prior to Hot Air Drilling Tests

Table 4-7

JD 23-P Hard-Matrix StratapaxTM Bit Air Drilling Test Results

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit N x 10 ³ (lb x 10 ³)		Penetration Rate m/h (ft/h)		Torque N·m (lbf·ft)		Air		Flow m/s (ft ³ /min)
										Temperature °C (°F)		
1	Carthage marble	1	25	22.2	(5.0)	9.1	(30.0)	2 034	(1 500)	220	(428)	0.45 (950)
			25	33.4	(7.5)	12.3	(40.2)	3 051	(2 250)	207	(405)	0.45 (950)
			25	44.5	(10.0)	13.8	(45.4)	4 406	(3 250)	204	(399)	0.45 (950)
1	Carthage marble	1	38	22.2	(5.0)	10.5	(34.5)	2 102	(1 550)	205	(401)	0.45 (950)
			38	33.4	(7.5)	16.0	(52.5)	3 186	(2 350)	205	(401)	0.45 (950)
			38	44.5	(10.0)	20.1	(66.0)	4 067	(3 000)	205	(401)	0.45 (950)
1	Carthage marble	1	49	22.2	(5.0)	14.1	(46.3)	2 034	(1 500)	206	(403)	0.45 (950)
			49	33.4	(7.5)	22.2	(72.8)	3 118	(2 300)	206	(403)	0.45 (950)
2	Nugget sandstone	1	25	22.2	(5.0)	8.8	(29.0)	2 305	(1 700)	248	(478)	0.46 (983)
			25	33.4	(7.5)	14.6	(48.0)	3 390	(2 500)	248	(478)	0.46 (983)
			25	44.5	(10.0)	17.4	(57.1)	4 067	(3 000)	248	(478)	0.46 (983)
2	Nugget sandstone	1	38	22.2	(5.0)	7.6	(24.8)	2 373	(1 750)	249	(480)	0.46 (983)
			38	33.4	(7.5)	15.9	(52.2)	4 203	(3 100)	249	(480)	0.46 (983)
			38	44.5	(10.0)	21.5	(70.6)	5 423	(4 000)	248	(478)	0.46 (983)
2	Nugget sandstone	1	50	22.2	(5.0)	8.3	(27.3)	2 034	(1 500)	249	(480)	0.46 (983)
			50	33.4	(7.5)	18.9	(62.1)	3 796	(2 800)	249	(480)	0.46 (983)
			50	44.5	(10.0)	26.1	(85.7)	5 152	(3 800)	249	(480)	0.46 (983)

Figure 4-15. Penetration Rate versus Weight on Bit Test Results for Christensen JD 23-P Bit Drilling Carthage Marble and Nugget Sandstone

diamond layer and markedly worn. No other diamond compact cutters in this bit exhibited any damage. The spalling damage was apparently due to insufficient negative rake, which failed to keep the brittle diamond layer in compression.

After the gage cutter wear was observed, no further testing was done with the hard-matrix Stratapax™ bit in order to avoid damaging it beyond repair.

• S-1, Modified, Bit Tests

The stud-type, steel-body bit was tested using all three rock types. One hole was drilled in Carthage marble, four holes in Nugget sandstone, and two in Sierra white granite. All the S-1 bit tests were run with a $0.43\text{-m}^3/\text{s}$ ($916\text{-ft}^3/\text{min}$) air flow, with the input air temperature maintained in the 240° to 263°C (464° to 505°F) range in most cases.

The Carthage marble results and the results of the first test in Nugget sandstone are summarized in Table 4-8. Three speeds were used, and weight on bit was varied from a minimum of 17.8 kN (4000 lb) in marble to a maximum of 77.8 kN (17 500 lb) in sandstone. The penetration rate/weight-on-bit relationships are shown in Figures 4-16 and 4-17.

No diamond compact cutter wear was observed after the first hole was drilled in the sandstone. Therefore, three more holes were drilled in an effort to create some measurable wear. These tests were performed at 50 rpm, with constant weight on bit. One hole was drilled with 44.5 kN (10 000 lb) on the bit, followed by two holes with 66.7 kN (15 000 lb) on the bit. For each of these constant-speed, constant-weight-on-bit tests, the penetration rate gradually and steadily decreased as the hole depth increased. This result is illustrated in Table 4-9, where the penetration rate is given for the first and last 10.2 cm (4 in.) drilled in each instance. After the completion of the fourth hole in sandstone, the bit was removed from the drill stand for examination. Again, no measurable wear of the diamond compacts was apparent. The -25° -back-rake cutters on the gage (cutters Nos. 35, 36, 37, and 38) were still sharp and in essentially new condition. Thus, cutter dulling was not responsible for the decreasing penetration rates. However, a significant degree of carbide-stud wear for cutters on the crown of the bit had taken place. For example, the stud for cutter No. 24, which was a new, -20° -rake stud, was markedly worn on one side, behind the Stratapax™ blank. Other studs on the crown showed similar wear patterns. Apparently the development of wear flats on these studs, which do not have sufficient end and side clearance, was partly responsible for reducing the penetration rate. Examination of the data in Table 4-9, tests Nos. 6 and 7, might also lead to the conclusion that the lower section of the sandstone block was harder than the upper portion.

The S-1, modified, bit was then tested by drilling Sierra white granite. Two holes were drilled, each at two speeds (25 and 50 rpm) at weights on bit from 44.5 to 155.7 kN (10 000 to 35 000 lb). The test results are summarized in Table 4-10. The bit drilled the first hole slowly (Test No. 8). Examination of the bit after the drilling of this hole showed the development of significant wear of some of the diamond compact cutters. There was some localized bluing of the bit body near the gage, indicating

Table 4-8

S-1, Modified, StratapaxTM Bit Air Drilling Test Results
for Variable Speeds and Weights on Bit

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit		Penetration Rate		Torque		Temperature		Air	
				N x 10 ³	(lb x 10 ³)	m/h	(ft/h)	N·m	(lbf·ft)	°C	(°F)	m ³ /s	(ft ³ /min)
3	Carthage marble	2	25	17.8	(4.0)	2.7	(8.7)	1 152	(850)	249	(480)	0.43	(916)
			25	26.7	(6.0)	4.1	(13.4)	1 491	(1 100)	249	(480)	0.43	(916)
			25	35.6	(8.0)	5.0	(16.5)	1 898	(1 400)	249	(480)	0.43	(916)
			25	44.5	(10.0)	6.0	(19.7)	2 441	(1 800)	249	(480)	0.43	(916)
			25	53.4	(12.0)	7.2	(23.7)	2 847	(2 100)	249	(480)	0.43	(916)
3	Carthage marble	2	38	17.8	(4.0)	2.7	(8.8)	881	(650)	252	(486)	0.43	(916)
			38	26.7	(6.0)	3.5	(11.5)	1 152	(850)	252	(486)	0.43	(916)
			38	35.6	(8.0)	5.1	(16.7)	1 559	(1 150)	252	(486)	0.43	(916)
			38	44.5	(10.0)	6.9	(22.5)	2 034	(1 500)	252	(486)	0.43	(916)
			38	53.4	(12.0)	8.8	(28.8)	2 576	(1 900)	252	(486)	0.43	(916)
3	Carthage marble	2	50	17.8	(4.0)	3.9	(12.8)	814	(600)	257	(495)	0.43	(916)
			50	26.7	(6.0)	4.7	(15.3)	1 085	(800)	257	(495)	0.43	(916)
			50	35.6	(8.0)	6.3	(20.6)	1 491	(1 100)	257	(495)	0.43	(916)
			50	44.5	(10.0)	8.5	(27.9)	1 898	(1 400)	257	(495)	0.43	(916)
			50	53.4	(12.0)	12.5	(41.1)	2 576	(1 900)	257	(495)	0.43	(916)
			50	62.3	(14.0)	13.7	(45.0)	2 983	(2 200)	257	(495)	0.43	(916)
4	Nugget sandstone	2	25	26.7	(6.0)	1.6	(5.3)	1 288	(950)	258	(496)	0.43	(916)
			25	44.5	(10.0)	5.8	(18.9)	2 712	(2 000)	258	(496)	0.43	(916)
			25	55.6	(12.5)	8.6	(28.1)	3 457	(2 550)	258	(496)	0.43	(916)
			25	66.7	(15.0)	10.7	(35.0)	4 203	(3 100)	258	(496)	0.43	(916)
4	Nugget sandstone	2	38	26.7	(6.0)	4.1	(13.6)	1 356	(1 000)	260	(500)	0.43	(916)
			38	44.5	(10.0)	7.9	(25.9)	2 305	(1 700)	260	(500)	0.43	(916)
			38	55.6	(12.5)	11.9	(39.1)	3 118	(2 300)	260	(500)	0.43	(916)
			38	66.7	(15.0)	16.1	(52.9)	3 864	(2 850)	260	(500)	0.43	(916)
4	Nugget sandstone	2	50	26.7	(6.0)	4.4	(14.4)	1 356	(1 000)	260	(500)	0.43	(916)
			50	44.5	(10.0)	8.2	(26.9)	2 102	(1 550)	260	(500)	0.43	(916)
			50	55.6	(12.5)	15.0	(49.3)	2 983	(2 200)	260	(500)	0.43	(916)
			50	66.7	(15.0)	18.6	(61.0)	3 661	(2 700)	260	(500)	0.43	(916)
			50	77.8	(17.5)	22.9	(75.0)	4 474	(3 300)	260	(500)	0.43	(916)

Figure 4-16. Penetration Rate versus Weight on Bit Test Results for S-1, Modified, Bit Drilling Carthage Marble

Figure 4-17. Penetration Rate versus Weight on Bit Test Results for S-1, Modified, Bit Drilling Nugget Sandstone

Table 4-9

S-1, Modified, StratapaxTM Bit Air Drilling Tests in
Nugget Sandstone at Constant Speed and Constant Weight on Bit

Test No.	Hole No.	Section of Hole	Speed rpm	Weight on Bit		Penetration Rate m/h (ft/h)	Torque		Temperature		Air	
				N x 10 ³	(lb x 10 ³)		N·m	(lbf·ft)	°C	(°F)	m ³ /s	Flow (ft ³ /min)
5	3	First 10.2 cm (4 in.)	50	44.5	(10)	8.6 (28.1)	2 034	(1 500)	262	(504)	0.43	(916)
5	3	Last 10.2 cm (4 in.)	50	44.5	(10)	5.4 (17.8)	1 627	(1 200)	262	(504)	0.43	(916)
6	4	First 10.2 cm (4 in.)	50	66.7	(15)	18.0 (59.0)	3 390	(2 500)	259	(498)	0.43	(916)
6	4	Last 10.2 cm (4 in.)	50	66.7	(15)	11.2 (36.7)	2 644	(1 950)	261	(502)	0.43	(916)
7	5	First 10.2 cm (4 in.)	50	66.7	(15)	14.6 (48.0)	3 118	(2 300)	263	(505)	0.43	(916)
7	5	Last 10.2 cm (4 in.)	50	66.7	(15)	8.8 (28.8)	2 169	(1 600)	263	(505)	0.43	(916)

that high frictional heat was generated. The conditions used for Test No. 8 were repeated for the second hole in the granite. The data in Table 4-10 show that the bit began to fail catastrophically at 50 rpm and 155.7 kN (35 000 lb) weight on bit. Examination of the bit after Test No. 9 showed that 12 Stratapax™ drill blanks had become detached. Eleven of these cutters were recovered intact from a parking lot adjacent to the test site, where the hot air exhaust had ejected them.

The condition of the four gage cutters, Nos. 35, 36, 37, and 38, indicated that the bit may not have been running true. Both Stratapax™ cutters that were diffusion-bonded to the -25°-rake steel studs were still attached. However, diamond compact No. 37 was approximately one-third worn away, while the corresponding cutter (No. 35), 180° removed from it, was no more worn than it was following the Nugget sandstone tests. In addition, this cutter was still "on-gage." The two -25°-gage cutters brazed to tungsten carbide studs (Nos. 36 and 38) were similarly worn. Cutter No. 36 was missing, and the stud was badly worn. The opposite cutter (No. 38) was still attached and showed a relatively small wear flat. Figure 4-18 shows the locations of the cutters that became detached. Note that 7 of the 12 lost cutters were located between Nos. 34 and 36 inclusive, only slightly more than a 90° sector of the bit circumference. This portion of the bit showed the maximum discoloration due to overheating.

Examination of the recovered Stratapax™ drill blanks and the studs without cutters showed residual braze material on both the compact substrates and the studs. Apparently the bonds failed primarily within the braze line. The 11 Stratapax™ drill blanks that were detached were inspected ultrasonically for thermal degradation of the sintered diamond layer. No bulk thermal damage was detected--a promising and necessary condition for the successful application of diamond compacts to air drilling systems.

Most of the studs that lost their cutters had large wear flats on the ends. This condition was most pronounced for studs Nos. 17 through 21 on the crown of the bit and Nos. 30 through 34 nearer the gage. In contrast to similar cases of stud wear developed under drilling conditions using water or mud, there were no thermally generated heat check cracks in the studs. In addition, there were no cases of stud fracture and carbide spalling. Apparently the bulk temperature of the studs was high enough to prevent the difference between the surface and bulk temperature from becoming great enough to cause surface tensile failure.

Several of the diamond compacts were examined using scanning electron microscopy, and failure by shear in the braze alloy was confirmed. No evidence of failure by oxidation or fatigue was observed, and no visible evidence that failure occurred within the cemented tungsten carbide studs or drill blank substrates was detected.

The Stratapax™ drill blanks that became detached while drilling the Sierra white granite were ejected from the drilling system so rapidly that the fine structure of the braze attached to the cutters was not damaged by the accompanying rock particles. Further study of these specimens may provide additional useful information for improving the brazing attachment technology for diamond compacts.

Table 4-10

S-1, Modified, StratapaxTM Bit Air Drilling Tests
in Sierra White Granite

Test No.	Rock Type	Hole No.	Speed rpm	Weight on Bit		Penetration Rate		Torque		Air Temperature		Air Flow	
				N x 10 ³	(lb x 10 ³)	m/h	(ft/h)	N·m	(lbf·ft)	°C	(°F)	m ³ /s	(ft ³ /min)
8	Sierra white granite	1	25	44.5	(10)	1.3	(4.2)	1 763	(1 300)	251	(484)	0.43	(916)
			25	66.7	(15)	2.0	(6.4)	2 508	(1 850)	164**	(327)	0.43	(916)
			25	89.0	(15)	2.5	(8.3)	3 254	(2 400)	220	(428)	0.43	(916)
								to 3 279	to (2 750)*				
			25	111.2	(25)	3.2	(10.6)	4 610	(3 400)	231	(448)	0.43	(916)
8	Sierra white granite	1	50	66.7	(15)	2.2	(7.3)	1 966	(1 450)	246	(475)	0.43	(916)
			50	89.0	(20)	2.9	(9.6)	2 644	(1 950)	250	(482)	0.43	(916)
			50	111.2	(25)	3.6	(11.8)	3 186	(2 350)	250	(482)	0.43	(916)
			50	133.5	(30)	4.5	(14.6)	3 729	(2 750)	253	(487)	0.43	(916)
9	Sierra white granite	2	25	44.5	(10)	0.4	(1.4)	1 763	(1 300)	237	(459)	0.43	(916)
			25	66.7	(15)	0.5	(1.7)	2 983	(2 200)	240	(464)	0.43	(916)
			25	89.0	(20)	1.2	(4.1)	3 864	(2 850)	243	(469)	0.43	(916)
			25	111.2	(25)	1.7	(5.6)	4 610	(3 400)	237	(459)	0.43	(916)
9	Sierra white granite	2	50	89.0	(20)	1.7	(5.5)	2 847	(2 100)	246	(475)	0.43	(916)
			50	111.2	(25)	2.0	(6.5)	3 932	(2 900)	246	(475)	0.43	(916)
								to 4 203	to (3 100)*				
			50	133.5	(30)	2.1	(6.8)	4 406	(3 250)	240	(464)	0.43	(916)
			50	155.7	(35)	1.9	(6.3)	4 610	(3 400)	240	(464)	0.43	(916)
								to 4 745	to (3 500)*				
			50	133.5	(30)	0.7	(2.2)	4 068	(3 000)	240	(464)	0.43	(916)
								to 4 406	to (3 250)*				
			50	155.7	(35)	0.7	(2.3)	4 406	(3 250)	240	(464)	0.43	(916)

*Torque was erratic at these operating conditions.
**Flame-out in gas fired heat exchanger.

CUTTERS DETACHED			
-20° WC STUDS		-25° WC STUDS	
LS BRAZE		LS BRAZE	
16	21	32	
17	30	36	
18	31		
19	33		
20	34		

Figure 4-18. Location of 12 Stratapax™ Cutters Detached from S-1, Modified, Bit During Test No. 9

• Torque Measurements

Although the principal objectives of the air drilling tests were to determine the wear characteristics and the potential failure mechanisms of Stratapax™ drag bits under very harsh conditions, the torques generated by the two bits provide some interesting comparisons.

The torque values for the JD 23-P hard-matrix bit drilling the relatively soft Carthage marble were significantly lower than those generated by the stud-type bit. This is shown by graph in Figures 4-19 and 4-20. This result was not unexpected, because Christensen has shown that decreasing the cutter back rake increases cutter efficiency and reduces rock-cutting forces when soft formations are drilled.

The torque advantage for the -7° -back-rake cutters on the hard-matrix bit was eliminated when the rock was changed to the harder, more brittle sandstone. Figures 4-21 and 4-22 are plots of all the data points taken for both bits at rotary speeds of 38 and 50 rpm. At these speeds, the torque-penetration rate relationship is essentially identical for the two bits. Because diamond layer spalling was obtained with the -7° cutters after only 0.91 metre (3 feet) of drilling, it appears that the greater back-rake cutter should be utilized for drilling sandstone formations, such as the graywacke in The Geysers.

• Conclusions and Recommendations

The preliminary conclusions and recommendations, based on these limited air drilling experiments, are as follows:

1. The -25° -back-rake cutters were superior in wear and chipping resistance to the -7° cutters when abrasive, relatively hard sandstone was drilled. The -25° -rake angle may be superior to the -20° -rake cutter, particularly for gage cutter application, and will be used for the third-generation geothermal bits in the bit development program.
2. The Sandia stud design, with the greatly increased end and side clearance, should be used wherever possible. Insufficient clearance leads to early rubbing and wear of the studs against rock, increasing frictional heat generation, reducing attachment life, reducing penetration rate, increasing torque, and increasing the chances for stud fracture.
3. The performance of the S-1, modified, bit during the air drilling of the Nugget sandstone, was promising; especially promising was the apparent high wear resistance of the diamond compacts under very hot conditions. The test results indicate that a stud-type Stratapax™ bit has a good chance of performing well in The Geysers, providing that the bit design includes the high-clearance-type studs to permit reasonable cutter wear without the development of large tungsten carbide wear surfaces.
4. The hot air drilling experiment in the granite took place in a severe test environment. There are currently no applications for deep-hole drilling of granite with diamond compact bits using only air. The objective of the granite test was to wear the bit

Figure 4-19. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Carthage Marble; 25 rpm

Figure 4-20. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Carthage Marble; 50 rpm

Figure 4-21. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Nugget Sandstone; 38 rpm

Figure 4-22. Torque versus Penetration Rate Test Results for S-1, Modified, and JD 23-P Bits Drilling Nugget Sandstone; 50 rpm

rapidly so that the effect of wear on bit performance and bit integrity could be evaluated in a reasonable rock, such as the sandstone. Drilling granite with hot air caused catastrophic failure and termination of the experiments. If this kind of testing is done again, drilling in granite should be carried out using water, followed by hot air testing in sandstone.

5. The performance of the steel studs with the diffusion-bonded cutters was promising but not conclusive, because only two steel-stud-supported cutters were used. Testing should be continued using a bit constructed entirely with steel studs, with both diffusion- and braze-bonded cutters. Steel studs are attractive from the point of view of ease of manufacture, economy, and the ease of replacement in the bit body. However, application areas should be chosen with care. Erosive drilling conditions will destroy steel studs far faster than they will destroy cemented tungsten carbide studs.
6. The "LS"-type braze attachment failures apparently occurred within the bond line. The exact failure mechanism is not clear and should be identified, if possible. Appropriate research will be undertaken as part of this program.

Laboratory Rock Cutting Studies — Installation of the equipment needed to perform the laboratory cutting tests was completed on schedule. The wiring of the 54-inch, vertical-turret lathe was completed, and the machine is operational. The designing of rock-cutting tooling for the lathe, including tooling necessary for force measurements as well as rock fixturing and rock handling, was completed, and fabrication of the tooling is under way. All worn lathe parts were replaced. The lathe was evaluated by dry-cutting Nugget sandstone and is operating satisfactorily. All the special tooling necessary to utilize Stratapax™ PDC cutters on this machine was finished.

The 54-inch, vertical-turret lathe, 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 that was used in the past. The smaller instrumented lathe was relocated and will be used for more delicate experiments such as the rock-cutting heat-generation determinations.

The mud circulation system to effect accurate control of the fluid flow rate and direction for mud circulation for the 54-inch, vertical-turret lathe was designed, fabricated, and installed. The 100-gallon-capacity tanks and the pumps are in place, and the special enclosure mounted on the machine to confine the fluid and return it to the tanks was installed. The wiring for the pumps was completed, and the fluid circulation system was tested and found to be functioning properly.

All the materials for suitable sepiolite- and bentonite-base mud compositions were obtained. The materials for a polymer-base fluid based on hydroxyethyl cellulose were ordered.

Controlling the flow rate and direction of the fluid in the mud circulation system is particularly important for the experiments aimed at determining diamond compact cutter heat generation. The design concepts for the

mud circulation system were reviewed by Sandia before the system was fabricated in order to assure that these experiments will provide usable information for Sandia's diamond compact cutter temperature modeling studies.

The Stratapax™ drill blanks, including some smaller blanks for friction measurements, the accompanying studs, and all the necessary rock materials were received.

With the 12-inch Pratt and Whitney lathe used to turn Jack Fork sandstone, preliminary rock-cutting experiments were carried out to establish the feasibility of utilizing small thermocouples inserted into the Stratapax™ cutter substrate and supporting stud to monitor tool temperature. Both dry and liquid-cooled tests were carried out successfully. Temperature data from four thermocouple locations were sampled continuously, using a Fluke 2240A data logger in conjunction with a Texas Instruments (T.I.) Silent 700 terminal equipped with magnetic tape. The data were recorded sequentially at a rate of five data points per second, stored on tape, and subsequently printed out using the T.I. terminal.

Because it will be necessary to obtain cutting-force measurements as well as temperature data, a special integrating circuit was designed to accept the piezoelectric dynamometer charge amplifier output, which is comprised of three force-component channels, and to then modify the signals so that they can also be recorded by the data logger/tape/terminal system. A prototype circuit was built and tested cutting rock. The performance was excellent, and the final three-channel device was constructed, checked out, and installed in the data collection system. The equipment necessary to measure and control mud properties such as mud weight and viscosity was obtained and set up. The mounting fixture for the piezoelectric dynamometer was finished and installed on the machine.

The details of the Stratapax™ cutter/stud design to be used, together with the preliminary specifications for "worn" cutters, were forwarded to Sandia for review and suggestions, particularly with regard to the precise locations of the thermocouples. 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 data collection technique for both cutting forces and tool temperatures was demonstrated, and the technical details and experimental plans for the rock-cutting experiments were reviewed.

Single-Cutter Experiments — Single-point rock-cutting experiments with Stratapax™ diamond compact tools using the 54-inch vertical-turret lathe were started in July. A total of 15 experiments cutting Nugget sandstone and Tennessee marble with sharp tools were completed. Tests were conducted dry and with water as a coolant. These are baseline experiments that must be completed prior to the investigating of cutting-tool temperatures with worn diamond compacts.

Of the 15 experiments completed, 5 are suspect because of difficulties encountered with the instrumentation, including erratic zero-voltage shifts in one of the charge amplifiers in the piezoelectric dynamometer system and

malfunctioning of the high-speed oscillograph recorder caused by high temperatures and excessive humidity in the rock drilling laboratory. The charge amplifier was replaced and a less sensitive pen-type recorder substituted for the oscillograph during the hot, humid period of the summer.

A set of five Stratapax™ cutters was prepared with which to perform the first cutting-tool temperature measurements. Three of these cutters are sharp, and two have been "pre-worn" by grinding back 1.2 mm (0.047 in.) on the diameter of the compact. Each tool has four 1.0-mm (0.040-in.) diameter holes, made by electrical discharge machining, in which to insert thermocouples at specific locations relative to the diamond cutting edge. A fifth thermocouple will be spot-welded to the back end of the cemented tungsten carbide stud to provide a reference ambient temperature data point. The thermocouple locations are shown in Figures 4-23 and 4-24. The first temperature measurements will be made as soon as the sharp cutter experiments described above are completed.

Each rock cutting test produces approximately 150 discrete sets of data, each consisting of up to nine values (a time value, three voltage values from the dynamometer, and five temperature values). Because it is impractical to handle this large volume of information manually, an existing computer program has been modified to take the taped data from the data logger and transform it into a data file that can be subsequently utilized with any desired computer program for data reduction. The modified program has been debugged, and processing of the data for the first 10 cutting experiments has been initiated.

Figure 4-23. Thermocouple Locations in a Worn Stratapax™-Stud Cutter

Figure 4-24. Thermocouple Locations in a Sharp Stratapax™-Stud Cutter

Blank

108a

5. DRILLING FLUIDS

Improved drilling fluids are needed 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 needed 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 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 determining any reduction in the corrosion of drill pipe with the use of N_2 as a drilling fluid, and of identifying and developing foam drilling fluids capable of operating in temperature environments to $310^{\circ}C$ ($590^{\circ}F$) and having chemical and foaming stability and anticorrosive and antioxidant properties. The demonstration of a technique of N_2 generation from diesel engine exhaust using a catalyst and the field testing of a high-temperature drilling mud, HTM-1, were successfully completed this fiscal year. 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 DRILLING FLUIDS</u>													START OCT 80
ADVANCED SCREENING													
CORROSION TESTS													
HIGH-TEMPERATURE STABILITY TESTS													

LEGEND: **ACTIVITY PERIOD**
 - - - - - **RESCHEDULED**

○ **PLANNED START**
 ● **STARTED**

▽ **PLANNED COMPLETION**
 ▼ **COMPLETED**

5.1 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 was issued defining the basic problems to be encountered, the various solutions thought to be obtainable, and a project procedure. The initial surfactant screening has been completed. The testing of surfactants at 260°C (500°F) in various chemical environments has been completed except for any new surfactants that may be submitted in the future. Testing is continuing at 310°C (590°F).

FY80 Progress

An aqueous foam generator that provides uniform, fine-celled, aqueous foams with controlled density was used in the evaluation of the effects of high-temperature cycles on surfactant solutions. A description of the generator and apparatus used to generate foams follows. The basic setup is depicted by the schematic, Figure 5-1.

The aqueous foam generator (static mixer) consists of an 11.7-cm (4.6-in.) long, 4.6-mm (0.18-in.) i.d., stainless-steel tube packed with 1.5 g (0.05 oz) of coarse stainless-steel wool, 0.051 mm thick by 0.635 mm wide (0.002 in. thick by 0.025 in. wide). The steel wool is packed into a 9.7-cm (3.8-in.) section of the tube.

The setup includes an air or nitrogen gas supply at 0.35 MPa (50.0 psig) for gas flow and solution overpressure. Flow rates of 10 to 12 gpm (0.02 to 0.03 lb/min) for the liquid and 200 to 250 cm³/min (0.007 to 0.009 ft³/min) for the gas are possible. Metering valves with micrometer heads have been used to control gas and liquid flow rates. Shutoff valves are used in the gas and liquid lines to minimize wear on the metering valves.

Foams with a density of $45.0 \pm 5.0 \text{ kg/m}^3$ ($2.8 \pm 0.3 \text{ lb/ft}^3$), ≈ 0.045 liquid volume fraction, have been used. If the foams generated are used to evaluate foam drainage or other foam properties, precise temperature control is necessary for repeatable results.

Figure 5-1. Aqueous Foam Generator

Surfactants were obtained from the major surfactant suppliers and the drilling industry. These surfactants were evaluated by the standard project procedure after their 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 5-1 and 5-2. The ratings at 260°C (500°F) are an update of the data published in Reference 1.

The ratings at 310°C (590°F) represent 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 Tables 5-1 and 5-2. 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. Candidate surfactants are still being evaluated after exposure to a 310°C (590°F) temperature in various aqueous environments.

Table 5-3 presents the data gathered on all of the surfactant solutions tested in a deionized-water/air environment. Many of these surfactants will not be tested in various chemical environments because of poor performance in these tests or because similar surfactants, from the same manufacturers, have already been tested.

The data in Table 5-3 show that there are several classes of surfactants with sufficient stability to survive in the geothermal drilling environment. The next major step is to evaluate foams at high temperatures and pressures; the evaluation will be performed when the autoclave, which has been ordered, arrives.

Corrosion coupons to evaluate the corrosivity of selected surfactant solutions have been machined and will be exposed to surfactant solutions. Corrosion inhibitors, recommended by suppliers for high-temperature aqueous environments, are also being collected for evaluation.

A presentation, "Aqueous Foams for Geothermal Drilling Fluids," was presented at the Gordon Research Conference in August 1980.

References

1. P. Rand, "Aqueous Foams for Geothermal Drilling Fluids: I. Surfactant Screening," Transactions, Volume 3 (Geothermal Resources Council, September 1979) pp 565-568.

Table 5-1

**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 ^a Air	Brine-II ^b Air
Alpha olefin sulfonate	Lakeway 301-10	0.5	E	E	E	E	E	E	U
Alpha olefin sulfonate	Sulframin 14/16 AOS	0.5	E	E	G	E	E	E	U
Alpha olefin sulfonate	Surflow S-398	0.5	E	E	E	E	E	E	U
Proprietary anionic	Thermophoam BWID	0.5	E	E	E	E	P	E	U
Coco betaine	Velvetex BC	0.5	E	E	E	P	E	E	P
Quat. ammonium chloride	Apogen 461	0.5	E	E	E	U	E	NT	E
Alkyl ethoxylate	Witconol SN-90	1.0	E	E	E	E	U	E	P
Proprietary anionic	Schwebel S-1100	0.5	E	E	P	E	P	E	U
Sulfonated quat. ammonium	EWS-121	0.5	E	E	E	U	U	NT	E
Alkyl ethoxylate	Tricol LAL-23	1.0	G	E	E	P	U	E	NT
Ether sulfonate	80-69068	0.5	E	E	G	P	U	NT	E
Quat. ammonium chloride	Arquad S-50	0.5	E	E	E	U	P	NT	U
Alkyl aryl sulfonate	Richonate 60B	0.5	E	E	U	E	U	NT	U
Alkyl aryl sulfonate	UDET-950	0.5	E	E	U	E	U	NT	U
Proprietary nonionic	PEN-5E	1.0	E	E	P	G	U	NT	U
Alkyl aryl ether sulfonate	Triton X-200	0.5	G	G	U	U	U	NT	U
Amine ethoxylate	Varonic K215-LC	1.0	G	G	G	G	E	NT	NT
Alkyl aryl ethoxylate	Witconol NP-120	1.0	P	E	P	P	P	NT	U
Alkyl amide sulfonate	Igepon TC-42	0.5	P	E	U	P	U	NT	U
Alkyl aryl sulfonate	Ninex N-300	0.5	G	G	U	G	U	NT	U
Proprietary anionic	Adofoam BF-1	0.5	G	P	U	P	U	NT	NT
Alkyl ester sulfonate	Lanthanol LAL	0.5	U	U	U	U	U	NT	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

^a A low-solids synthetic geothermal brine

^b 10.0 wt-% NaCl/2.0 wt-% CaCl₂ brine

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

Table 5-2

**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

Table 5-3

Surfactant Solutions Tested In A Deionized Water/Air Environment

Chemical Type	Trade Name	Wt-% Active Ingredient	Original Properties				Effect of 260°C (500°F)				
			Density kg/m ³ (lb/ft ³)	Drainage Time min	Cell Structure	pH	Drainage Time min	Change in Drainage Time, %	Cell Structure	Change in pH	Rating
Alpha olefin sulfonate	Surflow S-398	0.5	44.8 (28.0)	9.13	Good	11.12	10.49	+19.9	Good	+0.01	E
Alpha olefin sulfonate	Sulfotex AOS	0.5	48.4 (30.2)	7.61	Good	8.65	9.53	+23.7	Good	-4.30	E
Alpha olefin sulfonate	Lakeway 301-10	0.5	45.7 (28.5)	8.44	Good	8.05	9.21	+9.1	Good	-0.69	E
Proprietary anionic	Thermophoam BW-D	0.5	48.3 (30.2)	7.32	Good	10.30	8.88	-6.1	Good	-1.42	E
Alkyl aryl sulfonate	Sunteck XIV	0.5	47.6 (29.7)	7.26	Good	6.45	8.66	+19.3	Good	-2.98	E
Anionic fluorochemical	FC-99	0.5	44.9 (28.0)	7.30	Good	6.13	8.18	+12.1	Good	-3.00	E
Alpha olefin sulfonate	Sulframin 14/16 AOS	0.5	43.6 (27.2)	7.45	Good	6.70	8.09	+8.6	Good	-2.49	E
Alkyl aryl sulfonate	Richonate 60B	0.5	45.2 (28.2)	8.06	Good	5.88	8.01	-0.6	Good	-2.03	E
Quat. ammonium chloride	Apogen 461	0.5	42.8 (26.7)	7.66	Good	7.23	7.64	-0.3	Good	-3.17	E
Amphoteric fluorochemical	L-4357	0.5	44.3 (27.7)	11.30	Good	9.49	7.38	-34.6	Good	-1.31	G
Alkyl aryl sulfonate	UDET-950	0.5	47.0 (29.3)	7.23	Good	9.51	7.18	-0.7	Good	-2.48	E
Quat. ammonium chloride	Arquad S-50	0.5	45.8 (28.6)	7.10	Good	6.17	7.01	-1.3	Good	-1.50	E
Coco betaine	Velvetex BC	0.5	42.6 (26.6)	6.68	Good	5.03	6.90	+3.3	Good	+0.73	E
Anionic fluorochemical	L-4587	0.5	44.3 (27.7)	9.92	Good	9.34	6.77	-31.7	Good	-6.68	G
Ether sulfonate	80-69067	0.5	44.5 (27.8)	6.22	Good	5.24	6.49	+4.3	Good	-2.22	E
Quat. ammonium chloride	Arquad C-50	0.5	44.6 (27.8)	6.65	Good	6.71	6.36	-4.4	Good	-1.64	E
Proprietary anionic	S-1100	0.5	45.0 (28.1)	6.14	Good	8.53	6.34	+3.2	Good	-4.41	E
Ether sulfonate	80-69068	0.5	44.3 (27.7)	6.11	Good	5.78	5.73	-6.2	Good	-2.88	E
Sulfonated quat. ammonium	EWS-121	0.5	48.2 (30.1)	5.34	Good	6.85	5.64	+5.6	Good	-3.10	E
Proprietary	MA-943	0.5	45.5 (28.4)	8.29	Good	7.24	5.59	-32.6	Fair	+1.69	P
Alkyl aryl sulfonate	Ninex N-300	0.5	42.2 (26.3)	10.20	Good	6.76	5.58	-45.3	Good	-2.48	G
Alkyl aryl sulfonate	Petro BAF	0.5	44.5 (27.8)	6.00	Good	8.81	5.21	-13.2	Good	-4.01	E
Proprietary nonionic	PEN-SE	1.0	45.0 (28.1)	3.10	Good	5.72	4.93	+59.0	Good	-0.27	E
Alkyl amide sulfonate	Igepon TC-42	0.5	40.2 (25.1)	5.33	Good	7.64	4.88	-8.4	Fair	-0.25	P
Imidazoline amphoteric	Amphoterge NEX	0.5	43.9 (27.4)	8.23	Good	7.22	4.83	-41.3	Poor	-0.50	P
Alkyl aryl sulfonate	Petro P	0.5	46.4 (29.0)	4.92	Good	9.77	4.46	-9.3	Good	-4.28	E
Proprietary quaternary	M-Quat 155-104	0.5	45.5 (28.4)	6.36	Good	9.17	4.33	-31.9	Fair	-2.49	P
Petroleum sulfonate	Sunteck VII	0.5	45.6 (28.5)	4.67	Fair	11.48	4.32	-7.5	Good	-0.07	P
Ether sulfonate	79-69005	0.5	44.6 (27.8)	4.43	Good	3.64	4.29	-3.2	Good	-0.25	E
Ethoxylated quat. ammonium	Ethoquad 18/25	1.0	47.2 (29.5)	3.59	Fair	3.87	4.22	+17.5	Fair	-0.03	P

NF = no foam

Ratings: E -- Excellent

G -- Good

P -- Poor

U -- Unsatisfactory

Table 5-3 (Continued)

Surfactant Solutions Tested In A Deionized Water/Air Environment

Chemical Type	Trade Name	Wt-% Active Ingredient	Original Properties				Effect of 260°C (500°F)				
			Density kg/m³ (lb/ft³)	Drainage Time min	Cell Structure	pH	Drainage Time min	Change in Drainage Time, %	Cell Structure	Change in pH	Rating
Alkyl aryl ether sulfonate	Triton X-200	0.5	46.3 (28.9)	5.52	Good	7.20	4.06	-26.4	Good	-2.21	G
Ethoxylated amine	Mazeen C-15	0.5	48.7 (30.4)	2.63	Fair	9.70	4.04	+53.6	Fair	-2.10	P
Alkyl aryl ethoxylate	Witconol NP-120	1.0	49.8 (31.1)	3.44	Good	6.52	3.81	+10.7	Fair	-2.77	P
Proprietary nonionic	Mazawet 77	1.0	44.3 (27.7)	2.86	Good	6.77	3.66	+30.0	Good	-3.22	E
Proprietary amphoteric	HC-2	0.5	46.8 (29.2)	6.17	Good	5.29	3.60	-41.6	Poor	+3.33	P
Ethoxylated amine	Varonic K215LC	0.5	48.1 (30.0)	2.83	Fair	9.62	3.45	+21.9	Fair	-2.85	P
Petroleum sulfonate	Petrostep 450	0.5	48.4 (30.2)	3.70	Fair	7.69	3.27	-11.6	Poor	-1.99	P
Petroleum sulfonate	Petrostep 420	0.5	49.4 (30.8)	4.42	Fair	10.41	3.20	-26.7	Fair	-6.12	P
Proprietary anionic	Howco Suds	0.5	41.8 (26.1)	6.70	Good	8.46	3.16	-52.8	Fair	-5.94	P
Ether sulfate	TD-1	0.5	42.5 (26.5)	6.38	Good	8.42	2.87	-55.0	Fair	-6.02	P
Proprietary	Magcofoamer 77	0.5	45.1 (28.6)	5.34	Good	6.64	2.80	-47.5	Fair	-3.00	P
Alkyl ethoxylate	Witconol SN-90	1.0	45.9 (28.7)	2.65	Good	5.62	2.69	+1.5	Good	-2.05	E
Alkyl ethoxylate	Tricol LAL-23	1.0	46.2 (28.8)	3.18	Good	6.58	2.57	-19.2	Good	-2.78	E
Proprietary	Adofoam BF-1	0.5	47.7 (29.8)	4.31	Good	8.43	2.42	-43.8	Good	-5.91	G
Proprietary	MA-945	0.5	45.4 (28.3)	5.09	Good	6.87	2.37	-53.4	Poor	-4.29	P
Imidazoline amphoteric	Monateric CA-35	0.5	46.6 (29.1)	6.81	Good	7.44	NF	NF	NF	+1.12	U
Proprietary amphoteric	Ampho B11-34	0.5	45.5 (28.4)	8.48	Good	6.18	NF	NF	NF	-0.02	U
Amphoteric fluorochemical	Zonyl FS3	0.5	49.5 (30.9)	12.4	Good	4.18	NF	NF	NF	-1.07	U
Imidazoline amphoteric	Amphoterge K2	0.5	47.3 (29.5)	10.69	Good	9.70	NF	NF	NF	-1.57	U
Imidazoline amphoteric	Monateric 1000	0.5	45.4 (28.3)	5.01	Good	8.92	NF	NF	NF	-1.88	U
Alkyl ester sulfonate	Lanthanol LAL	0.5	44.6 (27.8)	6.43	Good	6.35	NF	NF	NF	-2.39	U
Alkyl sulfonate	Alkanol 189S	0.5	48.1 (30.0)	4.37	Good	5.97	NF	NF	NF	-2.72	U

NF = no foam

Ratings: E — Excellent

G — Good

P — Poor

U — Unsatisfactory

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
<p><u>N₂ / DRILL PIPE</u></p> <p><u>CORROSION TEST</u></p> <p>PLANNING AND COORDINATION</p> <p>DRILL PIPE INSPECTION</p> <p>INSTRUMENTATION CHECKOUT (BACA 20 WELL)</p> <p>FIELD TEST (BACA 21 WELL)</p> <p>FINAL REPORT</p>													<p>AFTER TEST NOV 80</p> <p>NOV 80</p> <p>DEC 80</p>

LEGEND: **ACTIVITY PERIOD**
 - - - - - **RESCHEDULED**

○ PLANNED START
● STARTED

▼ PLANNED COMPLETION
▼ COMPLETED

5.2 N₂/Drill Pipe Corrosion Test

Sandia National Laboratories
Technical Consultant: B. Caskey (505) 844-8835

Project Objective

The purpose of this test is to obtain data on the rate at which drill pipe corrosion occurs when air is used as the principal component of the drilling fluid and, alternatively, when an inert gas, N₂, is used as the principal component. These data when combined with onsite inert gas generation data, will form the basis for an economic study to evaluate the reduction of drilling costs through the use of inert gas drilling fluids.

Project Status

All planning, coordination, fabrication, and inspection were completed. The test will be performed during the drilling of a geothermal well by Union Geothermal at the Baca location in New Mexico.

FY80 Progress

Planning and coordination for this test resulted in a Sandia-Union contract that provides for Union to contribute the use of a geothermal well and other resources. Other persons consulted during the planning of the test were representatives from Loffland, Magcobar, and Baroid. As part of the planning effort, a review draft of the proposed test plan was delivered to all participants in June. A few comments were received and were incorporated in the final issue.

EG&G will provide the instrumentation and sampling capabilities for the test. They will instrument the fluid flow systems, collect fluid samples, and record the test data on digital tape. In preparation for the test, a complete checkout and shakedown of these systems was carried out in August.

PA, Incorporated, inspected 24 joints of the new drill pipe at their Odessa, Texas, facility in early July. The company is scheduled to inspect the pipe again in November, after the tests are completed.

The deeper part of the well will be alternately drilled with air and with N₂ as the primary component of the drilling fluid. The air will be supplied by Magcobar/Dresser compressors, and the liquid nitrogen will be trucked to the site, pumped, and vaporized by NOWSCO Services.

All preparations were completed and the N₂ drill pipe corrosion field test was scheduled to be conducted at the Baca 21 well during the last few days in September 1980. However, the well was completed at a depth that was less than the depth at which the test was to be initiated. As a result of the early completion, the field test was rescheduled to take place during the drilling of the Baca 22 well in early November 1980.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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

5.3 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 1981 (proposed)
Contract Number: DE-AC04-77ET27144
Technical Consultant: B. Millard (505) 846-0310

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).

Project Status

State-of-the-art studies were 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 was determined for the Microcomputer System software development. The installation site for the geothermal drilling fluid test system was tentatively selected. A contract extension is under consideration, and a new schedule is being developed.

FY80 Progress

System Hardware — Development of the Geothermal Drilling Fluid Test System (GDFTS) continued during fiscal year 1980. The pressure vessel is being fabricated by National Forge. Because of a variety of system modifications, including a redesign of the cooling jacket, and fabrication problems, the completed vessel will not be shipped from National Forge until mid-December 1980.

The water cooled interface plate between the hot drilling fluid and the instrumentation compartment has been fabricated. This stainless-steel plate was built in two halves to allow machining of a water chase in one half of the plate. Problems were encountered in brazing the two halves together; however, this task was successfully completed by Wall Colmonoy in Ohio in June 1980. The interface plate was successfully tested with an internal pressure of 100 kPa (1600 psi) in the water passage in August 1980. The final machining of mounting holes for equipment in the instrumentation compartment and of slots and holes to accommodate equipment projecting into the drilling fluid has been completed. Present plans call for this plate to be included in the hydrostatic test of the completed pressure vessel to be conducted at National Forge in December 1980.

The initial design work on the high-pressure, 41.4 MPa (6000 psi), argon supply system was initiated in July 1980. Components for the

pressure system were ordered in August 1980. The planned location of the gas-containing cylinder of the high-pressure intensifier was changed from outside to inside the test pit after the suitability for vertical operation was verified. Investigations into the alternative of substituting nitrogen for argon as the pressurizing gas are being conducted to determine any potential cost savings.

The status of the hardware that will be used to make fluid measurements during drilling fluid tests is described below.

- Filter

Layout drawings were completed in August 1980 for the system that will be used to withdraw spurt-loss and cake-loss filtrates from the high-pressure collection chambers to weighing cups located outside the pressure vessel. The filtrate is cooled and passed through an electrically controlled valve inside the pressure vessel. Then the filtrate passes through a shutoff valve, a pressure drop valve, a pneumatically controlled valve which reduces the pressure to near ambient, a three-way valve, a hydro-cyclone to control splatter, and finally into the receivers. The spurt-loss and cake-loss filtrate receivers are then weighed. This task is estimated to be 75% complete.

- Filter Medium

C. E. Tyler, fine-filter media, 200 x 1400 stainless-steel mesh, has been selected and procured.

- Densitometer

The densitometer is 75% complete. The device consists of a displacement transducer that measures the movement of a triangular bob positioned in the test fluid.

- Corrositivity

An off-the-shelf corrosivity measuring system has been procured. This system, manufactured by Petrolite, has three probes. The corrosion probes for the initial testing phase have been obtained and have been coated with ceramic insulation.

- Rheometer

Machining of the rheometer parts was completed in November, and testing of the assembled rheometer was satisfactorily completed in December 1979. The proximity sensor that will be used for sensing rheometer torque was received in April and tested in May 1980. A slight amount of high frequency vibration caused an undesirable increase in the scatter of the electronically sensed torque data. The scatter was satisfactorily reduced by installing an electronic damping circuit between the proximity sensor and the digital readout.

System Software — The effort needed to write and implement the software system that is required for controlling the GDFTS and logging the data produced is being conducted by Systran Corporation. An Intel microcomputer is being used to provide the required functions. Work on the software

development was initiated in January 1980 and has progressed on schedule. Simulation of a complete GDFTS test using the computer software was successfully completed in June 1980. The values for all parameters that would cause a GDFTS test to be aborted were defined, and the computer control procedures for all abort conditions have been established.

A recent decision to put the pressure intensifier, the external filtrate collection system, and the vessel temperature under software control will require additional software work be performed. Systran will accomplish this work as soon as appropriate contract modifications are made.

Test Facility Building -- E. Ripperger of the Engineering Mechanics Department, University of Texas, completed an analysis in December 1979 concerning the consequences of a pressure vessel failure inside the pit. Based on estimates of static overpressure, shock wave pressure, and projectile energy to be withstood by the pit, its cover, and the vents, Ripperger provided reliable design parameters for the pit to house the pressure vessel.

Final drawings for the building to house the GDFTS were completed in July 1980. Drawings for the pit cover designed to contain the shock wave and vessel fragments in the unlikely event of a pressure vessel failure were completed in August 1980.

Approval to build the GDFTS building at NL Petroleum Services, Houston is still pending. Because the building must be completed before the final system checkout can proceed, a contract time extension beyond March 1981 may be required in order to complete the project.

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>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

5.4 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: J. Kelsey (505) 844-6968

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 clay morphology are continuing.

FY80 Progress

Saponite Studies -- Saponite is a trioctahedral smectite with the formal composition

It is the magnesian analog of the montmorillonite, commercially known as bentonite, with the formal composition

Large amounts of saponite occur in the Amargosa Valley in Nevada, where it is mined by Industrial Mineral Ventures (IMV), Inc., of Colorado. The saponite sample for the experiments was obtained from this deposit through IMV. Fluids containing 4% saponite were prepared in distilled and de-ionized water. Salts of NaCl, KCl, and CaCl₂ were added to these fluids at 1% concentrations. These fluids, with and without the addition of salts, were subjected to hydrothermal treatments within the temperature range of 93.3° to 371.1°C (200° to 700°F). The original samples contained impurities of mica, feldspar, calcite, and dolomite. These impurities make up about 10% of the samples, the rest being saponite. The products of hydrothermal runs in saponite/water, saponite/KCl, saponite/NaCl, and saponite/

CaCl₂ were examined with X-ray diffraction. The results are tabulated in Tables 5-4 and 5-5. These data suggest that

1. Saponite does not lose its swelling capability within the temperature range of 93.3° to 371.1°C (200° to 700°F) and
2. Saponite does not undergo any structural or chemical changes during the above experimental conditions.

Saponite-based fluids were prepared with and without the addition of salts of NaCl, KCl, and CaCl₂, as described above. The run products in the saponite/water, saponite/NaCl, saponite/KCl, and saponite CaCl₂ systems were examined, and the results are described below.

• Saponite/H₂O Systems

The typical morphological features of the saponite particles after the runs at 93.3° through 371.1°C (200° through 700°F) are shown in Figures 5-2 through 5-7. No changes in morphological features of saponites are observed up to the 260°C (500°F) runs (Figures 5-2 and 5-3). The saponite particles seem to be well dispersed and separated into individual flexible and curled layers during the hydrothermal run at 315.6°C (600°F), as shown in Figures 5-4 and 5-5. Morphological features of saponite again display some changes after the hydrothermal run at 371.1°C (700°F). As seen in Figures 5-6 and 5-7, saponite seems to develop thick aggregates of platy particles.

• Saponite/NaCl Systems

Typical saponite particles in this system are shown in Figures 5-8 through 5-11 after the runs from 93.3° to 260°C (200° to 500°F). Very little change was observed in this temperature range, except thin and curled layers of saponite seem to develop as a result of dispersion of aggregates with increasing temperatures.

X-ray diffraction and electron microscopic examination and rheological measurements are continuing for other saponite-based fluids.

• Saponite/KCl Systems

Electron microscopic observations 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 5-12 through 5-16 show the typical saponite particles found in each sample.

• Saponite/CaCl₂ Systems

For the saponite/CaCl₂ 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 H₂O and NaCl systems. Those aggregates also

Table 5-4

X-Ray Diffraction Data on the Products of the Hydrothermal Runs
in Saponite/Water and Saponite/NaCl Systems

Systems	Hydrothermal Conditions °C (°F)	Run Time Hours	Saponite before and after Glycolation		Major Observed Reflections			
			Before Å	After Å	Mica Å	Feldspar Å	Calcite Å	Dolomite Å
Saponite and Water	93.3 (200)	24	14.3	17.5	9.98	3.23	-	-
	148.9 (300)	24	14.3	17.4	9.94	3.22	-	2.885
	204.4 (400)	24	14.3	17.8	9.98	3.23	-	-
	260.0 (500)	24	13.4	17.4	9.94	3.23	-	-
	315.6 (600)	16	13.3	17.5	9.98	3.23	-	-
	371.1 (700)	16	14.3	17.1	9.98	3.23	-	-
Saponite and NaCl	93.3 (200)	24	14.1	17.3	9.96	3.23	-	-
	148.9 (300)	24	14.6	17.2	10.00	3.23	-	-
	204.4 (400)	24	14.4	17.5	9.91	3.23	-	-
	260.0 (500)	24	13.4	17.5	9.95	3.23	3.03	-
	315.6 (600)	16	13.2	17.3	9.98	3.23	-	-
	317.1 (700)	16	14.1	17.1	9.96	3.23	3.03	-

Table 5-5

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

Figure 5-2. Typical Saponite Particles after the Hydrothermal Run at 93.3°C (200°F) in Saponite/Water System

Figure 5-3. Saponite Particles after the Run at 260°C (500°F) in Saponite/Water System

Figure 5-4. Saponite Particles after the Run at 315.6°C (600°F) in Saponite/Water System

Figure 5-5. Saponite Particles after the Run at 315.6°C (600°F) in Saponite/Water System

Figure 5-6. Saponite Lamellar Aggregates after the Run at 371.1°C (700°F) in Saponite/Water System

Figure 5-7. Other Saponite Aggregates after the Run at 371.1°C (700°F) in Saponite/Water System

Figure 5-8. A Thick Saponite Aggregate after the Run at 93.3°C (200°F) in Saponite/NaCl System

Figure 5-9. Typical Saponite Aggregates after the Run at 148.9°C (300°F) in Saponite/NaCl System

Figure 5-10. Typical Saponite Aggregates after the Run at 204.4°C (400°F) in Saponite/NaCl System

Figure 5-11. Typical Saponite Aggregates after the Run at 260°C (500°F) in Saponite/NaCl System

Figure 5-12. Large Aggregate of Saponite after the Run at 93.3°C (200°F) in Saponite/KCl System.
Mag: 13 000X

Figure 5-13. Typical Form of Saponite Aggregate after the Run at 148.9°C (300°F) in Saponite/KCl System.
Mag: 13 000X

Figure 5-14. 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 5-15. Typical Form of Saponite Aggregate after the Run at 315.6°C (600°F) in Saponite/KCl System. Mag. 32 500X

Figure 5-16. Small and Scattered Saponite Aggregates due to Dispersion after the Run at 371.1°C (700°F) in Saponite/KCl System. Mag: 13 000X

change from smaller aggregates to larger ones at higher temperatures, 204.4° to 260°C (400° to 500°F). The saponite/CaCl₂ run at 260°C (500°F) shows a morphology that looks like that in saponite/H₂O run at 371.1°C (700°F). The similarity may indicate that the effect of CaCl₂ on saponite at 260°C (500°F) is approximately equal to that of H₂O and NaCl at 371.1°C (700°F). The thick and platy aggregates found in saponite/CaCl₂ run at 260°C (500°F) are probably the result of calcium substitution in the inter-layer cation sites; calcium binds the structure more tightly than other monovalent cations. Figures 5-17 through 5-20 show the typical aggregates found in the sample.

Figure 5-17. Fluffy Aggregates of Saponite after the Run at 93.3°C (200°F) in Saponite/CaCl₂ System.
Mag: 22 100X

Figure 5-18. Fluffy Aggregates of Saponite after the Run at 148.9°C (300°F) in Saponite/CaCl₂ System.
Mag: 13 000X

Figure 5-19. Platy Particles Developing around the Saponite Aggregates after the Run at 204.4°C (400°F) in Saponite/CaCl₂ System. Mag: 32 500X

Figure 5-20. 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

Bentonite Studies -- One original and 16 treated bentonite samples were examined by X-ray diffraction. The results of the diffraction examination for each sample are presented in Table 5-6.

The original bentonite sample is composed of smectite and a small amount of feldspar. The smectite has a 12-Å basal reflection that expands to 17 Å with glycolation. In the treated bentonite samples, smectite is abundant, but some samples contain illite, quartz, and feldspars. The X-ray data indicate that the bentonite/CaCl₂ samples have all three minerals, whereas the bentonite/KCl samples have only quartz. These base align properties of the samples may be source dependent.

After treatment of the bentonite sample with various salts, the following two characteristics were noticed in some of the samples:

1. Development of a 34-Å reflection: Samples from KCl and NaCl runs showed a weak reflection at 34 Å after glycolation. This reflection is exactly twice the original basal reflection at 17 Å. This phenomenon may be the result of a change in stacking sequence.
2. Decrease of the d-value of (001) reflection: The KCl runs at 316° and 371°C (600° and 700°F) showed a distinct decrease in (001) reflection from 15 Å to 11 Å, indicating little expansion after glycolation. This property may be the result of structure collapse.

The 17 bentonite samples were studied by electron microscopy to investigate the morphological changes and the reactions that may occur during the hydrothermal treatments. In those treatments, the 4% clay slurries were subjected to the conditions indicated in Table 5-6. A summary of observations follows.

The original material mainly consisted of fluffy smectite flakes, with few particles showing elongated, illite-like lath that extended out from the smectite flakes, as shown in Figure 5-21.

Most of the smectite particles retained their original morphology, as did the particles in the original starting material at 93°C (200°F) runs for 24 hours in the presence of KCl and NaCl. However, some of the flakes disintegrated into smaller flakes. As the temperature increased from 149° to 260°C (300° to 500°F), the fluffy smectite flakes turned into somewhat platy particles that were thinner than the original flakes (Figures 5-22 and 5-23). At the higher temperatures of 316° and 371°C (600° and 700°F), the platy particles replaced most of the fluffy smectite and formed aggregates (Figure 5-24). Similar results were obtained in the bentonite/CaCl₂ system, but the aggregates seemed to be more compact.

Attapulgitite Studies -- The hydrothermal experiments with the Floridan attapulgitite showed that attapulgitite starts to convert to a smectite at 204°C (400°F) and in large quantities at 260°C (500°F). Synthetic mixtures of a smectite from Cheto, Arizona, and the Floridan attapulgitite were prepared at 10% intervals. The X-ray patterns of these synthetic mixtures were compared with those of the patterns obtained after the hydrothermal runs. Thus, it was possible to quantify the rate of the conversion in the

Table 5-6

**X-Ray Diffraction Data on the Products of the
Hydrothermal Runs in Bentonite Systems**

Systems	Hydrothermal Conditions °C (°F)	Run Time Hours	Bentonite before and after Glycolation		Other Minerals Present in Bentonite Clay		
			Before Å	After Å	Quartz Å	Feldspar Å	Illite Å
Bentonite and KCl	93 (200) ^a	24	12.2	17.0	+	+	+ ^b
	149 (300)	24	15.2	33.7, 17.1	+	-	- ^c
	149 (300)	72	15.2	33.2, 17.1	+	-	-
	204 (400)		15.0	33.6, 17.1	+	-	-
	260 (500)	24	15.1	34.0, 17.4	+	-	-
	316 (600)	24	10.9	12.6	+	+	-
	371 (700)	24	11.0	12.3	+	+	-
Bentonite and CaCl ₂	93 (200) ^a	24	15.0	34.0, 17.5	+	-	-
	149 (300)	24	12.2	17.0	+	+	+
	149 (300)	72	11.8	17.1	+	+	+
	204 (400)	24	12.4	17.1	+	+	+
	260 (500)	24	12.3	16.5	+	+	+
Bentonite and NaCl	316 (600)	24	12.5	34.0, 17.5	+	-	-
	371 (700)	24	12.6	33.0, 17.0	+	-	-
Bentonite and gel	316 (600)	24	13.1	17.1	+	+	+
	371 (700)	24	13.0	17.3	+	+	+
Original bentonite sample B-1227-11			12.0	17.1	-	+	-

^aThe data on the bentonite/KCl 93°C (200°F) run may be in error because they do not agree well with the rest of the KCl runs. The same is true of the CaCl₂ runs at 93°C (200°F). Also, the Ca-saturated smectite does not show a (001) reflection at 15 Å, but at 12 Å, which should be the (001) reflection of a Na- or K-smectite. A mistake in labelling the samples is suspected.

^b+ = presence

^c- = absence

Figure 5-21. Original Bentonite Particles before the Hydrothermal Treatments

Figure 5-22. Typical Bentonite Particles after the Hydrothermal Treatment at 149°C (300°F) in the Presence of-KCl

Figure 5-23. Development of Platy Smectite Morphology after the Hydrothermal Run at 260°C (500°F) in the Bentonite/KCl System

Figure 5-24. Platy Smectite Particles Which Are Probably Formed after Dissolution of the Original Bentonite during the Hydrothermal Run at 371°C (700°F) in the Presence of KCl

temperature interval from 149° to 371°C (300° to 700°F). This analysis was based on the comparison of the intensities of a 17.0-Å glycolated smectite reflection with the 10.5-Å attapulgite reflection. The results showed that about 30% of attapulgite converts at 204°C (400°F) to smectite in the distilled water system. The amount of smectite increases to 60% after the 260°C (500°F) run, and no attapulgite remains after the 316°C (600°F) run in the distilled water system. Similar results are obtained in the presence of NaCl, as shown in Figure 5-25. In the KCl system, the amount of smectite is small after the 204°C (400°F) run, but, at higher temperatures, the rate of the conversion is similar. It is also important to note that the commercial attapulgite sample from Florida, and also Georgia, originally contains about 10 to 15% smectite, which is a montmorillonite. Other impurities in the sample are calcite, at 5%, and illite, at 5%. The X-ray data in Figure 5-25 indicate that the basal spacings of the smectites formed from attapulgite vary from 14.5 to 15.8 Å in the distilled water system, from 14.7 to 15.5 Å in the KCl system, and from 15.1 to 15.8 Å in the NaCl system. These basal spacings are unusual for the Na or K unsaturated smectites, the basal spacings of which are normally about 12-Å. The observed larger basal spacing indicates that Mg and possibly Ca are the interlayer cations in the smectites formed in these systems. Those may be cations inherited from the original attapulgite structure, and they seem to attach to the structure more than the usual exchangeable interlayer cations. This observation is significant in that the characteristics of the interlayer cation of smectite have a bearing on smectite's rheological properties.

• Electron Microscopy Observations

Both the original attapulgite and the smectites formed from it were examined with an analytical electron microscope, JEM-100CS, in the imaging modes SEM,* STEM,** and TEM,† and the X-ray spectra were obtained from these individual particles. The intensities of the characteristic X-ray spectra for the elements Mg, Al, Si, Fe, and in some cores, Ca and K, were measured. These intensities were then normalized by setting Si-K counts equal to 1.00. For each sample, 10 different attapulgite particles and 10 smectite particles were measured. The average of these counts and their standard deviations are given in Table 5-7. The results in this table indicate that

1. The chemistry of the individual attapulgite fibers is rather uniform, and the Mg/Al ratio is about 1:1, as expected from the bulk chemistry of the commercial sample (with 9.52% of MgO and 8.96% Al₂O₃).
2. The Al content of the attapulgite aggregates is somewhat higher, because these aggregates entrap small flakes of illite and smectite impurities.
3. The chemistry of the newly formed smectites shows a greater variation in their Mg and Al contents, as suggested by their large

* Scanning electron microscope

** Scanning transmission electron microscope

† Transmission electron microscope

Figure 5-25. X-Ray Pattern of Attapulgite Samples Subjected to Hydrothermal Reactions at Various Temperatures in Attapulgite/Water, Attapulgite/KCL, and Attapulgite/NaCL Systems; The 17Å Reflection of Smectite is Hatched

Table 5-7

Intensity Ratios and the Standard Deviations of the X-Ray Spectra Obtained from the Original Attapulgite and the Smectites Formed at Various Temperatures

Particle Designation and Treatment	Electron Mode	Mg	Al	Si	Fe	Ca	K
Original Attapulgite Fiber	STEM/area	0.09±0.01	0.09±0.01	1.00	0.05±0.02	n.d.	n.d.
Attapulgite aggregate	STEM/area	0.08±0.01	0.13±0.01	1.00	0.06±0.06	0.04±0.02	n.d.
Smectite/204°C (400°F)/ Distilled Water	STEM/spot	0.09±0.06	0.24±0.08	1.00	0.07±0.04	0.17±0.25	0.06±0.05
Smectite/260°C (500°F)/ Distilled Water	STEM/area	0.08±0.03	0.26±0.09	1.00	0.02±0.12	n.d.	n.d.
Smectite/316°C (600°F)/ Distilled Water	STEM/area	0.16±0.05	0.16±0.04	1.00	0.08±0.02	0.03±0.02	0.01±0.01
Smectite/371°C (700°F)/ Distilled Water	STEM/area	0.14±0.02	0.15±0.05	1.00	0.08±0.03	0.03±0.02	0.01±0.01

NOTE: STEM = scanning transmission electron microscope

standard deviations. These smectites seem, however, to have larger Al contents than Mg.

4. The smectites formed at 316° and 371°C (600° and 700°F) seem to have equal amounts of Mg and Al in their chemistry, and their chemistry varies less than does the chemistry of the smectites formed at 204° and 260°C (400° and 500°F).
5. The ratio Mg + Al/Si for the smectites is significantly larger than for the original attapulgite. The excess of silicon, in fact, has been observed to precipitate as amorphous spherules.

Original attapulgite consists of fibers and aggregates of fibers. A typical aggregate of these fibers is shown in Figure 5-26. The original sample contains about 10 to 15% smectite, 5% illite, and 5% calcite. The attapulgite fibers have a length of about one micron or less and a thickness of 300 to 500 Å.

At 204°C (400°F), the attapulgite fibers begin to convert to a smectite. These smectites appear as thin platelets, as shown in Figures 5-27 and 5-28, along with the attapulgite fibers. The smectites seem to have precipitated after the dissolution of attapulgite fibers. As mentioned previously, the smectite particles contain more Al than Mg as compared to the chemical composition of the attapulgite fibers. Similar smectites develop in the attapulgite/distilled water system at 260°C (500°F). Smectites that form at higher temperatures have a different morphology. Figure 5-29 shows the typical smectite aggregates formed at 316°C (600°F) in the attapulgite/distilled water system. These smectites consist of irregularly folded, thin layers. They also contain a large number of spherical particles of silica. At this temperature, no more attapulgite fibers remain in the system.

Smectites formed at 371°C (700°F) display more platy forms, as shown in Figure 5-30, in which spherical silica particles are also distinctly visible.

Because the attapulgite to smectite conversion takes place more readily than the sepiolite to smectite conversion, the use of attapulgite for the high-temperature drilling fluids is favorable.

Attapulgite-based fluids were hydrothermally treated in the presence of MgCl₂ and CaCl₂ at 149°, 204°, and 260°C (300°, 400°, and 500°F) for 24 hours. The morphological features and chemical composition of the smectites formed in this system have been examined with analytical electron microscopy. For studying the chemical compositions, characteristic X-rays from smectite particles were detected and processed with an ORTEC EEDS. II system. Particles were first examined in the STEM mode at 100 keV. The X-ray spectral data on smectites formed at 260°C (500°F) in the attapulgite/MgCl₂ and attapulgite/CaCl₂ systems are listed in Tables 5-8 and 5-9.

As previously mentioned, the X-ray spectral data of the original attapulgite fibers show the following average intensity ratios with respect to Si/K α intensity:

Figure 5-26. Original Attapulgite Fibers. Mag: 20 000X

Figure 5-27. Typical Smectite Platelets Formed at 204°C (400°F) in the Attapulgite/Distilled Water System. Mag: 43 000X

Figure 5-28. Smectite Platelets and Attapulgite Fibers in the Attapulgite/Distilled Water System. Mag: 43 000X

Figure 5-29. Typical Smectite Particles Formed at 316°C (600°F) in the Attapulgite/Distilled Water System

Figure 5-30. Platy Forms of Smectite Formed from Attapulgite at 371°C (700°F) in the Attapulgite/Distilled Water System

Table 5-8

X-Ray Spectral Data on Attapulgite/MgCl₂ at 260°C (500°F)

Particle Designation	X-Ray Mode	Integrated Intensities (Counts/100 s)					Intensity Ratio Specified Element/Si				
		Al	Mg	Si	Fe	K	Al	Mg	Si	Fe	K
TA1SMC	STEM/area	220	71	1162	256	111	0.19	0.06	1.00	0.22	0.10
TS1SMC	STEM/spot	234	110	1853	195	--	0.13	0.06	1.00	0.11	--
TA2SMC	STEM/area	240	103	1332	244	109	0.18	0.08	1.00	0.18	0.08
TS2SMC	STEM/spot	482	38	2724	211	80	0.18	0.01	1.00	0.08	0.03
TA3SMC	STEM/area	660	233	2469	392	126	0.27	0.09	1.00	0.16	0.05
TS3SMC	STEM/spot	810	147	4122	377	38	0.20	0.04	1.00	0.09	0.01
TA4SMC	STEM/area	427	252	2061	254	53	0.21	0.12	1.00	0.12	0.03
TS4SMC	STEM/spot	735	216	3303	287	20	0.22	0.07	1.00	0.09	0.01
TA5SMC	STEM/area	202	129	924	153	45	0.22	0.14	1.00	0.16	0.05
TS5SMC	STEM/spot	478	127	2123	193	23	0.22	0.06	1.00	0.09	0.01
TA6SMC	STEM/area	213	113	1292	158	28	0.16	0.09	1.00	0.12	0.02
TS6SMC	STEM/spot	497	117	3320	123	28	0.15	0.04	1.00	0.04	0.01
TA7SMC	STEM/area	381	225	2136	219	31	0.18	0.11	1.00	0.10	0.01
TA7SMC	STEM/spot	754	296	4101	282	59	0.18	0.07	1.00	0.07	0.01
TA8SMC	STEM/area	358	172	1693	177	126	0.21	0.10	1.00	0.10	0.07
TS8SMC	STEM/spot	504	148	2015	101	60	0.25	0.07	1.00	0.05	0.03
TA9SMC	STEM/area	61	89	411	21	4	0.15	0.22	1.00	0.05	0.01
TS9SMC	STEM/spot	198	62	797	43	11	0.25	0.08	1.00	0.05	0.01

Note: STEM = Scanning
Transmission
Electron
Microscope

Statistical Analysis					
Area	Mean:	0.20	0.11	0.13	0.05
	Std. Dev.:	0.04	0.05	0.05	0.03
Spot	Mean:	0.20	0.06	0.07	0.02
	Std. Dev.:	0.04	0.02	0.02	0.01

Table 5-9

X-Ray Spectral Data on Attapulgite/CaCl₂ at 260°C (500°F)

Particle Designation	X-Ray Mode	Integrated Intensities (Counts/100 s)						Intensity Ratios (Specified Element/Si)					
		Al	Mg	Si	Fe	K	Ca	Al	Mg	Si	Fe	K	Ca
TA1314	STEM/area	273	248	2121	149	25	—	0.13	0.12	1.00	0.07	0.01	—
TS1314	STEM/spot	805	646	7604	442	—	524	0.11	0.08	1.00	0.06	—	0.07
TA1SMC	STEM/area	204	166	1467	150	—	—	0.14	0.11	1.00	0.10	—	—
TS1SMC	STEM/spot	728	624	5336	366	—	—	0.14	0.12	1.00	0.07	—	—
TA2SMC	STEM/area	215	183	1393	153	157	—	0.15	0.13	1.00	0.11	0.11	—
TS2SMC	STEM/spot	390	380	5197	185	—	—	0.08	0.07	1.00	0.04	—	—
TA3SMC	STEM/area	274	151	1166	293	38	70	0.23	0.13	1.00	0.25	0.03	0.06
TS3SMC	STEM/spot	96	43	609	206	—	13	0.16	0.07	1.00	0.34	—	0.02
TA4SMC	STEM/area	258	149	1340	520	159	148	0.19	0.11	1.00	0.39	0.12	0.11
TS4SMC	STEM/spot	272	75	1425	561	155	52	0.19	0.05	1.00	0.39	0.10	0.04
TA5SMC	STEM/area	244	272	2021	225	96	235	0.12	0.13	1.00	0.11	0.05	0.12
TS5SMC	STEM/spot	160	111	882	135	—	55	0.18	0.13	1.00	0.15	0.00	0.06
TA6SMC	STEM/area	440	326	3796	466	44	243	0.12	0.09	1.00	0.12	0.01	0.06
TS6SMC	STEM/spot	576	190	5838	130	66	40	0.10	0.03	1.00	0.03	0.01	0.01
TA7SMC	STEM/area	441	281	2203	265	70	51	0.20	0.13	1.00	0.12	0.03	0.03
TS7SMC	STEM/spot	389	122	3617	86	27	12	0.11	0.03	1.00	0.02	0.01	0.00
TA8SMC	STEM/area	395	372	2751	195	64	263	0.14	0.14	1.00	0.07	0.02	0.10
TS8SMC	STEM/spot	564	202	4868	115	51	61	0.10	0.04	1.00	0.02	0.01	0.01
TA9SMC	STEM/area	511	301	2748	238	85	222	0.19	0.11	1.00	0.09	0.03	0.08
TS9SMC	STEM/spot	592	288	4880	253	44	85	0.12	0.06	1.00	0.05	0.01	0.02

Note: STEM = Scanning Transmission
Electron Microscope

Statistical Analysis						
Area	Mean:	0.16	0.12	0.14	0.05	0.06
	Std. Dev.:	0.04	0.02	0.10	0.04	0.05
Spot	Mean:	0.13	0.07	0.12	—	0.02
	Std. Dev.:	0.04	0.04	0.14	—	0.03

<u>Electron mode</u>	<u>Mg</u>	<u>Al</u>	<u>Si</u>	<u>Fe</u>	<u>Ca</u>
STEM/area	0.09±0.01	0.09±0.01	1.00	0.05±0.02	--
STEM/spot	0.10±0.02	0.09±0.01	1.00	0.03±0.02	--

The X-ray spectral data on the smectites in Tables 5-8 and 5-9 show a significant increase in Mg/Si intensity compared with the corresponding intensity ratio in the original attapulgite fibers. The Mg/Si intensity ratios increase from 0.10/1.00 in the original fibers to 0.16/1.00 and 0.20/1.00 in smectites formed in the CaCl₂ and MgCl₂ systems, respectively. Thus, the chemical make-up of these smectites is significantly different from those of the original attapulgite fibers.

X-ray Microanalysis Using Thin Films -- Thin films in which absorption and fluorescence effects are negligible provide a simple relationship between intensities and concentrations of elements in these films. The clay minerals occur naturally in thin crystallites. The thin film analysis was applied to the clay minerals such as sepiolite, attapulgite, and saponite in order to follow in at least a semiquantitative manner the changes in the chemistry of these minerals during the hydrothermal reactions. The chemical analysis of the bulk samples, including the impurities, of these samples were obtained with atomic absorption spectroscopy and are listed in Table 5-10. The intensity/concentration relationship for thin films is given by the equation

$$C_A/C_B = K_{A-B}(I_A/I_B),$$

where C_A and C_B are the concentrations of elements A and B in the film and I_A and I_B are the measured intensities of the characteristic X-ray lines of the elements A and B respectively. The proportionality coefficient K_{A-B} is known as the K factor. This relationship holds as long as the thickness of the film is below the so-called critical thickness; otherwise absorption and fluorescence connections are required for the measured intensities. The critical thickness of a film is calculated by the relationship

$$t_c \leq 0.1/(\mu/\rho)_s \cdot \csc(\psi) \cdot \rho,$$

where $(\mu/\rho)_s$ is the mass absorption coefficient of the sample for the measured X-ray line, ψ is the take-off angle between the X-ray detector and the sample surface, and ρ is the density of the sample. The critical thickness of attapulgite was calculated to be 0.4493 microns for silicon-K α radiation. The critical thickness of sepiolite was found to be 0.3154 microns for the Si-K α line and 0.2102 microns for the Mg-K α lines. Attapulgite, sepiolite, and saponite particles with thicknesses below the above critical values were easily obtained. The measured intensity ratios of I_{Mg}/I_{Si} are listed in Table 5-10 along with the concentration ratios (C_{Mg}/C_{Si}) obtained from the bulk chemical analysis. The K-factors were then calculated by $(C_{Mg}/C_{Si})/(I_{Mg}/I_{Si})$ and also given in Table 5-10. The intensities were measured with STEM in area and spot modes. These two modes generate different intensity ratios and therefore different

Table 5-10

Chemical Analysis of the Bulk Samples of Sepiolite,
Attapulgitite 150, and Saponite

Chemical Analysis	Clay Mineral Bulk Samples		
	Attapulgitite	Sepiolite	Saponite
Components			
SiO ₂	68.0	67.1	57.6
MgO	10.5	26.5	19.10
Al ₂ O ₃	12.0	2.7	10.22
Fe ₂ O ₃	5.0	0.66	2.89
CaO	1.7	1.48	2.06
K ₂ O	1.0	0.55	4.11
Na ₂ O	0.7	0.32	3.22
P ₂ O ₅	nd	nd	nd
TiO ₂	0.7	nd	nd
LiO ₂	nd	0.11	0.11
Concentration ratio			
C _{Mg} /C _{Si}	0.20	0.50	0.42
Intensity ratios			
(I _{Mg} /I _{Si}) _{area}	0.09	0.21	0.27
(I _{Mg} /I _{Si}) _{spot}	0.09	0.18	0.24
K-factors			
(K _{Mg-Si}) _{area}	2.21	2.40	1.60
(K _{Mg-Si}) _{spot}	2.21	2.78	1.80

Notes: Each component amount is weight-%

nd = not determined

K-factors. The intensity data obtained from the particles after the hydrothermal experiments are being examined. This examination may produce a semiquantitative concept about the chemistry of the individual particles formed under hydrothermal conditions from attapulgite, sepiolite, and saponite.

East Mesa Core Study -- Formation damage, apparently caused by sepiolite-based high-temperature drilling fluid, is being studied by Terra Tek, Inc., on cores from the East Mesa known geological resource area (KGRA) under a separate project. Three of these cores were provided by Terra Tek for further mineralogical examination. The results of X-ray diffraction studies on these cores follow.

The core sections received were 10.2 cm (4 in.) in length and 5.1 cm (2 in.) in diameter. The samples carried the designations East Mesa, 64, and East Mesa, 76. Because the cores were previously subjected to flow tests with sepiolite mud, each core was sampled at 2.5-cm (1-in.) intervals, and the mineralogy, especially the clay content, at each section was examined. These sections were labeled A, B, C, and D from the top to the bottom of the core. The bulk samples were first X-rayed in randomly selected powders. The clays in -2-micron fractions were separated by sedimentation within the suspensions that had been prepared from the lightly ground samples. Oriented clay films were prepared from -2-micron fractions after the suspensions were washed to a salt-free state, i.e., base align deflocculated.

The results of the X-ray diffraction analyses presented in Table 5-11 indicate that the amount of calcite in the core increases towards the bottom for Core 76, whereas no such trend was present in Core 64. The clay mineralogy in both cores was similar. Chlorite and illite/smectite mixed layers were the only clay minerals present. In Core 64, the chlorite content increased from the top to the bottom of the core. These clays are distinctly different from the clays in the mud, in which sepiolite and bentonite are the predominant components, occurring in a ratio of 3 to 1. Hence, it should be easy to determine with the SEM whether or not the clays from the drilling mud are penetrating into the cores during the flow tests. These SEM studies are in progress.

Test Equipment -- A high-temperature FANN 50C viscometer was received and installed. Calibration tests were completed, and the equipment is ready for use in future studies.

Table 5-11

X-Ray Diffraction Analyses of East Mesa Cores

Sample Number	Sample Fraction	Quartz %	Feldspars %	Calcite %	Chlorite %	Illite/Smectite Mixed Layer %	Kaolinite %
76-A	bulk	60	25	10	5	-	-
76-A	-2 μ	-	+	-	50	50	-
76-B	bulk	60	25	10	5	-	-
76-B	-2 μ	-	-	10	50	40	-
76-C	bulk	70	15	15	-	-	-
76-C	-2 μ	-	-	10	40	50	-
76-D	bulk	50	20	25	5	-	-
76-D	-2 μ	-	+	10	50	40	-
64-A	bulk	75	15	10	-	-	-
64-A	-2 μ	-	-	5	50	40	-
64-B	bulk	75	25	+	-	-	-
64-B	-2 μ	-	-	+	50	50	-
64-C	bulk	70	25	5	-	-	-
64-C	-2 μ	-	+	+	60	40	-
64-D	bulk	75	20	5	-	-	-
64-D	-2 μ	-	+	-	70	30	-

NOTE: + = presence

- = absence

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

5.5 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 was to demonstrate catalytically supported thermal combustion as a means of generating an inert gas, nitrogen (N_2), from the exhaust stream of a commercially available diesel engine. An existing, proprietary catalyst was used with supplemental No. 2 diesel fuel over the load range of the diesel engine to achieve this objective. This performance objective was 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--the replacement of air with N_2 in foam drilling and air drilling and in the aeration of drilling muds to help prevent the corrosion of drill pipe.

Project Status

The parametric test program and the durability tests were completed. Control of emissions in the catalytic generation of N_2 was demonstrated. Additional experiments may be conducted subsequent to fabrication of a full scale field unit.

FY80 Progress

During the first month of the project, the overall project planning, test rig design, instrumentation systems specifications, and catalytic reactor fabrication were completed. A schematic of the facility is shown in Figure 5-31.

The fabrication of the test facility and its analytical instrumentation were completed. The exhaust analysis equipment and necessary calibration gases are listed in Table 5-12. Commissioning tests of the facility were also completed. Difficulties experienced with the engine/generator/-load set and the analytical train were resolved. Engine valve failure resulted in the replacement of the original Allis-Chalmers DES-60 diesel engine. The exhaust characterization of the replacement engine at resistor loads in the range of 0 to 60 kV is similar to that of the original engine and is shown in Figures 5-32, 5-33, and 5-34. Additional problems with setting engine load were caused by malfunctioning of the electrical load dissipation equipment. These problems were corrected by the rental contractor. Some minor adjustments were required to obtain a good reference zero for the oxygen analyzer train.

Figure 5-31. Schematic of Engine/Combustor/Analytical Train

Table 5-12

Exhaust Analysis Equipment and Calibration Gases

Exhaust Analysis Equipment

1. Beckman Model 402 Hydrocarbon Analyzer
(flame ionization)
2. Horiba Model AIA-21 CO₂ Nondispersive
Infrared Gas Analyzer
3. Horiba Model AIA-21 AS CO Nondispersive
Infrared Gas Analyzer
4. Infrared Industries Model IR-703 CO-05
O1-FI-RI Nondispersive Infrared CO
Gas Analyzer
5. AeroChem Chemiluminescence NO_x Monitor
Model AA-3
6. Teledyne Model 311 Portable Trace
Oxygen Analyzer

Calibration Gas Cylinders

1. Fuel Gas -- 40% H₂/60% N₂
2. Propane in N₂ -- 93 ppm C₃H₈
3. Low CO₂ in N₂ -- 4.28% CO₂
4. High CO₂ in N₂ -- 8.27% CO₂
5. Low ppm CO in N₂ -- 10.2 ppm CO
6. High ppm CO in N₂ -- 200 ppm CO
7. Low % CO in N₂ -- 2% CO
8. High % CO in N₂ -- 6% CO
9. Low NO_x in N₂ -- 10.2 ppm NO_x
10. High NO_x in N₂ -- 205 ppm NO_x
11. Zero gas -- N₂

Figure 5-32. Exhaust Characterization of Allis-Chalmers DES-60 and Replacement Diesel Engines; Temperature

Figure 5-33. Exhaust Characterization of Allis-Chalmers DES-60 and Replacement Diesel Engines; CO_2 and O_2 Emissions

Figure 5-34. Exhaust Characterization of Allis-Chalmers DES-60 and Replacement Diesel Engines; CO Emission

The parametric test program was then completed; the program test conditions and test variables are shown in Table 5-13. 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 5-35 shows the NO_x, CO₂, and CO emissions versus fuel/air ratios, at-catalyst and overall.^x Difficulties with the O₂ analyser train prevented reliable O₂ measurements from being made. Thus, although low O₂ measurements ≤ 10 Vppm 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 the catalyst inlet reference velocity. The 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, 48kW (64.3 hp); and at 60% load, 36 kW (48.3 hp) are presented in Tables 5-14 through 5-16.

Table 5-13

Parametric Test Program Conditions and Variables

Generator Load Bank Setting kW	O ₂ Content of Exhaust Wt %	Catalyst Inlet Temperature °C (°F)	Engine F/A Ratio lb/lb	Overall F/A Ratio lb/lb	Reference Velocity m/s (ft/s)
0	18.66	182 (360)	0.0137	0.1285→0.071	5.2 (17)
0	18.66	182 (360)	0.0137	0.1285→0.071	6.1 (20)
0	18.66	182 (360)	0.0137	0.1285→0.071	6.7 (22)
12	17.65	232 (450)	0.0168	0.1225→0.072	5.8 (19)
12	17.65	232 (450)	0.0168	0.1225→0.072	7.0 (23)
12	17.65	232 (450)	0.0168	0.1225→0.072	7.9 (26)
24	15.37	299 (570)	0.0239	0.1193→0.0723	6.4 (21)
24	15.37	299 (570)	0.0239	0.1193→0.0723	7.9 (26)
24	15.37	299 (570)	0.0239	0.1193→0.0723	9.1 (30)
36	12.09	343 (650)	0.0372	0.1129→0.0725	7.3 (24)
36	12.09	343 (650)	0.0372	0.1129→0.0725	8.8 (29)
36	12.09	343 (650)	0.0372	0.1125→0.0725	10.0 (33)
48	10.33	371 (700)	0.0399	0.1064→0.073	7.9 (26)
48	10.33	371 (700)	0.0399	0.1064→0.073	9.7 (32)
48	10.33	371 (700)	0.0399	0.1064→0.073	11.2 (37)
60	8.01	393 (740)	0.0474	0.0983→0.0732	8.5 (28)
60	8.01	393 (740)	0.0474	0.0983→0.0732	10.6 (35)
60	8.01	393 (740)	0.0474	0.0983→0.0732	12.5 (41)

 Figure 5-35. NO_x , CO_2 , and CO Emissions versus Fuel/Air Ratio

Table 5-14

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 5-14 (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 5-15

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	HC _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 5-16

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	

As shown in Table 5-17, the O_2 concentration in the diesel exhaust varies with load. Because the project objective is to deplete the 21% O_2 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. Because the catalyst is currently limited to a maximum operating temperature of 1260°C (2300°F), the maximum catalytic convertor O_2 depletion is limited to ~10%. For intermediate and low load settings of the engine, a modification of the convertor system is required.

Table 5-17

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 effect was attributed to hot catalyst radiation baking the uncooled diffuser transition section approaching the catalyst.

At the 60-kW (80.4-hp) load, the O_2 concentration at the catalyst inlet is low enough to allow stoichiometric and fuel-rich operation to be carried out without the risk of excessive catalyst temperatures. The results indicate that both O_2 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 5-36, 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 O_2 level allows stoichiometric operation but is closer to the allowable maximum than is the O_2 level at the 60-kW (80.4-hp) load. The results are essentially the same in both cases. 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%.

The 100-hour durability test at the maximum engine load condition of 60 kW (80.4 hp) was completed. Emissions from the diesel inert gas

Figure 5-36. Converter Exhaust CO₂ versus Fuel/Air Ratio

generator at the maximum load condition are shown in Table 5-18. Emission levels of NO_x and O_2 remained at less than 10 ppm. A CO level of less than 1% was achieved.

The catalyst durability tests at the engine load condition of 48 kW (64.3 hp) were also completed. Emissions from the diesel inert gas generator at the 48-kW load condition are shown in Table 5-19. Emission levels of NO_x and O_2 remained at less than 10 ppm.

Since 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/converto system is to be operated. One method for a limited load range is depicted by the schematic in Figure 5-37. In this system, part of the converto exhaust is recycled to the engine exhaust/catalytic converto 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 converto 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 5-38. In this example, two converters operate in series, and, depending on the mode of operation, the converters can accomplish full load-range capability and have the best potential for minimum CO production under the following conditions:

1. Diesel exhaust $\text{O}_2 \leq 10.0\%$
 - 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 $\text{O}_2 > 10.0\%$
 - 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 converto" designed to eliminate residual O_2 , CO, NO_x , etc.

Additional factors to be considered in reviewing modified N_2 generating systems are listed in Table 5-20. Process steps to be added downstream of the inert gas generator may be H_2O , CO_2 , and S removal. Available

Table 5-18

**Emissions Data From Catalyst Durability Test
at 60-kW (80.4-hp) Engine Load**

Elapsed Time of Life Test hours	Emissions			
	HC ^a ppm ^b	CO ^c %	NO _x ppm	O ₂ ^d ppm
3.5	-	9.6	0.14	<10
10.5	270	7.6	0.30	<10
12.5	-	6.2	0.05	<10
20.5	105	5.2	0.25	<10
31.0	-	5.0	0.40	<10
38.0	350	6.8	0.17	<10
44.0	100	5.0	0.55	<10
51.5	200	5.0	0.31	<10
54.5	300	5.0	0.20	<10
64.0	-	5.4	0.50	<10
70.0	-	4.6	0.40	<10
76.5	-	3.0	0.15	<10
83.0	30	0.7	0.50	<10
89.0	30	0.6	0.35	<10
93.5	30	4.4	0.08	<10
97.0	38	0.8	0.05	<10
100.0	50	0.7	0.10	<10

^aHC = hydrocarbons.

^bppm = parts per million.

^cVariable emission levels caused by small variations in fuel flow under manual control operation.

^dppm over baseline reading.

Table 5-19

**Emissions Data From Catalyst Durability Test
at 48-kW (64.3-hp) Engine Load**

Elapsed Time of Life Test hours	Emissions			
	HC ^a ppm ^b	CO ^c %	NO _x ppm ^x	O ₂ ^d ppm
4.5	3250	7.7	<10	<10
9.0	3500	7.7	<10	<10
18.0	5000	10.0	8.9	<10
22.5	5000	10.0	1.5	<10
28.0	4750	9.2	1.2	<10
32.0	2700	10.0	-	<10
46.0	-	9.5	1.4	<10
52.5	-	5.6	0.9	<10
67.0	-	4.8	0.5	<10

^aHC = hydrocarbons.

^bppm = parts per million.

^cVariable emission levels caused by small variations in fuel flow under manual control operation.

^dppm over baseline reading.

Vppm = Volume, parts per million

Figure 5-37. Schematic of Inert Gas Generator Using an Exhaust Gas Recirculation System; Limited Load Range

Vppm = Volume, parts per million

Figure 5-38. Schematic of Inert Gas Generator Using a Two-Stage Converter System; Unlimited Load Range

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.

A final report on the project has been prepared and will be published separately.

Table 5-20

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.	

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GEOHERMAL 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
FIELD EVALUATION OF HTM-1 MUD SYSTEM MAURER ENGINEERING LABORATORY TESTS FIELD TESTS	<p>AS REQUIRED</p> <p>IMPERIAL VALLEY</p>												

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

5.6 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 31 August 1980
Contract Number: 07-7068 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project was to determine the performance of the high-temperature mud system (HTM-1) under field conditions. Appropriate laboratory tests were also 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

A suitable well for testing HTM-1 was identified, and a field test was completed in May 1980. Laboratory testing of sample formulations and tests of mud samples from the field tests were also conducted. A final report has been prepared and will be published separately.

FY80 Progress

Laboratory Tests — 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 5-21 and were stirred for 40 minutes at high speed.

The first 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 5-22.

Table 5-21

HTM-1 Sample Formulations

Sample No.	Formulation		
I.	Water	0.16 m ³	(1.0 bbl)
	Thermogel	6.8 kg	(15.0 lb)
	Aquagel	2.3 kg	(5.0 lb)
	Brown coal	9.1 kg	(20.0 lb)
	Cypan	1.1 kg	(2.5 lb)
	Naolt	0.91 kg	(2.0 lb)
II.	Water	0.16 m ³	(1.0 bbl)
	Thermogel	6.8 kg	(15.0 lb)
	Aquagel	2.3 kg	(5.0 lb)
	Knife River lignite	9.1 kg	(20.0 lb)
	Cypan	1.1 kg	(2.5 lb)
	Naolt	0.91 kg	(2.0 lb)
III.	Water	0.16 m ³	(1.0 bbl)
	GeoGel	6.8 kg	(15.0 lb)
	Aquagel	2.3 kg	(5.0 lb)
	Knife River lignite	9.1 kg	(20.0 lb)
	Cypan	1.1 kg	(2.5 lb)
	Naolt	1.1 kg	(2.5 lb)

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 stored at Sandia was sampled. Visual inspection indicated that the material was dry, flowed 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 5-23. A composite

Table 5-22

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 5-23

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

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 5-24.

The composite coal sample was then used to prepare the two HTM-1 formulations shown in Table 5-25. The muds were stirred for 40 minutes at high speed, rolled at 66°C (150°F) for 18 hours, and static aged at 288°C and 3.5 MPa (550°F and 500 psi) for 24 hours and for 15 days. The mud properties after exposure to these conditions are shown in Table 5-26. The static-aged samples exhibited an increase in viscosity, gel strengths, and American Petroleum Institute (API) filtrates. Low shear strengths of 12.0 to 14.4 Pa (25 to 30 lb/100 ft²) after static aging indicated very little tendency toward solidification at temperatures up to 288°C (550°F). The shear strength of the sample aged 15 days showed that the mud will not solidify under these conditions.

HTM-1 Sample V was used in salt and solid contaminant tests. The contaminant was added to the mud, stirred 10 minutes, and tested. Each sample was rolled at 66°C (150°F) for 16 hours and then tested again. The results of these tests are contained in Table 5-27. The mud tested with salt and solid contaminants demonstrated the ability to tolerate up to 42.5 kg/m³ (15 lb/bbl) of salt and 283.5 kg/m³ (100 lb/bbl) of low-specific-gravity solids.

Gypsum and cement are sometimes encountered in drilling operations. In order to determine the effects of these contaminants on HTM-1, tests were conducted with laboratory-prepared samples of HTM-1. Additions of 5.7 kg/m³ (2 lb/bbl) of each material were made to separate samples of HTM-1. Neither of the contaminants had much effect on the rheological or filtration control characteristics of the mud when tested initially or after rolling 16 hours at 66°C (150°F). Cement increased the pH of the mud from 9.6 to 11.0 and increased the filtrate at 177°C and 3.5 MPa (350°F and 500 psi) from 21.0 cm³ to 24.4 cm³ (1.28 in.³ to 1.49 in.³). Gypsum contamination had even less effect on the mud properties than did the cement. Mud pH was lowered slightly, but, when the pH was readjusted with caustic soda, the mud properties were almost identical to those of the uncontaminated mud. Properties of the mud are indicated in Table 5-28.

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.

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.

Table 5-24

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 5-25

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 5-26

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)

Table 5-27

Mud Contaminants Tests: Salt and Solids

Conditions/Properties	Sample Number V							
	Salt Contamination							
Salt, kg/m ³ (lb/bbl)	0 0	0 0	14.2 (5)	14.2 (5)	28.3 (10)	28.3 (10)	42.5 (15)	42.5 (15)
Rolled at 65.6°C (150°F), hours	0	16	0	16	0	16	0	16
Plastic viscosity, Pa·s (cp)	0.022 (22)	0.017 (17)	0.013 (13)	0.013 (13)	0.016 (16)	0.016 (16)	0.017 (17)	0.017 (17)
Yield point, Pa (lb/100 ft ²)	2.9 (6)	3.8 (8)	2.4 (5)	2.4 (5)	5.8 (12)	6.2 (13)	8.1 (17)	7.2 (15)
10-second gel, Pa (lb/100 ft ²)	1.4 (3)	1.0 (2)	1.0 (2)	1.0 (2)	1.0 (2)	1.0 (2)	1.9 (4)	1.4 (3)
10-minute gel, Pa (lb/100 ft ²)	1.9 (4)	1.9 (4)	4.8 (10)	1.9 (4)	12.0 (25)	5.8 (12)	23.9 (50)	11.0 (23)
pH	11.1	9.6	10.0	10.5	9.8	9.9	9.6	10.3
API* Filtrate, ml (in. ³)	4.8 (0.29)	4.4 (0.27)	3.8 (0.23)	4.0 (0.24)	4.5 (0.25)	4.5 (0.25)	5.0 (0.31)	5.2 (0.32)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)	-	21 (1.28)	-	24 (1.46)	-	25 (1.53)	-	25 (1.53)
Conditions/Properties	Solids Contamination							
Shale, kg/m ³ (lb/bbl)	0 0	0 0	141.8 (50)	141.8 (50)	212.6 (75)	212.6 (75)	283.5 (100)	283.5 (100)
Rolled at 65.6°C (150°F), hours	0	16	0	16	0	16	0	16
Plastic viscosity, Pa·s (cp)	0.022 (22)	0.017 (17)	0.023 (23)	0.027 (27)	0.028 (28)	0.036 (36)	0.035 (35)	0.049 (49)
Yield point, Pa (lb/100 ft ²)	2.9 (6)	3.8 (8)	3.8 (8)	6.7 (14)	5.8 (12)	12.5 (26)	7.2 (15)	14.4 (30)
10-second gel, Pa (lb/100 ft ²)	1.4 (3)	1.0 (2)	1.4 (3)	1.4 (3)	1.4 (3)	3.8 (8)	1.9 (4)	3.8 (8)
10-minute gel, Pa (lb/100 ft ²)	1.9 (4)	1.9 (4)	12.0 (25)	8.6 (18)	21.1 (44)	28.7 (60)	22.5 (47)	31.6 (66)
pH	11.1	9.6	9.5	9.5	9.5	9.7	9.5	9.7
API* filtrate, ml (in. ³)	4.8 (0.29)	4.4 (0.27)	3.6 (0.22)	3.2 (0.20)	3.6 (0.22)	3.2 (0.20)	3.2 (0.20)	3.2 (0.20)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)	-	21 (1.28)	-	16 (0.98)	-	17 (1.04)	-	18.8 (1.15)

*API = American Petroleum Institute

Table 5-28

Mud Contaminants Tests: Cement and Gypsum

Conditions/Properties	HTM-1 Sample			
	Cement Contamination			
Cement, kg/m ³ (lb/bbl)	0 0	0 0	5.7 (2)	5.7 (2)
Rolled at 65.6°C (150°F), hours	0	16	0	16
Plastic viscosity, Pa·s (cp)	0.022 (22)	0.017 (17)	0.016 (16)	0.018 (18)
Yield point, Pa (lb/100 ft ²)	2.9 (6)	3.8 (8)	1.9 (4)	2.4 (5)
10-second gel, Pa (lb/100 ft ²)	1.4 (3)	1.0 (2)	1.0 (2)	1.4 (3)
10-minute gel, Pa (lb/100 ft ²)	1.9 (4)	1.9 (4)	1.9 (4)	2.4 (5)
pH	11.4	9.6	11.3	11.0
API filtrate, ml (in. ³)	4.8 (0.29)	4.4 (0.27)	4.8 (0.29)	4.8 (0.29)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)	- -	21 (1.28)	- -	24.4 (1.49)
	Gypsum Contamination			
Gypsum, kg/m ³ (lb/bbl)	0 0	0 0	5.7 (2)	5.7 (2)
Rolled at 65.6°C (150°F), hours	0	16	0	16
Plastic viscosity, Pa·s (cp)	0.022 (22)	0.017 (17)	0.016 (16)	0.018 (18)
Yield point, Pa (lb/100 ft ²)	2.9 (6)	3.8 (8)	1.9 (4)	3.4 (7)
10-second gel, Pa (lb/100 ft ²)	1.4 (3)	1.0 (2)	1.0 (2)	1.0 (2)
10-minute gel, Pa (lb/100 ft ²)	1.9 (4)	1.9 (4)	2.4 (5)	1.9 (4)
pH	11.1	9.6	10.3	10.3
API filtrate, ml (in. ³)	4.8 (0.29)	4.4 (0.27)	4.0 (0.24)	3.9 (0.24)
Filtrate at 176.6°C (350°F), 3.5 MPa (500 psi), ml (in. ³)	- -	21.0 (1.28)	- -	21.4 (1.31)

Field Test — Field testing the HTM-1 mud system was completed in May 1980. McCulloch used HTM-1 to deepen its Mercer No. 228 well. Brown coal used in the HTM-1 formulation was shipped from Sandia to the test site. Dresser Magcobar furnished all of the remaining mud additives used in the HTM-1 mud. Maurer Engineering supplied the equipment and personnel for testing, monitoring, and evaluating the performance of HTM-1. The drilling contractor was Republic Drilling.

McCulloch's Mercer No. 228 well was being used as an injection well. The 34.0-cm (13.375-in.) thick casing was set at 1219 metres (4000 feet). A drilling rig was moved on location during the last week of April, and rig-up operations were begun. Drilling began at 1219 metres (4000 feet). A conventional bentonite mud was used to drill from 1219 metres to 2316 metres (4000 feet to 7600 feet). The mud was converted to an HTM-1 mud after a trip to change bits. Water, sepiolite, brown coal, sodium polyacrylate, and caustic soda were added to the mud while drilling was being carried out with a new bit. The exact amount of water dilution was determined by pilot testing on location. Daily treatments were also based on daily tests and on pilot tests run on location.

HTM-1 was used to drill the interval from 2316 metres to 3328 metres (7600 feet to 10 920 feet). The formation temperature was 232°C (450°F) at the bottom of this interval. Under these conditions, the HTM-1 mud system performed well. There was no mud solidification, no corrosion problem, and no serious lost circulation.

The following mud tests were run daily:

Physical Properties

Mud density
Funnel viscosity
Plastic viscosity
Yield point
10-second gel
10-minute gel
API filtrate
Cake thickness
Filtrate at 177°C (350°F) and
3.5 MPa (500 psi)
Sand content
Water content
Oil content
Solids content

Chemical Properties

Bentonite
Calcium
Magnesium
Chloride
Carbonate
Bicarbonate
Hydroxide
API alkalinity

Each time a test was run, the sample was given an identifying number, the well depth at the time the sample was obtained was indicated, and the sample source was identified. Material additions were based on pilot tests run on location. Other pertinent information obtained included a complete bit record and records on daily operations, casing and equipment, daily material additions, and pilot tests.

The results of the field test are being analyzed. A detailed report on the results of the field test will be prepared and published separately.

6. COMPLETION TECHNOLOGY

Geothermal well costs are strongly dependent on completion techniques. 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 that will extend well life and improve production. Projects are presently under way 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, (3) designing and demonstrating a system using a controlled cavitation technique for downhole geothermal well cleaning and scale removal, (4) investigating drilling fluid/formation interactions, and (5) defining current problems with completion equipment and recommending potential solutions. 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 identification of failure modes for geothermal well casing. 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.

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 the designing of an operational downhole geothermal well cleaning and scale removal system were established. The development of this system is nearing completion.

The first phase of a project to investigate the effect on rock permeability of drilling mud invasion has been completed. The evaluation of the laboratory test results for two mud systems indicated that (1) permeability impairment due to formation/drilling fluid interaction is time dependent, with significant impairment occurring within 48 hours residence time, (2) permeability impairment is temperature dependent, with lower temperature, 100°C (212°F), exposures resulting in greater impairment than higher temperature, 200°C (392°F), exposures, and (3) both temperature and time dependence vary with drilling fluid chemistry. A report on the experiments was published separately. A follow-on project to continue the study of drilling fluid/formation interactions is under way.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

6.1 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 were purchased from a commercial supplier. Diagnostic techniques for determining the performance of these perforators were developed. A test chamber was designed and constructed for the heating of perforators at elevated temperatures. After heating, the explosive charges are fired into a target and the performance of the perforator evaluated from a study of the target. Trials with the chamber were made in order to establish that it will function as designed. Perforators containing the explosive HNS have been heated for 2-hour periods at different temperatures in the special test chamber. The explosive charges were fired into a target and were found to function properly at temperatures up to 250°C (482°F).

FY80 Progress

Ten different types of commercial perforators, designed to function at ordinary oil-well temperatures, were purchased for testing.

An experimental chamber was designed, constructed, and tested for the evaluation of perforating explosive charges at elevated temperatures. A schematic of the chamber is shown in Figure 6-1. The chamber is designed to bring the perforator up to a predetermined temperature rapidly and maintain that temperature. The temperature of the perforator can be monitored continuously during the heating process.

Trials without explosives were run with the chamber, and a few minor deficiencies were identified and corrected.

After 2 hours at 150°, 200°, and 250°C (302°, 392°, and 482°F), perforators containing the explosive HNS were detonated and allowed to perforate a composite target composed of a 9.5-mm (0.375-in.) thick steel plate securely attached to an aluminum block. The performance of each perforator was evaluated by measuring (1) the diameter of the jet entrance hole, (2) the depth of the hole, and (3) the volume of the hole. The data obtained were compared with the data gathered at ambient temperature, and the performance at the elevated temperature was found to exceed the ambient temperature performance.

Figure 6-1. Schematic of Test Apparatus

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

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

▽ PLANNED COMPLETION
 ▼ COMPLETED

6.2 Completion Technology Consultation

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

Project Objective

The project objective was 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-the-art level, geothermal well completion technology, 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 1st quarter of the FY80 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 was concluded.

FY80 Progress

Cementing Tools -- The activities essential for defining the types of downhole primary cementing equipment needed in geothermal wells were planned and organized. A minimum of time was spent on a literature review, because previous reports served as a background to this study. The greatest amount of time was spent in contacting operators, suppliers, and manufacturers for documentation of failures.

J. Rowley of the hot dry rock (HDR) project, LASL, was interviewed concerning cementing equipment failures. Operators and service companies in The Geysers, California, were contacted by phone, and meetings were scheduled in Santa Rosa, California. Downhole cementing equipment and monitoring tool requirements for detection of geothermal well failures were covered in the meeting.

CTC met with Union Oil of California and Aminoil in Santa Rosa, California, to discuss current cementing practices in The Geysers. Service companies in the area, including Halliburton, Smith Tool Company, Tillett Tool and Supply Company, and Midway Fishing Tool Company, were contacted to assess the limitations of cementing equipment. A contact was also made with Shell's Geysers operations group in Ventura, California.

The work on establishing the needs and defining requirements for cementing tools was being completed as the fiscal year ended. A final report is being prepared and will be published separately.

Monitoring Tools -- All major wireline companies were contacted, and a list of casing inspection equipment available to the geothermal industry was compiled. Mechanical as well as electrical monitoring equipment was investigated. The emphasis was placed on the temperature limitations of existing equipment. Geothermal well designs were reviewed to determine the dimensional requirements of monitoring equipment. Mechanical casing inspection techniques, such as the use of impression packers and mechanical or slick line calipers, were also reviewed. The applicability of logging tools that have been developed by SNL was also assessed.

Additional contacts with logging companies were made in the Houston area, including a meeting with the Atlas Oilfield Services Group of Dresser Industries.

Three of the four most active geothermal operators, Union Oil Company of California, Aminoil, and Shell, were contacted in Santa Rosa and Ventura, California, to assess the current casing designs and inspection needs in The Geysers and Imperial Valley. Temperature profiles within various casing strings were assessed to determine the environmental requirements of casing inspection equipment and to set priorities for critical tool development.

The work on defining the types of monitoring tools required for detecting geothermal well failures was completed at the close of the fiscal year. A final report, Casing Inspection Technology and Critical Development Needs as Applied to Geothermal Wells, was published separately.¹ Some of the conclusions of this report follow.

- Critical Inspection Needs

The two major categories of geothermal completions, hydrothermal steam and hydrothermal hot water, have important similarities. Wellheads, casing sizes, and maximum temperatures are relevant to these two categories and represent criteria suitable for the development of universal geothermal casing inspection equipment. Table 6-1 indicates that casing failures are common to all geothermal wells and that inspection is needed during completion and production.

U.S. geothermal operators routinely utilize 34.0-cm (13-3/8-in.) surface casing, 24.4-cm (9-5/8-in.) intermediate liners, and barefoot completions. Frequently, 18-cm (7-in.) or smaller slotted production liners are used. Casing inspection equipment should function properly in these casing sizes and be adaptable to minor variations in size. (See Table 6-2.)

At present, the maximum temperatures in producing wells are 249°C (480°F) within surface casing, 282°C (540°F) within intermediate liners, and up to 327°C (620°F) within production liners. However, maximum temperatures are seldom reached. The temperatures within surface casing and intermediate liners rarely exceed 260°C (500°F) during drilling and completion.

Table 6-1

Geothermal Well Casing Failures

Type of Failure	Cause of Failure	Resulting Damage
Drilling Wear	<ul style="list-style-type: none"> • High-velocity, abrasive air-drilling cuttings • Drill pipe rotation without rubber protectors • Drill pipe drag through casing doglegs 	<ul style="list-style-type: none"> • Casing leak • Reduced collapse resistance • Reduced burst pressure
Collar or Thread Failure	<ul style="list-style-type: none"> • Improper casing design • Factory defect • Improper installation 	<ul style="list-style-type: none"> • Casing leak • Parted casing
Collapse	<ul style="list-style-type: none"> • Reservoir compaction with production • Fault slippage • Poor cement job • Entrapped fluid (tieback and liner overlap) 	<ul style="list-style-type: none"> • Restricted passage • Loss of well
Internal Corrosion	<ul style="list-style-type: none"> • Oxidation • Corrosion stress cracking • Hydrogen embrittlement 	<ul style="list-style-type: none"> • Leak • Reduced casing strength • Sudden failure of high-strength steels
Internal Erosion	<ul style="list-style-type: none"> • Production of abrasive sand particles 	<ul style="list-style-type: none"> • Casing/wellhead leak • Reduced burst/collapse strength • Liner slot erosion
External Corrosion	<ul style="list-style-type: none"> • Poor cement job • Cross flow behind casing • Cathodic/anodic action at bed boundaries 	<ul style="list-style-type: none"> • Casing leak • Reduced burst/collapse resistance
Buckling	<ul style="list-style-type: none"> • Thermal expansion • Compaction and shortening • Enlarged open hole • Non-uniform cement support • Sand production 	<ul style="list-style-type: none"> • Elliptical, restricted passage • Radical changes in deviation or direction • Pipe collapse and well loss

During completion operations, inspection equipment capable of operating at 260°C (500°F) within surface casing and intermediate liners is needed for monitoring (1) the quality of the cement job, (2) drilling wear, (3) collapse, and (4) the dogleg severity.

The evaluation of the cement can be made in liquid-filled casing, but, once air drilling is begun in the The Geysers, all other inspection may require exposure to air or steam environment.

Inspection equipment capable of operating at production temperatures, 327°C (620°F), is needed for monitoring collapse and buckling, internal and external corrosion, and the slots in the production liner. The inspection must be accomplished without cooling or well killing, both of which are costly and may initiate formation or casing damage. However, surface casing and intermediate liners normally are not exposed to temperatures above 249°C (480°F) and 282°C (540°F), respectively. Corrosion monitoring equipment must function properly through small quantities of scale.

In Table 6-2, critical monitoring needs are summarized for the typical casing string in each of the following four categories of hydrothermal wells:

1. Steam wells prior to completion,
2. Steam-producing wells,
3. Hot water wells prior to completion, and
4. Hot-water-producing wells.

Table 6-2 also includes the maximum temperature expected in each downhole situation.

• Existing Casing Inspection Equipment

A variety of techniques have been devised by the petroleum industry to monitor casing deterioration or failure. In general, four basic types of monitoring equipment are used:

1. Mechanical wireline: equipment run on non-electric cable,
2. Electric wireline: equipment run on electric wireline,
3. Mechanical inspection: equipment run on drill pipe, and
4. Surface inspection: equipment that monitors production.

Each of the groups of equipment has merit and may be used during the life of a well. The complexity of instrumentation generally increases from mechanical inspections, which involve simple clock-type recorders, to electric wireline surveys that are quite sophisticated.

• Mechanical Wireline

Non-electrical wireline surveys are widely used in oil and gas wells to gather downhole data. The wide use of mechanical wireline surveys today is primarily an extension of minor well maintenance operations such as removing paraffin from tubing or bailing sand. The convenience and economics of gathering downhole production data during such operations has encouraged the development of a variety of instruments. Mechanical surveying devices are normally run by service companies, but, in remote areas, operators occasionally purchase equipment.

Table 6-2

Operational Parameters and Inspection Needs for Hydrothermal Wells

Well Type	Casing Size, cm (in.) ^a	Maximum Temp. in Casing, °C (°F)	Monitoring Needs
Hydrothermal Steam Wells Prior to Completion	Surface casing	127 (260)	Cement evaluation Drilling wear Dogleg severity Installation damage
	34.0 (13-3/8)	227 (440)	
	Protection liner		
	24.4 (9-5/8)	127 (260)	Cement evaluation Installation damage
	Tieback string		
	27.3 24.4 (10-3/4)(9-5/8)		
Hydrothermal Steam-Producing Wells	Surface casing	227 (440)	Internal corrosion, erosion External corrosion Buckling Collapse Collar or thread failure
	34.0 (13-3/8) ^b	238 (460)	
	Protection liner		
	24.4 (9-5/8)	227 (440)	Collapse Internal corrosion, erosion
	Liner tieback		
	27.3 24.4 (10-3/4)(9-5/8)		
Hydrothermal Hot Water Wells Prior to Completion	Surface casing	82 (180)	Cement evaluation Drilling wear Dogleg severity Installation damage
	34.0 (13-3/8)	243 (470)	
	Intermediate liner		
	24.4 (9-5/8)	327 (620)	Installation damage
	Slotted production liner		
	17.8 (7)		
Hydrothermal Hot-Water-Producing Wells ^c	Surface casing	249 (480)	Internal corrosion, erosion External corrosion Buckling Collapse Collar or thread failure
	34.0 (13-3/8)	282 (540)	
	Intermediate liner		
	24.4 (9-5/8)	327 (620)	Collapse Slot deterioration Buckling
	Slotted production liner		
	17.8 (7)		

^aMinimum wellhead i.d. 25.4 cm (10 in.) in all cases^bIn wells without tieback strings only^cInternal scaling likely

Mechanical wireline surveys have the following advantages:

1. Inexpensive, reliable equipment,
2. No rig required,
3. Minimal electronics,
4. Variety and availability of service companies,
5. Minimal training of personnel, and
6. Adaptability to extreme environments.

Wireline surveys differ from other techniques of monitoring casing and well performance in that data are acquired and recorded within the downhole equipment. The only information available to the wireline operator during the survey is (1) surface tension, (2) depth, (3) time, and (4) rate of descent or ascent. The correlation of downhole data with depth depends on an accurate assessment and comparison of the downhole data with surface records.

Following are several mechanical wireline tools that may be considered for geothermal well application, with modifications or improvements as suggested previously under "Critical Inspection Needs." These tools include

1. Kinkmeters--Sperry Sun gyroscopic devices used to measure lateral casing deflection (buckling),
2. Deformed-casing calipers--tools with long feelers that record pipe deformation such as collapse or eccentricity,
3. Microscopic calipers--sensitive multiple-feeler tools for detecting internal defects such as pitting or thinning,
4. Spinner flowmeters--tools with exposed vanes that record the velocity of the fluids in which they are immersed, and
5. Temperature recorders--temperature-sensing devices that record data during brief stops at selected stations.

The following conclusions were drawn from information gathered on the mechanical wireline tools:

1. Buckled or collapsed casing can be surveyed by deformed-casing calipers in casing 29.8 cm (11-3/4 in.) or smaller in temperatures less than 204°C (400°F).
2. The severity of buckling can be assessed in casing larger than 10 cm (4 in.), but insulating flasks are needed to increase the temperature ratings of tools to above 110°C (230°F).
3. Internal casing damage can be evaluated by corrosion calipers in casing 34.0 cm (13-3/8 in.) or smaller in temperatures less than 260°C (500°F).
4. Casing leaks can be located under certain conditions by spinner flowmeters or by temperature surveys in wells having temperatures of less than 260°C (500°F) and 316°C (600°F), respectively.

• Electrical Wireline Inspection Equipment

Electric well logs are surface recordings of data transmitted via multi- or single-conductor cables from downhole tools or sondes. Surface recording in logging, as opposed to recording in the sonde itself, offers the advantage of immediate access to the data. The variety of surveys now available include direct or indirect evaluation of electrical, radioactive, acoustical, magnetic, and electromagnetic properties of formations or casing as well as environmental parameters such as flow rate, temperature, pressure, hole direction, deviation, and diameter.

The tools investigated and their geothermal well applications follow:

1. Cement bond logs--indicate pipe-to-cement bonding and cement compressive strength,
2. Photon logs--investigate the bulk density of fluids, cement, gravel packs, and other materials in the annulus around the casing,
3. Subsidence logs--measure the change in the length of the casing joints as the formation thickness changes,
4. Electrical deformed-casing calipers--give a continuous reading of the minimum i.d. of the casing,
5. Internal calipers--describe the casing's internal surface by using up to 64 independently reading feelers,
6. Borehole televiewers--describe the inside walls of the casing,
7. Casing potential profile logs--measure corrosion-causing electrical potentials with downhole electrodes,
8. Electronic calipers--measure internal diameters by evaluating currents induced around the casing's internal circumference,
9. Induction casing thickness logs--measure the phase shift of electromagnetic waves within the varying thickness of steel,
10. Flux leakage-eddy current logs--discriminate between internal and external casing corrosion,
11. Spinner flowmeters--measure the velocity of fluid movement around the tool,
12. Noise surveys--detect acoustic signals generated downhole by the turbulent flow of liquid or gas leaks in tubulars, and
13. Temperature logs--give a continuous temperature profile of the fluid inside the casing as the fluid is affected by various external conditions.

In general, equipment development can do little to change the physics of measurement. However, the upgrading of equipment so that tools can monitor larger casings and withstand higher temperatures can be of value. The following conclusions were derived from the information collected on these electric logging tools.

1. Cement jobs can be evaluated in wells with casings 34.0 cm (13-3/8 in.) or smaller and temperatures less than 260°C (500°F). However, the quality of the data concerning such large casings is questionable.
2. Buckled or collapsed casing can be evaluated in casing sizes up to 34.0 cm (13-3/8 in.) and at temperatures less than 149°C (300°F).
3. Internal casing damage can be surveyed by corrosion calipers in casing sizes up to 34.0 cm (13-3/8 in.) and at temperatures less than 177°C (350°F). Borehole viewers are available for surveys of casings up to 51 cm (20-in.) and in temperatures of 149°C (300°F).
4. External corrosion can be detected by casing potential profiles in air-filled casings 34.0 cm (13-3/8 in.) or smaller in temperatures less than 149°C (300°F) and in pressures less than 20.7 MPa (3000 psi).
5. Internal and external corrosion can be monitored by electromagnetic thickness-electronic caliper logs in casings 29.8 cm (11-3/4 in.) or less and temperatures below 232°C (450°F). Flux leakage-eddy current surveys are available for casings 21.9 cm (8-5/8 in.) or less and temperatures below 124°C (255°F).
6. Casing leaks can be detected by spinner flowmeters and temperature surveys in wells with temperatures less than 316°C (600°F). Noise surveys are available for temperatures up to 232°C (450°F).

• Mechanical Casing Inspection

Mechanical casing inspection techniques include all measurements made with drill pipe and associated equipment. When casing damage is suspected during drilling or initial well completion, the first and sometimes only data gathered are gathered by mechanical inspection. The costs associated with moving a rig onto a well usually prohibit the utilization of a rig on producing wells, but mechanical inspection is a logical first step in a workover program. The advantages are as follows:

1. The operation is reliable and simple,
2. Minimal training of personnel is required, and
3. The temperature limits of the tools are often compatible with the geothermal environment.

The following discussion is an overview of several non-wireline mechanical inspection tools or techniques that may be applicable to geothermal well casing inspection.

1. GO/NO-GO gage--This tool will locate the depth of the casing restriction and indicate the diameter of the restriction. It would be necessary to move a rig onto the well to run a work string.
2. Impression blocks--This technique recovers an impression of down-hole restrictions by forcing a malleable lead block into the damaged area. The technique is commonly used to record an impression of the top of parted tubing or packers so as to design a fishing tool. A rig is required to handle the work string. The usefulness of this technique may be limited by the low melting point of lead, which is 316°C (600°F).
3. Retrievable test packers--By utilizing pumped fluids and various ports and plugging devices, this system can determine the pressure integrity of the casing and the depth and extent of leaks. The technique has limitations: the standard temperature rating of the tools is 160°C (320°F), the minimum inside diameter required for tool passage is the casing i.d. minus 1.3 cm (0.5 in.), and a rig is required.
4. Impression packers--The impression packer has an inflatable element with a special type of rubber applied directly to the element or to a rubber sleeve that, in turn, fits over the element. The packer is positioned opposite damaged zones and inflated, pressing the soft rubber into all of the irregularities in the casing. The packer then is deflated but the soft rubber retains the impression.^{2 3} The shape and extent of the damage to the internal wall of the casing, e.g., pits, cracks, and holes, are examined with this system. The maximum temperature at which the packer can be used is presently 160°C (320°F). The maximum inflated diameter of the packer is approximately twice the deflated diameter less 1.3 cm (0.5 in.).^{4 5}

• Surface or Production Monitoring Techniques

Continuous records of production parameters such as sand production, flow rate, pressure, and temperature can often define the event, or series of events, that led to casing failure. Casing leaks are often characterized by unexplained temperature and pressure anomalies, and early detection could allow repairs to be initiated prior to more expensive failure. The following is a summary of commonly applied techniques and the parameters they may detect:

1. Surface pressure records--Continuous monitoring of the surface pressure will indicate changes that are caused by collapse or other casing failure. These changes diagnose casing leaks, which result in an increase in pressure, or restrictions to flow, which result in a decrease in pressure.
2. Surface temperature--Continuous monitoring may also indicate changing downhole conditions such as casing or liner leaks or other failures. Casing leaks may cause an increase in the flow rate but may also cool the production stream.

3. Bottomhole pressure--Flow restrictions become more obvious if the surface pressure can be continuously compared to bottomhole pressures. A variety of continuous bottomhole pressure sensors have been developed for service in the petroleum industry, but the reliability of these sensors is severely hampered by high temperatures. A current limitation is the 160°C (320°F) ratings of electrical pressure sensors.
4. Corrosion coupons--The parameters investigated by the evaluation of coupons are (1) the corrosion rate on the internal wall of the casing and (2) the effectiveness of corrosion inhibitors. The limitations are that (1) the results of the tests are site specific, (2) the tests are affected by film or scale, and (3) pitting of the coupons is not distinguished from uniform corrosion.
5. Corrosion probes--A variety of instruments are available to continuously monitor the corrosion of probes or coupons that are inserted into the flowline. The simplest technique monitors the resistance of a metal specimen as its cross-sectional area is reduced by corrosion. The limitations to the usefulness of corrosion probes include those affecting corrosion coupons plus errors introduced by conductive films such as iron sulfide.
6. Chemical analysis--The parameters investigated by this procedure include (1) the mass of produced iron, a measure of the internal corrosion rate, (2) the corrosivity of the production fluids, and (3) the effectiveness of corrosion inhibitors. To make an accurate analysis, the iron content of the formation fluid must be known, and this value must remain constant.
7. Sonic sand sensor--Sand production is a major source of well failures in many oil and gas fields around the world. Bridging, casing, and liner failures resulting from erosion, formation compaction, and subsidence are common problems caused by sand production. If the original well completion provides inadequate sand control, the well must either be recompleted or managed so that it produces in a manner that minimizes sand production.

Flowline sand detectors offer a means of monitoring sand production at various flow rates. It has been found that, under certain conditions, a minor reduction in flow rate significantly reduces sand production. The monitoring equipment consists of an acoustic sensing probe tuned to measure sound frequencies produced by sand impinging on the sensor. The amplitude of the produced sound is monitored as production is varied, until the maximum sand-free flow rates are determined.^{6 7}

Technology Transfer -- A paper, "Geothermal Well Casing Failure Modes," was prepared and presented to the 1980 American Society of Mechanical Engineers (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.

The technical paper, "Geothermal Well Completion: A Critical Review of Downhole Problems and Specialized Technology Needs," was presented to about 200 petroleum engineers at the Society of Petroleum Engineers (SPE) Southwest Texas Spring Symposium in Corpus Christi, Texas, on 9 April 1980. Although this particular geographical area does not have hydrothermal geothermal wells, the area is on the fringes of the Gulf Coast geopressured geothermal area; therefore, the technology presented at the symposium is highly relevant to the portion of southwestern Texas which borders the Gulf. Interest in the technology was expressed by some operators who are investing in western U.S. hydrothermal sites.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

————	ACTIVITY PERIOD	○	PLANNED START	▽	PLANNED COMPLETION
-----	RESCHEDULED	●	STARTED	▼	COMPLETED

6.3 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 28 November 1980
Contract Number: 13-2361 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The objective of this project was to develop and apply a controlled cavitation technique for downhole geothermal well cleaning and scale removal.

Work in this program was 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 (Contract Number 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 demonstration system design was based on the data obtained from this test. The water-powered, hydraulic, cleaning head motor was fabricated. The field demonstration has been rescheduled for early October 1980 because the coiled tubing planned for use in this test was found to have an insufficient pressure capacity under typical tensile stress.

FY80 Progress

Cleaning Head Rotator and Motor -- The water-powered, hydraulic, cleaning head rotator was designed and fabricated. This rotator incorporates a gerotor-type hydraulic motor that was modified to operate using water as the working fluid. The metal-to-metal sealing surfaces in the motor were redesigned, as suggested by the manufacturer, to incorporate a self-lubricating bearing material on both of the sealing faces of the motor.

The modification of the hydraulic motor involved replacement of the existing metal-to-metal wear surfaces on which the ends of the rotor slide. Several candidate materials that exhibit good self-lubricating properties were considered. Among the materials evaluated were aluminum bronze, P/M bronze, Fluorosint 500, Fluorosint 207, TFE, and Torlon 4301.

The P/M bronze was selected. This material is an oil-filled, self-lubricating bronze with a chemical composition of 90% copper and 10% tin.

The top section of the rotator was machined to incorporate a rotating seal utilizing two polytetrafluoroethylene-lined, spherical bearings and a high-pressure/high-temperature, graphite-carbon-glass-Teflon cartridge seal. Figure 6-2 shows the layout of the various components contained inside the rotator assembly. The feedwater for the modified hydraulic motor is obtained from the high-pressure supply line that carries the water to the cavitating cleaning nozzles. Approximately $6.3 \times 10^{-5} \text{ m}^3/\text{s}$ (1 gpm) will be utilized to supply the motor. The rpm is set by the orifice size. The orifice is installed into the bleed passage contained in the upper body of the rotator assembly. The feedwater is carried to the motor from the upper body by 0.635-cm (0.25-in.) o.d. stainless-steel tubing and swaged fittings.

This supply water will be bled from the central, 68.9-MPa (10 000-psi), $9.5 \times 10^{-4} \text{ m}^3/\text{s}$ (15-gpm) feed line. The bleed port was located 1.91 cm (0.75 in.) above the rotary seal shaft. The orifice will be installed into this bleed line, and the size will be selected to yield a motor rotational speed of 60 rpm. Experiments with the motor have indicated that the orifice size required for creating a 60-rpm rotation is 0.064 cm (0.025 in.). Previous experiments demonstrated that this speed allows the four-nozzle cleaning head (Figure 6-3) to operate most effectively.

The motor rotates the central 1.59-cm (0.625-in.) o.d. high-pressure tube by means of a set of 28-tooth, 14-1/2-degree-pressure-angle spur gears. One gear is attached to the motor; the other is attached to the rotating seal spindle.

The supply water enters the upper body of the rotator assembly at 68.9 MPa (10 000 psi) and travels through the hollow spindle of the rotating seal and the 1.59-cm (0.625-in.) tubing attached to the spindle. The water then enters the cleaning head attached to the bottom of the 1.59-cm (0.625-in.) turbine, where it is distributed to the four cleaning nozzles.

Threshold Intensity of Erosion -- Experiments to determine the threshold intensity of erosion of the calcium-based scale found in the East Mesa wells were completed. It was determined that the minimum intensity that must be produced at the scale surface is equal to 650 W/m^2 (0.42 W/in.^2). In the laboratory, this intensity was realized using a taper-jet-configuration nozzle, T-804, at a pressure of 68.9 MPa (10 000 psi) and at a distance from the nozzle of 15 cm (6 in.). When the nozzle distance is decreased to the optimum distance of 1.9 cm (0.75 in.), the intensity delivered to the scale surface increases to $15\,000 \text{ W/m}^2$ (9.7 W/in.^2).

Coiled Tubing Tests -- A search for a coiled tubing capable of withstanding the 103-MPa (15 000-psi) operating pressure was conducted. 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 had a 2.11-mm (0.083-in.) 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

Figure 6-2. Downwell Rotator Schematic

Figure 6-3. Cleaning Head, Multi-Nozzle Holder

(11 000 psi). However, a question arose 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 might cause the tube to rupture. Therefore, a limited test program was proposed that would allow Otis to burst test the tubing in their laboratory under simulated field conditions to verify the maximum allowable operating pressure.

The burst test on the coiled tubing was performed by Otis Engineering on 2 July 1980. Two burst tests were conducted on the heavy-wall, 2.11-mm (0.083-in.) thick, R-70 tubing. The test was designed to simulate the loads that the tubing would encounter during the field trial of the well cleaning/descaling system. The tubing was strung over the injector head assembly and tensile load was applied to the tubing to simulate the weight of a 610-metre (2000-foot) long tubing string. The internal pressure was increased until the failure point was attained.

The results of the tests indicated that the tubing was not as strong as was originally predicted. The theoretical burst of the R-70 was calculated to occur at 97 MPa (14 000 psi). Otis had successfully pressure tested a section of the tubing to 124 MPa (18 000 psi), which was the upper limit of the pump being used. However, this test had been conducted without the tubing being strung over the injector head and loaded to simulate the 610-metre (2000-foot) string.

When the tubing was placed under the tensile load over the injector head and pressurized, it burst at a pressure of 83 MPa (12 000 psi). A second test was conducted to verify this result, and, during this test, the tubing burst at 86 MPa (12 500 psi). It was apparent from these tests that the additional stresses incurred by the tubing bending over the injector head severely affected the tubing's performance. If the descaling test were undertaken, a safety margin of 16 MPa (2250 psi) would be available if the 69-MPa (10 000-psi) cleaning head/nozzle design pressure were utilized.

Subsequent to the burst test, additional information on the field performance of this tubing was supplied by Otis Special Services. Several of their coiled tubing units had incorporated this tubing during actual service jobs so that information could be obtained on the long-term reliability of the R-70 tubing. Otis reported that this tubing was proving to be unreliable because of its tendency to harden when in use. Otis' field reports indicate that the tubing is failing at pressures of 21 MPa (3000 psi) after several trips. Otis at first suspected that there might be a problem with the weld penetration at the seam of the tubing during manufacturing. However, after conferring with Republic Steel, this possibility was eliminated. Republic indicated that there may be a chemistry control problem during the manufacturing of the tubing material that contributes to the early failure of the tubing.

Otis, based on their field reports and the burst test results, would not endorse a 50% probability that the tubing would survive one trip at a 69-MPa (10 000-psi) operating pressure. Otis considered it unwise to proceed with the field test using this tubing in light of its unreliability. Hence, investigations of alternative delivery systems for injecting the cleaning tool into the well were undertaken. The use of a workover rig

and a small diameter drill pipe to deliver pressure downhole to the cleaning device is considered the best alternative. This alternative system will be field tested.

Field Tests — Because the coiled tubing was found to be inadequate, the field test has been rescheduled for early October 1980.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

6.4 Drilling Fluid/Formation Interactions

Contractor: Terra Tek, Inc.
Principal Investigator: D. Enniss (801) 582-2220
Contract Period: 10 March 1980 to 31 January 1981
Contract Number: 46-8747 (Sandia)
Technical Consultant: T. Hinkebein (505) 844-5202

Project Objective

The objective of this project is to study, under laboratory conditions, drilling fluid/formation interactions to investigate

1. Permeability alterations due to "salinity-contrast" exposure as a function of filtrate chemistry, temperature, and exposure rate,
2. Permeability reduction after exposure to drilling muds containing specific-sized bridging particles, as a function of particle size, particle size distribution, and temperature,
3. The best method of simulating formation damage in a fractured formation under laboratory conditions, and
4. The formation damage problems being experienced in the East Mesa KGRA.

Project Status

This project is the second phase of the study of formation damage associated with drilling fluids. Earlier work investigated drilling mud formation invasion effects upon permeability as a function of varying stagnation times, mud types, and temperature. The Phase I efforts were completed at the close of FY79, and a report was submitted early in FY80. The current phase of the investigation was initiated with laboratory tests to determine any effect in situ brines may have on drilling fluid/formation permeability. These tests were completed in July 1980. Work on the effects of drilling-fluid-entrained particles on formation permeability and on the simulation of formation damage in a fractured formation was also initiated. However, these efforts were suspended in order to accommodate a high-priority investigation into the formation damage problems being experienced in the East Mesa KGRA. This work was nearing completion at the close of the fiscal year.

FY80 Progress

Phase I -- Samples were prepared from core that was taken from Republic Geothermal, Inc., well 78-30RD, East Mesa, Imperial Valley and saturated with brine representative of the in situ state. An initial, undamaged, permeability measurement was made on samples that were at simulated in situ conditions including an overburden pressure of 34.5 MPa (5000 psi), a pore fluid pressure of 14.9 MPa (2165 psi), and a temperature

up to 200°C (392°F). All permeability measurements were made in the direction of backflow. Samples were then subjected to simulated "hot" mud circulation and stagnation times. Stagnation times varied from 12 to 48 hours. Following this "damage" sequence, permeability was measured again in the backflow direction and compared with the original value.

The following two drilling fluid systems were evaluated:

HTM-1: A high-temperature drilling fluid formulated for Sandia National Laboratories by Mudtech, Inc., Houston, Texas. Constituents per standard barrel, 0.16 m³ (42 gal), are

Bentonite	2.3 kg	(5 lb)
Sepiolite	6.8 kg	(15 lb)
Brown coal	9.1 kg	(20 lb)
Sodium polyacrylate	1.1 kg	(2.5 lb)
Sodium hydroxide	0.9 kg	(2 lb)

KCl-Polymer: A drilling fluid formulated and used by Republic Geothermal in East Mesa, California. Constituents per standard barrel, 0.16 m³ (42 gal), are

Potassium chloride (KCl)	4.5 kg	(10 lb)
Del HyVis B (trade name)	0.9 kg	(2 lb)
Sodium hydroxide	0.23 kg	(0.5 lb)
Sodium sulfite	0.06 kg	(0.125 lb)
Potassium phosphate dibasic (K ₂ HPO ₄)	0.06 kg	(0.125 lb)

The temperatures were controlled at 100°C (212°F) and 200°C (392°F), bounding the bentonite transformation temperature, which is approximately 150°C (302°F). The post-test analysis included scanning electron microscope (SEM) examination studies.

The testing was performed at Terra Tek's high-temperature, high-pressure geothermal testing facility utilizing specialized mud circulation equipment.

Test Results. A tabulated summary of the testing performed in this project is contained in Table 6-3. The data for both types of drilling fluid are included. The test designations appearing in this table are used in subsequent figures and therefore warrant explanation. For example,

Table 6-3

East Mesa Sandstone Formation Damage Summary

Test Number	Core Designation	Drilling Fluid	Temp. °C (°F)	Stagnation Time hours	Initial Permeability mD	Final Permeability mD	K _f /K _i Ratio
HTM-112-1	RPG-7155'	HTM	100 (212)	12	0.041	0.021	0.52
HTM-124-2	RPG-7151'	HTM	100 (212)	24	0.256	0.088	0.34
HTM-148-3	RPG-7161'	HTM	100 (212)	48	1.102	0.263	0.24
HTM-212-4	RPG-7151'	HTM	200 (392)	12	0.438	0.410	0.94
HTM-224-5	RPG-7159'	HTM	200 (392)	24	0.051	0.038	0.75
HTM-248-6	RPG-7160'	HTM	200 (392)	48	0.159	0.083	0.52
KC1-112-1	RPG-7162'	KC1	100 (212)	12	0.116	0.006	0.06
KC1-124-2	RPG-7163'	KC1	100 (212)	24	0.479	0.006	0.01
KC1-148-3	RPG-7144'	KC1	100 (212)	48	0.035	0.019	0.54
KC1-212-4	RPG-7163'	KC1	200 (392)	12	0.120	0.086	0.72
KC1-224-5	RPG-7164'	KC1	200 (392)	24	0.521	0.299	0.58
KC1-248-6	RPG-7145'	KC1	200 (392)	48	0.058	*	*

*Jacket failure, test aborted.

• HTM-1 Drilling Fluid

A graphical representation of permeability ratio ($K_{\text{final}}/K_{\text{initial}}$) versus stagnation time for the HTM-1 drilling fluid is contained in Figure 6-4. Extended time exposures of >12 hours at both 100°C (212°F) and 200°C (392°F) result in approximately linear decreases (~1.3%/h) in permeability ratio. Significant permeability impairment occurs at stagnation times of less than 12 hours at 100°C (212°F). Note that the shape of the curve in this region is arbitrarily drawn. The exposure to the higher temperature, 200°C (392°F), results in less permeability impairment than does the exposures to the lower temperature, 100°C (212°F).

On the basis of these data, it is hypothesized that the increased impairment in this drilling fluid/formation interaction is a result of the bentonite content of the drilling fluid. The two exposure temperatures bracket the transformation temperature of the montmorillonite clays, 150° to 175°C (302° to 347°F). Under the 100°C (212°F) condition, the clays are placed within the sample in their original form. At 200°C (392°F), the clays have undergone a transformation to illite, a more dehydrated clay structure, and are placed within the sample in this altered state. The clay/rock interaction during the internal filter cake formation appears to be sensitive to the nature of the invading clays.

The dynamic filtration data for the HTM-1 tests are contained in Figure 6-5. Filtrate volume in cm³ (in.³) is plotted versus $\sqrt{\text{time}}$. Conventional filtration theory predicts that filtrate loss should be proportional to the square root of time, $\sqrt{\text{time}}$. The nonlinearity of these filtration curves suggests that this conventional theory is not followed by the HTM-1 drilling fluids. Also, the filtration loss does not correlate with the initial permeability of the sample; that is, large initial permeabilities do not result in large filtrate losses. For example, the test showing the largest filtrate loss during dynamic filtration with this fluid was HTM-224-5, with an initial permeability of 50 μD . Only one other HTM-1 test sample had a lower permeability--HTM-112-1, with the initial permeability of 40 μD . Clearly the filter cake permeability is the dominant factor controlling filtrate loss. The sample having the largest permeability of those tested, HTM-148-3, with an initial permeability of 1.1 mD, demonstrates the closest approximation to the proportionality with time suggested by the conventional filtration theory.

Total filtration volumes, including both dynamic and static filtration, versus time are shown in Figure 6-6. Cumulative filtrate volumes are not directly comparable due to the variation in permeability and temperature of the test samples. This figure, however, does give an indication of the total amount of filtrate handled by the test sample. The pore volume of a typical test sample is on the order of 40 to 60 cm³ (2.4 to 3.7 in.³), i.e., 20% to 30% porosity. In tests HTM-224-5 and HTM-248-6, the drilling fluid filtrate probably would have displaced the original pore fluid, assuming significant channeling did not occur in the samples.

The rate of filtrate loss through the core is governed by both the permeability of the core and the filter cakes. Because these filtrations were conducted under constant pore and differential pressures, variations due to compressibility can be ignored. Impedance to the flow of the

Figure 6-4. Permeability Ratio versus Stagnation Time of the HMT-1 Drilling Mud; East Mesa Core

Figure 6-5. Dynamic Filtration of the HTM-1 Drilling Fluid; East Mesa Core

Figure 6-6. Total Filtration Volumes of the HTM-1 Drilling Fluid; East Mesa Core

filtrate through the filter cake and the sample is best represented as the sum of these respective impedances or:

$$R_{\text{total}} = R_{\text{filter cake}} + R_{\text{sample}} \cdot$$

The filter cake "flow impedance" can be determined as a function of time and is shown for the HTM-1 drilling fluid in Figure 6-7. Impedance to filtrate flow is clearly dependent upon temperature. Low-temperature filtrations result in impedances that are significantly higher than those produced by higher temperature filtrations. This result is consistent with the transformational characteristics of the bentonite clay constituent.

• KCl-Polymer Drilling Fluid

The permeability ratios ($K_{\text{final}}/K_{\text{initial}}$) of reservoir materials exposed to this drilling fluid system are very strongly a function of stagnation time. Permeability ratio versus stagnation time for the KCl-polymer system is shown in Figure 6-8. Exposure to the lower temperature, 100°C (212°F), causes very dramatic permeability impairment at stagnation times of less than 12 hours. The permeability ratio at 12 hours stagnation time is essentially zero. The curve connecting 0 hours and 12 hours stagnation has been arbitrarily drawn. With increasing time at 100°C (212°F), the permeability ratio demonstrates a considerable increase to approximately 0.50 at 48 hours. At the higher temperature, 200°C (392°F), permeability ratio changes are much less and appear to decrease linearly at a rate of approximately 1.8%/h.

It is significant to note that the two test temperatures bracket the maximum temperature at which the use of the polymer system is recommended. It is suspected that the degradational characteristics of the polymer play a key role in the differing temperature dependence.

Dynamic filtration data for the KCl-polymer tests are contained in Figure 6-9. The filtration of this drilling fluid system behaves much more closely to that predicted by conventional filtration theory than does the HTM-1 system. Tests KCl-224-5 and KCl-112-1 demonstrate very linear regions and excellent agreement to the proportionality with the square root of time that was predicted. Again, as with the HTM-1 drilling fluid, the initial permeability does not correlate with the filtrate loss. The dominant permeability in the system is clearly the permeability of the filter cakes.

Total filtration volumes, including the dynamic and the static, versus time are contained in Figure 6-10. Again, the cumulative volumes are not directly comparable. However, the magnitude of filtrate loss in the KCl-polymer system is significantly higher than in the HTM-1 system. The maximum volume handled in the HTM-1 system was 60 cm³ (3.7 in.³) and in the KCl-polymer system, 200 cm³ (12.2 in.³). Clearly, in all KCl-polymer tests, the pore fluid volume was displaced by the invading filtrate. Filter cake "flow impedance" for the KCl-polymer system is shown as a function of time in Figure 6-11. Flow impedance demonstrates temperature dependence, with higher temperature filtrations resulting in lower flow impedance. This effect is consistent with the higher filtration volumes observed in the 200°C (392°F) testing and with the basic temperature-dependent degradational characteristics of the polymer.

Figure 6-7. Flow Impedance of Filter Cake versus Total Filtration Time for the HTM-1 Drilling Fluid; East Mesa Core

Figure 6-8. Permeability Ratio versus Stagnation Time of the KCl-Polymer Drilling Mud; East Mesa Core

Figure 6-9. Dynamic Filtration of KCl-Polymer Drilling Fluid; East Mesa Core

Figure 6-10. Total Filtration Volumes of the KCl-Polymer Drilling Fluid; East Mesa Core

Figure 6-11. Flow Impedance of Filter Cake versus Total Filtration Time for KCl-Polymer Drilling Fluid; East Mesa Core

• SEM Analysis

A number of tested and untested samples were examined under a SEM. The results of such an examination are at best qualitative, given the alteration inevitable with dehydration and sample coating. Figures 6-12 and 6-13 are typical photographs obtained for the HTM testing. In a qualitative sense, much more open porosity was visible in the untested samples; clays were present but in generally small amounts. Post-tested samples exhibited considerably fewer visible pore channels, and, as can be seen from Figure 6-13, clays deposited from the drilling fluids were clearly visible. It was not possible in the samples observed to determine the depth of clay penetration.

Similarly, Figures 6-14 and 6-15 contain typical comparison photographs of the KCl-polymer test samples. Open porosity was clearly visible in both the untested and tested samples. A significant migration of in situ clays was not observed. The crystalline precipitation of KCl was observed in pore spaces but most likely occurred during the preparation of the sample for the SEM analysis.

In the limited SEM effort employed, it was not possible to isolate and identify quantities of polymer. Therefore, it was not possible to determine the depth of the polymer invasion.

• HTM-1 Drilling Fluid--Conclusions

The impairment of the permeability resulting from the interaction of this drilling fluid with a matrix permeability sample is time dependent. Decreases on the order of 1.3%/h are encountered, with the exposure to the lower temperature resulting in significant early time impairment. The exposure to the higher temperature, 200°C (392°F), results in less overall impairment. The transformation of the bentonite clay constituent, which comprises 25% by volume of the HTM-1 fluid, is the most probable mechanism involved in this temperature dependence. Clay/rock interaction is sensitive to the structural nature of the invading clay. The transformation of the sepiolite clay constituent, which comprises 75% by volume of the HTM-1 fluid, from a rod-like structure into a platelet can begin at 200°C (392°F).¹ Whether or not this transformation can occur at a sufficient rate to play a role in altering the bridging phenomenon in this system is presently unknown.

• KCl-Polymer--Conclusions

The impairment of permeability due to the exposure of matrix material to this drilling fluid system is both temperature and time dependent. Drastic decreases in the permeability ratio were experienced during the exposure to the lower temperature. This ratio approached zero at 12 hours stagnation time. Because tests were not conducted at stagnation times of less than 12 hours, the actual rate of decrease is not known but must exceed an average decrease of 8%/h. Long stagnation times result in an increasing recovery of permeability at this same temperature. The exposure to the higher temperature resulted in permeability ratios that decreased approximately linearly at 1.8%/h.

Figure 6-12. HTM Test Sample Not Exposed to Filtration (Mag: 1330X)

Figure 6-13. HTM Test Sample Following Completed Test Cycle (Mag: 1150X)

10 microns

Figure 6-14. KCl-Polymer Test Sample Following Completed Test Cycle (Mag: 630X)

1 micron

Figure 6-15. KCl-Polymer Test Sample; Close-up of KCl Precipitation in Pore Area (Mag: 6200X)

Polymer degradation is both time and temperature dependent. The maximum temperature at which this polymer system is recommended for use was exceeded during the 200°C (392°F) testing. It is therefore suspected that this degradation is a contributing factor in the time and temperature dependence of this system. At 200°C (392°F), the polymer would have experienced substantial degradation prior to being placed within the pore space of the sample. The testing at 100°C (212°F) is performed within the normal operating temperature range of this system, and, therefore, the polymeric chains would be intact during the filtration. Although possibly aided by the moderate temperature, the degradation of the polymer would occur principally because the polymer is unstable with time.

Phase II -- East Mesa core material was selected, and test samples were prepared for the testing of filtrate chemistry effects. In this testing, the permeability to a synthetic brine was determined during simulation of in situ overburden stress, pore fluid pressure, and temperature. The brine was formulated to be similar to the in situ brine and is based on East Mesa water quality reports. Following this initial permeability measurement, a fluid formulated to represent a typical drilling fluid filtrate was passed through the core. The permeability was again determined over the same time period, and any effects attributable to the change in permeating fluid were noted.

Procedures were developed for this testing, and all modifications and calibrations to the test apparatus were performed. Debugging tests of the computer data acquisition system and discussions with technical and area representatives of the leading drilling fluid service companies were completed. Formulation of the drilling fluid filtrate solutions were based upon the most commonly used systems in the Imperial Valley, which specify a 3% to 5% concentration of salt per barrel.

The tests to assess the effects of filtrate chemistry on geothermal formation permeability were completed in mid-July using 3% concentrations of CaCl₂ and NaCl solutions. Modifications to the preparation of samples for 275°C (527°F) test temperatures were not successful, and, in order to stay on schedule, this test parameter was lowered to 250°C (482°F). Data reduction was initiated at the completion of testing, and the results are being analyzed.

A review of available sandstone materials was initiated in the testing of particle size effects to determine a suitable testing material. Materials were evaluated according to the following criteria:

- Homogeneity
- Porosity
- Pore size uniformity
- Minimal clay content
- Permeability
- Availability

The following progress was made on the particle size distribution experiments:

- Material samples of 5, 20, and 50 μm were received from the manufacturers. The study of these samples by SEM was initiated to select the samples most uniform in size and shape.
- A literature search for core material tentatively identified the Nugget sandstone as fulfilling the criteria of uniform grain size, 15% to 20% porosity, less than 5% clay content, 1- to 200-mD permeability, and local availability.
- The thin section analysis, determination of physical properties, and permeability testing were proceeding to accurately characterize the local outcrops. An alternative to the local material was also being sought as a backup.

Work was also initiated on the investigation of the best method of simulating formation damage in a fractured formation. However, this effort, along with the work on particle size effects was suspended in mid-June in order to undertake a priority investigation into the formation damage problems being experienced by Republic Geothermal in their East Mesa wells. This new work involved tasks on permeability comparisons, filtrate chemistry sensitivity, and drilling solids effects. The particle size and fractured formation work will be continued early in the next fiscal year.

The permeability comparison testing was initiated on East Mesa core best representing the production intervals of Republic Geothermal East Mesa wells. Samples from depths of 1684, 1686, 1687, and 1694 metres (5526, 5530, 5534, and 5558 feet) were selected for testing from East Mesa material stored at Terra Tek. Absolute permeabilities to N_2 gas were determined, and those samples having significant, >10-mD, permeabilities were tested at temperature and pressure to determine their permeability to simulated in situ brine.

Discussions with Republic Geothermal helped to identify East Mesa core materials having zones of higher permeability than had the zones of other, previously tested East Mesa core samples. A comprehensive inventory of East Mesa core material was conducted to determine lithology, physical properties, and the number of samples remaining with these higher permeability zones. Core in storage at Terra Tek was selected for testing because (1) the zones of the Terra Tek core were similar to logged production zones and, in addition, had higher horizontal permeability values and (2) large amounts of stored core material were available at Terra Tek from which to prepare test samples, whereas inadequate amounts of Republic production zone core were available.

Work on the East Mesa task was continuing as FY80 ended.

References

1. N. Guven, Texas Tech University Presentation at Sandia Laboratories Geothermal Drilling and Completion Technology Advisory Panel Meeting, Washington, D.C., 11 December 1979.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

6.5 Completion Equipment Study

Contractor: Foster-Miller Associates, Inc.
Principal Investigator: B. Doherty (617) 890-3200
Contract Period: 1 August 1980 to 1 June 1981
Contract Number: 49-8367 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objectives of this project are to describe the problems that exist with the completion equipment and procedures currently in use and to describe the appropriate and necessary environmental conditions to which improved equipment and procedures will be subject. In conjunction with these objectives, recommendations for potential improvements will be made along with an estimate of the economic benefit of each improvement.

Project Status

Work on this project was initiated near the end of FY80. An organizational meeting was held on 28 August 1980 to coordinate the work by Foster-Miller and their subcontractor, Completion Technology Company, with Sandia's overall completion technology program.

FY80 Progress

This study was initiated late in FY80 and is designed to identify specific areas of inadequacy in geothermal completion equipment and procedures so that further development work may proceed in a justifiable and organized manner. The aspects of completion that will be addressed include

1. Liner hanging equipment and procedures,
2. Gravel packing equipment and procedures,
3. High-temperature-performing equipment and procedures,
4. Wellhead and well-control equipment,
5. Casing and tubing repair,
6. Remedial cementing,
7. Scale removal,
8. Inflow control agents, and
9. Well cleanup and initial testing criteria.

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7. 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. 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 (1) designing and fabricating a facility to test lost circulation materials and cementing techniques at simulated geothermal well conditions, (2) assessing the state of the art of mapping lost circulation zones in geothermal wells, and (3) evaluating the techniques and hardware that enable drilling through lost circulation zones in geothermal wells. Projects to determine the geological characteristics of lost circulation zones and to collect, collate, and analyze industry experience concerning the causes, prevention, and remedy of lost circulation in geothermal environments were completed during fiscal year 1980. 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>GEOLOGICAL CHARACTERIZATION OF LOST CIRCULATION TECH. REPS., INC.</u> LITERATURE SEARCH/ SURVEY DATA COLLECTION DATA ANALYSIS FINAL REPORT													

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▴ COMPLETED

7.1 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 July 1980
Contract Number: 46-8886 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project was to determine the geological characteristics of lost circulation zones in the volcanic sequences encountered during the drilling of geothermal wells. These characteristics were to be compared for consistency within each of several KGRAs. If specific lithologic properties were found to be related to lost circulation in each area, the results for the various KGRAs were to be compared to determine if the properties were of local or regional significance. In addition to rock properties, the effects of various drilling practices were to be considered to determine if lost circulation was naturally occurring or drilling induced.

Project Status

Information on lost circulation experience in geothermal well drilling in Cove Fort-Sulphurdale, Utah; Raft River, Idaho; and Valles Caldera, New Mexico; was included in the data collected. The project has been completed, and a final report is being published separately.

FY80 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 concentrated on lost circulation zones encountered in volcanic terrains.

The geologic areas investigated included Valles Caldera, New Mexico; the 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 also were 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. A 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.

USGS open file reports containing the electric and lithologic logs for the Cove Fort-Sulphurdale KGRA were reviewed. Lost circulation zones were not indicated on the logs either directly or through interpretation. The drilling summary reports provided by the DOE office in Idaho Falls contained only references that lost circulation was encountered, with no indication of what was done to solve the problem.

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 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 did 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 Enertech was made in a meeting with Sandia to avoid any duplication or unnecessary multiple interviews. Subsequently, the meeting participants, Tech. Reps., Enertech, and Sandia, visited the geothermal offices at LASL 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 LASL's Sigma Mesa Well was reviewed.

The information provided on the Fenton Hill drilling was of marginal use in attempting to characterize the geological aspects of lost circulation zones. A review of the completions reports of this drilling did not yield useful data. LASL 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 indicated a close correlation between rock type and lost circulation zones.

In order to supplement the information provided by LASL 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.

- LASL provided copies of the electric logs, sample descriptions, and notes for the Sigma Mesa Well. LASL 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 was of little use in determining the detailed geological characteristics of lost circulation zones.
- LASL 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 was 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 were in storage and not readily accessible. Because of previous commitments, company personnel were not available to locate the records.

Union Oil Company of California is drilling 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 that 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 National Reactor Testing Station (NRTS) located on the Eastern Snake River Plain (ESRP) of Idaho has lost circulation problems that are so severe that any new techniques that may be developed to solve these problems undoubtedly will be effective elsewhere. In addition, a substantially thicker sequence of basalts is found in the ESRP than in most volcanic areas associated with geothermal anomalies.

The Water Resources Division of the U.S. Geological Survey (USGS) at the NRTS office in Idaho provided a description of the geologic setting of the area, as well as the details of the local structural features and the stratigraphic sequence. The results of various liquid and gas injection well experiments and their relationship to the geological characteristics of the rocks were provided, along with several reports dealing with the various topics reviewed. Some of these reports contained data on the porosity and permeability of the rocks of the ESRP.

The core from one of the injection wells was examined. Except for providing a visual representation of the rocks described in the reports, the core provided no information regarding the size of fractures in lost circulation zones or the extent to which permeability is related to porosity for these rocks.

Excluding lava tubes because of their unpredictable and highly localized distribution, the most severe and commonly encountered lost circulation problems occur in the zones between overlapping lava flows. When an emplaced lava flow cools, extensive fracturing occurs at the surface. An overriding flow has a blocky cooling rind that forms at the surface and is incorporated into the base of the flow and overridden as the flow moves downslope. The combination of a highly fractured flow-top and a blocky basal portion of the overlying flow results in zones of extremely high permeability. These zones are not exposed in the NRTS area, but measurements were taken of some fracture zones in the top of a lava flow that is exposed.

According to the USGS in Denver, data are not readily available on lost circulation problems. However, this office has been working with an acoustical televiwer that may yield results in this area. Fractures can be identified by use of the televiwer, although additional data on the size and amount of lost circulation material are required in order to determine the permeability of fracture zones. The problem with the televiwer is its inability to distinguish open and sealed fractures. A report was completed by the USGS on this work, but the data will not be available until publication.

Although the Nevada Test Site (NTS) is not a KGRA, the volcanic rocks at the site are similar in origin and composition to the volcanic rocks in many areas that do have geothermal potential. Fennix & Scisson, Inc. (F&S), is the government contractor that supplies the technical personnel for the drilling and mining at NTS. The F&S Geology Division supplied the drill hole lithologic logs. Electric logs and drilling histories were supplied by the F&S Engineering Division. Cores are stored at the USGS Core Library and are available for examination, provided that a specific drill hole number and depth interval are requested.

Because of all the drilling that has been completed at NTS, the geological personnel contacted could not remember the specific details of specific drill holes. The drilling histories and daily drilling sheets generally provided only the 8-hour intervals during which circulation was lost and the amounts of lost circulation material used during each time interval. When the specific depths of lost circulation zones were determined, the electric logs showed no anomalous values that correlated with these zones.

Outcrops of various rock types were examined in the NTS Rainier Mesa area, and the possible influence that the fractures might have on drilling was investigated. The relatively brittle vitrophyre, welded tuff, and zeolitized tuff are extensively fractured. Because the outcrops are exposed at the surface, those fractures with widths that could cause significant lost circulation probably are the result of frost wedging and are not typical of the rock type as a whole. Most of the fractures have widths of less than 5.0 mm (0.2 in.). The granular, weakly consolidated, water-laid tuffs were able to dissipate imposed stresses by intergranular movement instead of by fracturing. This rock type has a porosity and permeability similar to that of a coarse-grained quartz sandstone and probably would cause some fluid loss if penetrated during drilling. Conventional lost circulation control techniques would stop the fluid loss.

In addition to their surface exposures, the zeolitized tuffs were examined in two of the tunnels into Rainier Mesa. Most of the fractures are closed. Those fractures that are open usually have a width in the range of 0.1 to 6.0 cm (0.04 to 2.36 in.). The lateral extent of the fractures could not be determined.

Lawrence Livermore National Laboratory (LLNL) showed movies, taken at NTS with a downhole camera, of several of the large-bore drill holes. If the hole diameter is known, the circumference can be established. On a single-frame picture from the movie, the ratio of the fracture width to the hole circumference also can be established. Determining this ratio would allow for the actual fracture width to be calculated. Each movie has a continuous readout of the depth being observed, so that the vertical extent of the lost circulation zone can be determined. A fracture permeability can be estimated based on the fracture data and on the amount and the size of the lost circulation material used. Sandia made arrangements to obtain copies of several films from LLNL.

A review of the various reports collected at NTS indicated that the detailed data required for this project were not included. F&S stated that the data were not available from any source at any location of which they were aware.

Data collection from private companies was unproductive. The drilling data and logs from Herkenhoff, Gordon, and Associates for the water wells located south of Los Alamos were reported by the firm to be of insufficient detail for use in determining the characteristics of lost circulation zones. All knowledgeable personnel of Phillips Geothermal were overseas or otherwise unavailable for interview during the project work period. Other than the reports on file with DOE, information on lost circulation zones from Union Geothermal was not available.

The preliminary conclusions based on the findings in this project were

1. Detailed quantitative data on the geological characteristics of lost circulation zones do not exist,
2. Electronic logging methods are able to measure the physical properties of the rocks and interstitial fluids, but these methods do not measure the dimensions of voids that might cause loss of drilling fluids,
3. Other equipment, such as an acoustical televiewer and a downhole camera, may locate fractures and voids, but the lateral extent and permeability of these features cannot be determined by using these instruments, and
4. If new techniques to control lost circulation are to be developed, experiments must be conducted in drill holes to determine the physical parameters of those zones for which present techniques to control fluid loss are not adequate.

A final report has been prepared and will be published separately.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

7.2 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 30 September 1980
Contract Number: 13-8769 (Sandia)
Technical Consultants: T. Hinkebein (505) 844-5202
J. Kelsey (505) 844-6968

Project Objective

The objective of this project was 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. The data will be used for thermal simulation of wells during drilling, production, and injection, using the GEOTEMP code.

Project Status

The project has been completed. A final report is being prepared and will be published separately.

FY80 Progress

Project Scope and Coordination -- Activities during fiscal year 1980 included compiling and reviewing literature on thermal/mechanical rock properties for geothermal formations, 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, and additional or expanded efforts were identified. These efforts included 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.

Coordination with the separate project on geological aspects of lost circulation was made to avoid any duplication of effort and to assure that companies and agencies interviewed were not subjected to unnecessary multiple interviews. In addition, each company contact was organized to address each area of interest in a single interview period.

Many companies were 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. Additional companies were considered on a continuing basis, and the

interview list was revised accordingly. The initial list of companies and agencies considered prime information sources included the following:

- Union Geothermal
- Phillips Geothermal
- Los Alamos Scientific Laboratory
- Department of Energy
- University of Utah
- Terra Services
- Mobil Oil
- Messenger
- Federal Electric Commission of Mexico
- IMCO
- Baroid
- Haliburton
- Exxon
- Shell

The information and data acquired during the literature search and interviews were organized in three categories: rock properties, well temperature histories, and lost circulation.

Rock Properties -- A literature search was initiated for thermal and mechanical properties of geothermal rock formations. Specific key words identified in Petroleum Abstracts for this purpose were

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

The search covered the years 1975-1979 and the first quarter of 1980 and identified 45 potential reference sources. Abstracts for these 45 references were requested. Based on a review of the abstracts, appropriate papers were selected as the final step in the search process. The selected papers were then reviewed for property data. The key word "Rock Property" provided more than half of the references.

- Union Geothermal

Thermal/mechanical rock properties for geothermal formations were discussed with Union. They suggested that Terra Tek be contacted regarding mechanical properties for Geysers 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 have been published and are available through DOE.

- Terra Tek, Inc.

Terra Tek, Salt Lake City, Utah, was contacted to obtain geothermal rock property data. Two documents were provided. Reference 1 contains information on test samples taken from cores from the East Mesa field of the Imperial Valley. The core material represents a sandstone at

1676 metres (5500 feet). Reference 2 provides data on granite cores from The Geysers. Samples from these cores were tested dry at a confining pressure of 13.8 MPa (2000 psi) to simulate effective stress overburden. Assuming a vertical and horizontal effective stress gradient of 0.01 MPa/m and 0.007 MPa/m (0.6 psi/ft and 0.3 psi/ft), respectively, then the mean normal effective stress is

$$1/3 (\sigma_{zz} + \sigma_{xx} + \sigma_{yy}) = 0.4 ,$$

which gives a representative depth of 1524 metres (5000 feet) for the confining pressure of 13.8 MPa (2000 psi).

The mechanical properties laboratory test data for the granite are shown in Figures 7-1 and 7-2 and represent pure compression from the reference state of 13.8 MPa (2000 psi), i.e., strains during hydrostatic loading to the reference state are not included in the plots. The straight-line portions of the plotted data can be used to calculate elastic moduli for the simulated depth conditions. The right-hand side of Figure 7-1 provides the Youngs modulus, and the left-hand side gives the Poisson ratio. Figure 7-2 gives the bulk modulus. The values for these properties are presented in Table 7-1. As a comparative test of the results, the Poisson ratio determined from the laboratory data shows reasonably close agreement with the value calculated from the other two moduli.

Table 7-1

Mechanical Properties of Geothermal Rocks^a

Property	Imperial Valley Sandstone	The Geysers Granite
Youngs modulus, E, kPa (psi) x 10 ⁶	12.69 (1.84)	43.64 (6.33)
Bulk modulus, K, kPa (psi) x 10 ⁶	7.38 (1.07)	20.68 (3.00)
Poisson ratio, γ		
From test data	0.17	0.13
Calculated from	0.21	0.15
$\gamma = \frac{3K-E}{6K}$		
Simulated depth, metres (feet)	1 676 (5 500)	1 524 (5 000) ^b
Test temperature, °C (°F)	175 (374)	200 (392)

^aDetermined from test data in References 1 and 2

^bBased on a 13.8-MPa (2000-psi) confining pressure and an assumed mean normal effective stress gradient of 9.2 kPa/m (0.4 psi/ft)

Figure 7-1. Mechanical Response of a Dry Granite Material

Figure 7-2. Volumetric Response of a Granite Material

Figures 7-3 and 7-4 show similar mechanical test data for the East Mesa sandstone. Figure 7-4, however, exhibits the entire loading curve for hydrostatic compression, and, therefore, only the straight line portion at $(\sigma_1 - P) = 21.3 \text{ MPa}$, which simulates a depth of 1676 metres (5500 feet), is used^P to evaluate the bulk modulus. In Figure 7-3, the curves for 1682 metres (5517 feet) are used to calculate the Youngs modulus and Poisson ratio. The modulus values for the sandstone are given in Table 7-1.

The values in Table 7-1 represent the matrix material only and, hence, are associated with effective stresses and strains. For the total material, which includes the effect of pore fluids, the moduli for "drained" conditions are the same as the matrix moduli, but for "undrained" conditions, the moduli are different due to pore fluid compressibility.

The thermal properties laboratory test data from Reference 2 on thermal conductivity and thermal diffusivity for granite are shown in Figures 7-5 and 7-6. The heat capacity for a range of rock types is presented in Figure 7-7 and indicates that property values are governed mainly by temperature rather than rock type. It is assumed that granite falls within the range shown in Figure 7-7. Table 7-2 lists data taken from Figures 7-5, 7-6, and 7-7 for two temperatures of interest, 100° and 200°C (212° and 392°F). The density is also presented.

Table 7-2

Thermal Properties of Geothermal Rocks*

Property	Imperial Valley Sandstone		The Geysers Granite	
Temperature, °C (°F)	100 (212)	250 (482)	100 (212)	200 (392)
Thermal conductivity, κ W/m·K (BTU/ft·h·°F)	3.47 (2.01)	2.90 (1.68)	2.30 (1.33)	1.90 (1.10)
Heat capacity, c J/g·°C (BTU/lb·°F)	0.900 (0.215)	1.075 (0.256)	0.900 (0.215)	1.050 (0.251)
Thermal diffusivity, K cm ² /s (ft ² /h)	0.018 (0.070)	0.015 (0.057)	0.011 (0.043)	0.008 (0.031)
Density, ρ ^{**} g/m ³ (lb/ft ³)	2.13 (133)	1.84 (115)	2.32 (144)	2.26 (141)
Simulated depth, metres (feet)	1 676 (5 500)	1 676 (5 500)	1 524 (5 000)	1 524 (5 000)

* Determined from test data in References 1 and 2

** Calculated from $\rho = \kappa/Kc$

Figure 7-3. Axial and Transverse Strain Behavior in Triaxial Compression of East Mesa Sandstone

Figure 7-4. Volumetric Compression of East Mesa Sandstone

Figure 7-5. Thermal Conductivity Variation with Temperature

Figure 7-6. Thermal Diffusivity Response to Temperature of Westerly Granite

Figure 7-7. Experimental Heat Capacities of Different Rock Materials

Figures 7-8 and 7-9 show data from Reference 1 for Imperial Valley sandstone. The property values for the sandstone at 100° and 250°C (212° and 482°F) are given in Table 7-2.

A comparison of values for granite and sandstone indicates an interesting characteristic. Although granite has a greater density than sandstone, as expected, the conductivity of the granite is significantly less. Intuition suggests that a denser material would be more conductive, but apparently the granite matrix material has a much greater resistance to heat flow than has quartz. This difference is also supported by data in Reference 3, which lists conductivity values for granite and sandstone.

Well Temperature Histories -- Interviews relative to well temperature histories were undertaken with Dresser-Magcobar in Houston, Texas, with Union Geothermal in Santa Rosa, California, and with LASL, New Mexico. Dresser had no data that could be released.

- Union Geothermal

Union Geothermal compiled drilling and production data and well completion information on The Geysers field for forwarding to Sandia and requested that copies of the data be obtained from Sandia. The data included 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. The company pointed out that the gradients have never been measured directly and that the data supplied by them are simply the best estimate. It was noted that the typical Geysers 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. Subsequently, 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 provided typical shut-in conditions associated with the range of production and injection histories.

Following the receipt by Sandia of the Union geothermal data on The Geysers, and in accordance with subsequent discussions with Sandia, the Union data could not be used for the purposes of the study due to proprietary reasons.

- Los Alamos Scientific Laboratory

Casing sizes, setting depths, cement intervals, and lithology were provided by LASL 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 LASL wells was measured, and results were forwarded to Enertech. Such data will be

Figure 7-8. Thermal Conductivity Measurements on East Mesa Sandstone

Figure 7-9. Thermal Diffusivity Measurement on East Mesa Sandstone

useful for correlation with GEOTEMP and will serve to estimate soil thermal properties by means of inverse simulation.

Using 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).

Based on the 29 January 1980 interview with LASL personnel and on information obtained from LASL publications, input data for thermal simulation of drilling of the LASL GT-2 well were compiled for application to GEOTEMP. Figure 7-10 shows the actual drilling schedule down to a depth of 1067 metres (3500 feet) in the GT-2 well. The total depth is 2932 metres (9619 feet), with a bottomhole temperature of 197°C (387°F). Additional data were requested from LASL to complete the drilling schedule to total depth. For simulation purposes, the depth-time plot in Figure 7-10 has been approximated by the four straight-line segments shown in Figure 7-11.

The average mud circulation time per day is required by GEOTEMP, because each day of drilling simulation is divided into a shut-in part (zero flow rate) and a circulating part. In Figure 7-12, the cumulative time as determined from the penetration rate for each 3.1-metre (10-foot) depth increment in the GT-2 well is plotted versus depth. Because depth penetration occurs only while drilling mud is circulating, the plot in Figure 7-12 represents the cumulative circulation time. For the depth interval shown in Figure 7-12, 37 to 488 metres (120 to 1600 feet), the circulating time is 2.25 days. As shown in Figure 7-10, the total time required to drill this depth interval is 6.75 days, indicating that the average circulating time per day is 8 hours. This average value will be assumed to occur throughout the drilling schedule.

The actual undisturbed geothermal temperature distribution is shown in Figure 7-13. A bilinear approximation of the geothermal gradient for use in GEOTEMP is presented in Figure 7-14.

Four drilling fluids were used in drilling the GT-2 well. Water-base mud, water, foam, and air were used for the depth intervals shown in Figure 7-10. In the GEOTEMP simulation, Figure 7-11, the different drilling fluids correspond to the four straight-line segments. Hence, the fluid properties can be changed in the simulation at the same time that the penetration rate is changed. The mud parameters follow:

Mud density	1108 kg/m ³	(9.25 lb/gal)
Plastic viscosity	0.01 Pa·s	(10.0 cp)
Yield point	1.4 Pa	(3.0 lb/100 ft ²)
Flow rate	0.008 m ³ /s	(3.0 bbl/min)

Although the mud viscosity for the GT-2 well was reported in units of 40 seconds, corresponding to the Marsh funnel viscosity, the GEOTEMP simulation requires values in terms of plastic viscosity and yield point. Because the funnel viscosity cannot be converted directly to plastic viscosity and yield point, typical values of these parameters were assumed for the water-base, low-solids mud used in drilling the GT-2 well.

Figure 7-10. Drilling Schedule for Los Alamos GT-2 Well

Figure 7-11. GT-2 Well Drilling Schedule Approximation for GEOTEMP Simulation

Figure 7-12. Mud Circulation Time for GEOTEMP Simulation of the Los Alamos GT-2 Well

Figure 7-13. Geothermal Temperature Distribution for Los Alamos GT-2 Well

Figure 7-14. Los Alamos GT-2 Well Undisturbed Temperature Distribution for GEOTEMP Simulation

The water properties correspond to fresh water properties. The air and foam properties were approximated in GEOTEMP with the assumption of low-density, low-heat-capacity fluids. Typical values for viscosity of air and foam were used.

The GT-2 casing and cement program for GEOTEMP simulation is shown in Figure 7-15. Three casing strings were included, with the deepest string of 27.3-cm (10.75-in.) casing set at 772.7 metres (2535 feet). Below this depth, the rock formation was granitic, and the hole was open. The drill pipe was 14.0 by 10.2 cm (5.5 by 4 in.). The well was completed with 11.4-cm (4.5-in.²) o.d. tubing set in a packer at bottomhole. Although the hole was deviated approximately 5°, the GEOTEMP simulation assumed a vertical well.

The temperature history work in this effort included a simulation of drilling for GT-2 and injection/production for the GT-2/EE-1 system of the Los Alamos HDR project.

A total of three geothermal fields was considered for determining typical and atypical temperature distributions. In addition to the Los Alamos geothermal field, The Geysers and Imperial Valley were also simulated. For each case, the GEOTEMP simulation included drilling, injection, and production histories.

Additional data regarding the HDR project were provided by LASL. The modifications to GEOTEMP were completed for handling the various HDR drilling fluids, namely mud, water, air, and foam, and for simulation of drilling, production, and injection.

Lost Circulation -- The results of Sandia's literature search on lost circulation were made available to Enertech. As part of the overall assessment of lost circulation in geothermal wells, the literature on lost circulation in both petroleum and geothermal wells was evaluated and categorized into specific subject areas. Each subject area was summarized and documented. Such a categorization had not been previously compiled. In this form, the lost circulation literature was more useful to this investigation and will be more useful to future investigations. The documentation by category serves as a single reference for quick review. Subject categories 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.

Figure 7-15. GT-2 Well Completion for GEOTEMP Simulation

The Sandia search was computer-based and considered the literature from 1969 to mid-1979. Enertech expanded 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.

The lost circulation literature search uncovered 64 references. Abstracts for these references were obtained and reviewed. From the literature acquired, several activities were selected for their practical value. The following are representative of the articles that were reviewed:

1. J. U. Messenger, "How to Combat Lost Circulation," Oil and Gas Journal;
2. J. U. Messenger, "How to Remedy Lost Circulation," Oil and Gas Journal;
3. Bill Rehm, "Lost Circulation Complicates Well Killing Operations," Oil and Gas Journal;
4. J. U. Messenger, "Barite Plugs Can Effectively Seal Off Active Gas Zones," Oil and Gas Journal;
5. J. U. Messenger, "Common Rig Materials Combat Severe Lost Circulation," Oil and Gas Journal;
6. J. L. Lummus, "A New Look at Lost Circulation," Petroleum Engineer, November, 1967; and
7. P. P. Scott, Jr., J. L. Lummus, and G. C. Howard, "Method for Sealing Vugular and Cavernous Formations," Drilling Contractor.

A list of companies to be interviewed was compiled. These companies were selected from those with extensive lost circulation experience and included the following:

Geothermal Operators:

1. Union
2. Chevron
3. Republic Geothermal
4. Los Alamos Scientific Laboratory
5. Phillips
6. Federal Electric Commission of Mexico

Petroleum Operators:

1. Exxon
2. ARCO
3. Gulf
4. Shell
5. Mobil

Drilling Mud Companies:

1. Dresser-Magcobar
2. Milchem
3. IMCO
4. Baroid
5. Oil Base

Consultants:

1. Chenevert Engineering
2. Terra Services
3. Completion Technology Company
4. Maurer Engineering

From this list of companies, 10 were selected for interview in accordance with the information survey plan developed in September 1979.

• Los Alamos Scientific Laboratory

Lost circulation occurrences were discussed in detail with LASL 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.

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 when published. Concentric drill string for control of lost circulation of drilling mud was successfully used in this well.

• Dresser-Magcobar

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 was being conducted. The research involved sodium silicate as a sealing agent. Due to the confidential nature of the project, Dresser declined to discuss the research before completion. If information and data on the project are made available in time, 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. Dresser expressed interest in applying GEOTEMP to cementing in geothermal wells.

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.

• Union Geothermal

Operations in Utah, in The Geysers, and in the Baca field were discussed with Union Geothermal. Lost circulation was a severe problem in Utah, accounting for nearly 30% of well costs, and was complicated by hydrogen sulfide gas that was difficult to control without circulation.

In the Baca area, lost circulation is a problem in fractured rock of the Bandelier tuff. Also, surface water seeping from the Caldera fill through fractures in the tuff may flow into the wellbore and cause hole-caving and sloughing. 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 Geysers field, the reservoir pressure is low, compared to the higher pressures of the water dominated reservoirs in Utah and Baca. Union suggested that the low-pressure conditions can magnify the lost circulation problem because of drilling-induced pressure-parting of the rock formations. Union is uncertain if 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 holes. 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.

• Consultant -- L. Capruano

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

As a general rule, Capruano 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, i.e., perlite and/or sand, is used in the cement system, and, if these are not successful, sodium silicate is used. A common cement system consists of a 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, Capruano 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, preventing the lost circulation zone below from affecting the cement placement in the casing-casing annulus; this technique eliminates voids and/or pockets of water between casing strings.

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

• IMCO Services

IMCO in Houston recommended that their office in Long Beach, California, be contacted about lost circulation during geothermal drilling. The meeting in Houston concentrated on lost circulation materials and the laboratory testing of lost circulation method effectiveness. A list of commercial lost circulation materials marketed by IMCO was provided.

In October 1979, IMCO designed and constructed a lost circulation test cell to evaluate an oil-base mud for a client. With the exception of testing performed for this one application, IMCO has not used the apparatus for any further testing. The IMCO cell is different from the standard American Petroleum Institute (API) cell for testing lost circulation materials. As part of the task to provide a list of existing experimental equipment for lost circulation evaluation, the IMCO test cell is described below.

The aluminum cell consists of a cylinder and slotted insert. The cylinder is 0.61 metre (24 inches) long with a 10.2-cm (4-in.) i.d. and 12.7-mm (0.5-in.) wall thickness. It is rated for a pressure of 3.5 MPa (500 psi) and is equipped with an electric heat strap to impose temperatures of up to 66°C (150°F). The cylindrical insert is split lengthwise into two halves that form a wedge-shaped slot along the length of the insert. The slot size is 30.5 cm (12 in.) vertically and 6.4 cm (2.5 in.) horizontally, with a variable slot width depending on the insert halves used in a given test. Different insert halves can be combined to give slot widths of 0.127, 0.25, 0.51, 1.27, and 2.54 mm (0.005, 0.01, 0.02, 0.05, and 0.1 in.). The insert with slot is installed in the cylinder, with the larger width of the wedge-shaped slot at the top.

Tests are performed with 1000 cm³ (0.26 gal) of mud on top of the slot. Fluid pressure is applied to force the mud through the slot. The duration of each test is 1 hour, with fluid loss readings taken at 15-minute intervals. The results are plotted in terms of fluid loss versus time for each slot size used. The depth in the slot where bridging occurs is observed upon the dismantling of the insert after each test.

Cell drawings and test results were requested, but IMCO prefers to keep the information proprietary at the present time.

• NL Baroid Laboratories

Baroid's experience with geothermal drilling is principally in the Imperial Valley, where the sedimentary formations are drilled with conventional liquid muds; air drilling is not common. With mud weights of less than 1078 kg/m³ (9 lb/gal), lost circulation is minimized. Above 1078 kg/m³ (9 lb/gal), lost circulation materials such as wood fibers are

used. If lost circulation occurs, it is drilling induced rather than naturally induced by fractures or vugs as in The Geysers. Although the formations in the Imperial Valley are composed of consolidated sands and shales, natural fractures have been observed by Baroid in some cores, but Baroid does not consider these fractures to be significant to the lost circulation.

In the Imperial Valley, Baroid considers the major drilling problem to be temperature, not lost circulation. Typical muds offered by Baroid for drilling in the 204° to 260°C (400° to 500°F) temperature range consist of lignite, clay, bentonite, and surfactant to reduce high-temperature gelation. In addition to the use of the surfactant, sepiolite is sometimes substituted for a portion of the bentonite to minimize gelation and baking. Ratios of sepiolite to bentonite range from 25 to 50%. Cypan is also used as an additive for high-temperature filtrate control but is very sensitive to calcium in formation water. Evaporative-type cooling towers are used to maintain mud temperatures below 54°C (130°F) inlet and 82°C (180°F) outlet.

With regard to cementing in the Imperial Valley, Baroid is not aware of lost circulation problems, even though cement weights exceed 1078 kg/m³ (9 lb/gal). It was mentioned that remedial cementing is often necessary because of cement fingering caused by underground water percolation. No well control problems due to high-pressure gas or hydrogen sulfide have been encountered.

Two types of casing problems in the Imperial Valley were noted. One is corrosion associated with underground water percolation. The other is thermal parting and/or buckling due to temperature changes during operations.

• Phillips Geothermal

Drilling experiences in six geothermal areas were discussed with Phillips Geothermal, Salt Lake City, Utah. The areas discussed were as follows:

Utah:	Roosevelt Hot Springs
Iowa:	Soda Lake/Mountain Home Site
Nevada:	Humboldt House Reservoir
Nevada:	Desert Peak
Nevada:	Steamboat Springs
California:	Plumas County

The greatest amount of experience with lost circulation has occurred in the Roosevelt lease, where six wells have been drilled by Phillips and five wells by other operators, including Getty, McCulloch, and Amax Thermal Power. Depths to the top of the reservoir at Roosevelt vary across the field between 366 and 2286 metres (1200 and 7500 feet). Lost circulation occurs in the granite, which is covered by a mantle of sedimentary formations.

In Roosevelt Well No. 82-33, drilled by Phillips, lost circulation was particularly severe. The problem was aggravated in part by the fact that no formation fluids were encountered during drilling of the lost circulation zone, and, hence, the fluid pressure differential was highly

overbalanced. The casing was finally set below 1829 metres (6000 feet). The well is presently used for reinjection of fluids produced during tests in nearby production wells. When first used as an injector, the well would not accept all fluid injected, and the casing was then perforated opposite the lost circulation zone. No injection problems have occurred since. Initially, after the casing was perforated, the well lost all injected fluid to the lost circulation zone, and no fluid remained standing in the casing. But, after a number of injection periods, the well began holding fluid, indicating that the lost circulation zone became less permeable.

The lost circulation problem in Well No. 82-33 started at 504 metres (1655 feet), when the drill pipe dropped 0.61 metre (2 feet). Approximately 2 weeks were required to drill through the lost circulation zone from 504 to 610 metres (1655 to 2000 feet). The day-by-day experience, as recorded, is shown in Table 7-3. The list of lost circulation materials used in this well, including huge amounts of lumped coal, alfalfa cubes, and plastic bags filled with wood and barite, demonstrates the severity of the problem. The extra cost in rig time and materials represents a major part of the total well cost.

Table 7-3

Lost Circulation Experience Record, Roosevelt Lease, Utah

DATE	Lost Circulation Control Activity
11-19-75	Lost returns at 1655 to 1657 ft; fractured formation. Mixed pit with 30% lost circulation materials (LCM); drilled to 1678 ft; no returns.
11-20-75	Lost 1400 bbl mud. Pumped 300 bbl mud, 35% LCM; hole filled to 50 ft. Pumped 300 bbl mud, 35% LCM. Pumped 100 bbl mud in drill pipe, 25 bbl; mud in annulus; no returns. Pumped high-water-loss pill; no returns. Mixed 1 pit mud, 35% LCM; pumped in hole. Mixed and pumped 50 sacks Class B cement; tagged top of cement.
11-21-75	Mixed and pumped 50 sacks Class B cement; tagged cement. Mixed and pumped 50 sacks Class B cement; tagged top of cement at 1647 ft. Dropped 2 tons alfalfa cubes plus 300 bbl of water; no fill in hole. Dropped 1-1/2 tons alfalfa cubes plus 200 bbl of water; no fill. Dropped 200 gal soaked burlap sacks. Dropped 1-1/2 tons alfalfa cubes plus 200 bbl of mud, 35% LCM.
11-22-75	Bit in hole; no fill. Pumped 200 gelled burlap sacks.

Table 7-3 (Continued)

Lost Circulation Experience Record, Roosevelt Lease, Utah

DATE	Lost Circulation Control Activity
	Pumped 3 tons lumped coal, 6 to 9 in. Pumped 2 tons alfalfa cubes. Hole filled up. Drilled bridges to 1650 ft; lost returns.
11-23-75	Dropped 180 burlap sacks in hole. Dropped 1 ton lumped coal, 6 to 9 in. Dropped 2-1/2 tons alfalfa cubes in hole. Dropped 2 tons lumped coal in hole.
11-24-75	Bit drilled bridges to 750 ft; lost returns. Bit to 1650 ft; hole clear. Dropped 7 plastic bags filled with mud (10-in. o.d. by 15 ft long) followed with gelled mud. Hole clear to 1658 ft.
11-25-75	Dropped 2 tons lumped coal in hole. Pumped 1 pit mud, 35% LCM; drilled bridges 1675 ft. Spot 150 sacks barite plug; no fill. Spot 150 sacks barite plug; no fill. Pumped 1 pit mud, 35% LCM.
11-26-75	Dropped 400 plastic bags filled with wood chips and barite in hole; flushed with 400 bbl mud; no fill.
11-28-75	Flushed 420 gal diesel oil. Flushed 840 gal diesel oil mixed with 6 gal DOC No. 12. Flushed with 200 sacks Class B cement.
11-30-75	Drilled 12 hours; no returns. Drilled 15 hours to 2004 ft; tried to run logs.
12-2-75	Ran 9-5/8 in., 40-ppf casing; set at 2001 ft. Pumped 200 sacks Class B cement plus silica flour. Pumped 600 sacks Class B cement plus silica flour. Drilled to 2160 ft; lost returns. Pumped mud with coarse mica flakes, Fibertex, Plug-It, cotton seed hulls. Pumped mud containing high seal paper. Drilled to 2240 ft; full returns. Carrying 12% LCM in mud.
12-4-75	Full returns.

No casing problems such as buckling or thread jump have occurred at Roosevelt, even though 10 to 12 cycles of on-off production have taken place.

Concentric drill string was considered and was inquired about for drilling lost circulation zones but has not been used. Phillips has not used any sensing devices or detection methods in lost circulation zones. However, it was reported that Amax Thermal Power has run the borehole televiewer in wells after drilling to inspect fractures.

In 1978, Phillips drilled wells in Idaho in two sites, Soda Lake and Mountain Home. All wells were nonproductive. Lost circulation was encountered in metamorphic formations but was controlled with commercially available lost circulation materials.

During 1976 through 1979, three sites in western Nevada were drilled by Phillips. In the Humboldt House reservoir, three wells were completed--two productive hot water wells and one dry well. No lost circulation problems were encountered. In the Desert Peak reservoir, three commercial wells were drilled without lost circulation. In the Steamboat Springs site, lost circulation was experienced at shallow depth down to 107 metres (350 feet). Near the surface in an interval of 17 to 21 metres (55 to 70 feet), a lost circulation zone consisting of rocks and boulders was plugged by using Class G cement. Cement plugs were also used between 58 and 61 metres (190 and 200 feet). Below 85 metres (279 feet), the hole was drilled without returns to 107 metres (350 feet), where a 50.8-cm (20-in.) casing was run and set with cement/perlite by dropping the mixture in the annulus. Between 914 metres (3000 feet) and a total depth of 937 metres (3073 feet), drilling was done by adding 143 m³ (900 bbl) of water or aerated water per day, but no lost circulation material was used.

In 1978, a well in Plumas County, California, was reentered for deeper drilling in metamorphic rock. Lost circulation was controlled with lost circulation material.

References

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2. D. O. Enniss, S. W. Butters, R. Lingle, R. G. Van Buskirk and F. R. Prater, "Capabilities to Measure Geothermal Material Properties at Simulated In Situ Conditions," Terra Tek Report TR79-49, submitted to Department of Energy, Division of Geothermal Energy, July 1979.
3. CRC Handbook of Chemistry and Physics (Boca Raton, FL: CRC Press, Inc., 1979) p E-16.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

7.3 Lost Circulation Mapping Tools and Techniques

Contractor: Maurer Engineering, Inc.
Principal Investigator: W. McDonald (713) 683-8287
Contract Period: 1 May 1980 to 31 October 1980
Contract Number: 49-1458 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project was to assess the state of the art of mapping lost circulation zones in geothermal wells. Tools and techniques were identified, described, and evaluated concerning their capabilities to map lost circulation zones. Cost, effectiveness, accuracy, and limiting factors such as high temperatures were considered in the assessment.

Project Status

A list of tools and techniques that can be used to map lost circulation zones was compiled. The list included mechanical and electrical devices as well as drilling-fluid-monitoring techniques. The survey of industry for additional information on lost circulation mapping tools and techniques was concluded. Twenty-five tools were selected as candidates for lost circulation mapping. The assessment has been completed, and preparation of the final report has been initiated.

FY80 Progress

A comprehensive list of tools was prepared for evaluation (Table 7-4). New tools included in the list were downhole cameras, televisions, and straddle packers.

Technical reports and brochures were collected for the tools in the master tool list. Explanations of the operation of the tools were compiled, as were descriptions of the techniques necessary for using the tools effectively and for interpreting the data gathered by them. Several people knowledgeable in the use and capabilities of the tools were located and assisted Maurer Engineering in this endeavor. A great deal of literature was collected on the various tools and techniques. This literature consisted of technique reports, case studies, brochures, price lists, etc. Most of the tools and/or techniques were well described in terms of operation, technique, and capabilities. Also, interviews were conducted. The companies and organizations contacted are listed in Table 7-5.

The collected data were classified into three major files that were appropriately coded for cross-referencing. These files were

- Manufacturer File — Included all manufacturers that were located who provide services and tools found in the master tool list.

Table 7-4

List of Tools Evaluated

<u>Type</u>	<u>Tool</u>
Acoustic	Borehole Televiewer Borehole Sound-Temperature Survey Sonic Logs
Electrical	Hot Wire Survey Hot Film Anemometer Dual Induction-Latero Log Induction Logs Sonic Potential Logs Lost Circulation Detector Fluid Velocity Indicator Conventional Resistivity Logs Micro-Resistivity Logs Focusing Electrode Logs Fracture Identification Logs Temperature Logs
Mechanical	Impression Packer Straddle Packers Spinner Survey
Radioactive	Neutron Logs Formation Density Logs Radioactive Tracer Logs Sonic-Neutron Log Spinner-Temperature Survey
Optical	Downhole Camera Downhole Television

Table 7-5

Companies and Organizations Contacted

Agnew & Sweet
Bakersfield, CA

Amoco Research Company
Tulsa, OK

Arrow Oil Tools
Tulsa, OK

Baker Service Company
Houston, TX

Birdewell/Seismograph Service
Company
Tulsa, OK

Dia-Log
Corpus Christi, TX

Dresser-Atlas
Houston, TX

Exxon USA
Houston, TX

GO Company
Houston, TX

Gulf Research and Development
Harmonville, PA

Halliburton/Welex
Houston, TX

Kuster Company
Lafayette, LA

Los Alamos Scientific Laboratory
Los Alamos, NM

Lynes
Houston, TX

N. L. McCollough
Houston, TX

Sandia National Laboratories
Albuquerque, NM

Schlumberger
Houston, TX

Simplec Manufacturing Company
Dallas, TX

Shell Development Company
New Orleans, LA

TAM International
Houston, TX

Water Well Dedevelopers
Yorba Linda, CA

Worth Systems
Fort Worth, TX

- Customer File -- Included all contacted companies that use the services and products outlined in this program. These companies were asked to give their evaluation of tool performance and their view on the cost effectiveness of the provided services.
- Tool File -- Was divided into five major categories by the type of sensing element utilized. The categories are acoustic, chemical, electrical, mechanical, and radioactive.

Using the data collected, the merits of each tool and technique were evaluated with respect to their capabilities to quantify fracture size and locate lost circulation zones. In order to assess each tool, a scheme was devised whereby numerical values were given to engineering judgments. This procedure resulted in each tool receiving a single score.

The criteria for evaluating the tools was broken down into the four categories of performance, risk, cost, and availability using the following definitions:

- Performance criteria - The capability to achieve needed operational characteristics, plus reliability.
- Risk - The possibility that performance may not be met because of the design approach, absence of testing, or some specific technical consideration.
- Availability - The availability of a design depending upon the stage of development.
- Cost - The estimated cost of the system including development and manufacturing costs.

Each category was weighted as follows:

• Performance	50%
• Risk	25%
• Availability	15%
• Cost	10%
	<u>100%</u>

Each criteria category was further divided into the following subelements:

1. Performance Criteria.

- Locate Zones - In order to locate a lost circulation zone, the tool must provide a characteristic response at the point of loss. The tool must provide information on the depth and orientation of the zone. The depth of the zone is the most important aspect of locating the zone and has greater importance than the orientation.
- Quantify Zone Size - To quantify zone size, the tool or technique must provide information on the height, width, and flow rate into the zone. This information allows the volume of the zone to be computed, its geometry to be described, and provides a direct measure of the rate of loss.

- Operate in Geothermal Well - This aspect of performance is the assessment of the tool's ability to operate at elevated temperature. In preliminary findings, the effects of pressure and the type and weight of drilling mud were found to have a profound influence on many tools ability to properly function. As a consequence of this, these parameters were incorporated into this category.
- Accuracy - When this facet of performance was examined two types of accuracy were found to be present. First, there is the accuracy of the measurements. Secondly, there is the accuracy with which the tool can define the location and size of the zone. This latter accuracy is a composite relationship between the type of measurements obtained, technique used, and other pertinent factors, such as sonde size.
- Reliability - Reliability is the ability of the tool to perform without downtime due to system failure.

2. Risk Criteria.

- Stage of Development - The stage of development reflects the current state-of-the-art of the tools and is representative of the risk involved in using the tool in terms of its degree of completion, referred to as timetable, temperature, and pressure capabilities.
- Design Approach - This element assesses the risk of using a particular tool to locate and quantify the zone with respect to the measurements obtained, the theory upon which operation is based, and overall design of the tool.
- Experience/Testing - Assesses the risk involved in using the tool in terms of its success in field conditions and in testing.

3. Cost Criteria.

- Cost Assessment - Compares the total cost to buy and operate a tool in relation to other tools. Cost for each tool was computed for the following standard set of well conditions:

Total Depth	24 384 metres (8000 feet)
Survey Length	1524 metres (500 feet)
Temperature	232°C (450°F)
Time (Round Trip)	6 hours

The adoption of a standard set of conditions, realistic in nature, allowed each tool to be judged in the same manner.

4. Availability Criteria.

- Availability - Concerned with the ease with which a tool can be acquired. For experimental tools, availability was judged on the proposed market entry date and total scheduled production.

The results of the evaluation process are shown in Tables 7-6 and 7-7. In Table 7-6, the tools are ranked on the basis of performance only. An overall ranking of the tools is shown in Table 7-7, considering performance, risk, availability, and cost.

Table 7-6

Tool Scores Based on Performance Only

Tool	Performance Criteria					Overall Perfor- mance	Rank
	Locate Zones	Quantify Size	Operate in Geothermal Well	Accuracy	Relia- bility		
Acoustic							
Borehole Televiewer	42	59	72	63	60	58	12
Sound-Temperature Survey	74	60	84	86	80	77	1
Sonic Logs	20	23	77	46	70	44	19
Electrical							
Hot Wire Survey	66	53	70	78	50	66	8
Hot Film Anemometer	66	59	86	83	70	73	2
Dual Induction-Latero Log	36	23	92	68	70	53	15
Induction Logs	34	26	82	63	70	54	14
Spontaneous Potential Logs	34	30	80	55	80	53	15
Lost Circulation Detector	74	56	67	78	70	70	5
Fluid Velocity Indicator	58	40	67	78	70	62	11
Conventional Resistivity Logs	34	23	79	63	70	52	16
Micro-Resistivity Logs	36	26	70	58	70	50	17
Focusing Electrode Logs	42	26	77	65	70	54	14
Fracture Identification Logs	42	26	76	70	70	56	13
Temperature Logs	58	33	90	73	80	64	10
Mechanical							
Impression Packer	26	63	90	65	90	64	10
Straddle Packers	58	53	75	78	90	69	6
Spinner Survey	58	60	77	78	60	68	7
Radioactive							
Neutron Logs	10	16	90	45	70	43	20
Formation Density Logs	18	26	90	43	70	47	18
Radioactive Tracer Logs	58	53	77	73	70	65	9
Sonic-Neutron Log	34	26	77	58	70	50	17
Spinner-Temperature Survey	66	60	77	86	70	72	3
Optical							
Downhole Camera	42	63	46	67	80	56	13
Downhole Television	82	70	50	88	70	72	4

Table 7-7

Overall Tool Scores

<u>Tool</u>	<u>Performance</u>	<u>Risk</u>	<u>Availability</u>	<u>Cost</u>	<u>Overall Score</u>	<u>Rank</u>
Acoustic						
Borehole Televiewer	29	13	High	P	68	12
Sound-Temperature Survey	39	17	High	C	84	1
Sonic Logs	22	10	High	D	59	24
Electrical						
Hot Wire Survey	33	15	NA	-	69*	9
Hot Film Anemometer	37	12	NA	-	70*	8
Dual Induction-Latero Log	27	11	High	D	65	15
Induction Logs	27	11	High	C	64	17
Spontaneous Potential Logs	27	10	High	A	67	13
Lost Circulation Detector	35	13	NA	-	69*	9
Fluid Velocity Indicator	31	11	NA	-	60*	23
Conventional Resistivity Logs	26	10	High	D	64	17
Micro-Resistivity Logs	25	10	High	D	63	20
Focusing Electrode Logs	27	10	High	D	64	17
Fracture Identification Logs	28	12	High	D	67	13
Temperature Logs	32	16	High	B	77	5
Mechanical						
Impression Packer	32	15	High	B	76	7
Straddle Packers	35	14	High	A	78	4
Spinner Survey	34	17	High	B	80	3
Radioactive						
Neutron Logs	22	8	High	C	57	25
Formation Density Logs	24	10	High	D	61	21
Radioactive Tracer Logs	33	15	High	B	77	5
Sonic-Neutron Log	25	10	High -	D	61	21
Spinner-Temperature Survey	36	17	High	C	81	2
Optical						
Downhole Camera	28	11	High	A	69	9
Downhole Television	36	13	Low	V	65	15

NA = Not available

*Adjusted Score Based on Technical Information Only vs Special Arrangements

V = Variable Special Arrangements Required

P = Purchase Price = \$30,000

A = <\$3,000 Per Run

B = \$3,000 - \$3,700 Per Run

C = \$3,700 - \$5,000

D = >\$5,000

The results of the evaluation process were analyzed, and the following observations were made.

The Sound-Temperature Survey received the top ranking because it offers excellent performance characteristics and reliability, and has the capability to provide these results in a wide range of harsh geothermal environments. It offers a greater capability to locate, and an equivalent capability to quantify, lost circulation zones in geothermal wells when compared to the Spinner-Temperature Survey combination. A schematic of the Sound-Temperature Survey system is shown in Figure 7-16.

Good results can be obtained in mapping lost circulation zones with the Spinner-Temperature Survey and the independent Spinner Survey, especially when they are used in clean, single-phase fluids. Tools with similar capabilities are the Lost Circulation Detector, Radioactive Tracer Logs, Straddle Packers, and the Hot Wire Survey.

The Straddle Packer and the Radioactive Tracer Log are good choices for mapping lost circulation zones, although some improvements are required. In the case of the Straddle Packer, higher temperature seals are required if the system is going to be used in hotter downhole intervals. Also, the addition of a pressure transducer to some of the packer systems could prove helpful. The scintillation meters and Geiger counters of the gamma ray logging tools used in tracing the radioactive material must be further hardened for deep, high-temperature applications.

The Temperature Log should only be used to locate the depth of lost circulation zones. The system is well suited to this task, particularly in deep portions of the well where large temperature differentials may exist at the point of circulation loss. However, the tool is limited in its capabilities to quantify lost circulation zones, but the system is attractive because it is widely available, inexpensive, and capable of operating in harsh geothermal environments.

Impression Packers are best used after the lost circulation zones have been located as, like the Temperature Log, they are limited in their capabilities to "map" lost circulation zones in the complete sense. Also, the method used in locating the lost circulation zone should provide the rate of loss into the zone. Subsequent use of Impression Packers then allows the zone to be completely quantified and the type of zone causing lost circulation to be determined.

In examining the Hot Film Anemometer, the Hot Wire Survey, and the Lost Circulation Detector, the Hot Wire Survey and the Lost Circulation Detector were found to be highly successful when used for lost circulation mapping. Testing of the latter tool was limited, however. Higher temperature tools and increased reliability, particularly in the case of the Hot Wire Survey, would add greater capabilities to map lost circulation zones. Like the Sound-Temperature Survey, the Hot Film Anemometer is not influenced by the mud type or weight, and has high-temperature and high-pressure capabilities. However, it is less accurate than the Sound-Temperature Survey.

Like Impression Packers, Downhole Cameras and the Borehole Televiwer are best used after the lost circulation zones have been located. The

Figure 7-16. Schematic of Borehole Sound-Temperature Survey System

Downhole Camera is widely available as a substitute for the Downhole Television which, although the most accurate for mapping lost circulation zones, is limited in range of effective operation, geothermal capabilities, and availability. Like the Downhole Television, the Downhole Camera shares the risk of failure at high temperatures, is restricted in the types of mud in which it can be used, and does not have a capability to determine flow rates.

Of the highest ranked tools discussed above, three currently are not available. No plans were found for reintroducing the Hot Film Anemometer, the Hot Wire Survey, or the Lost Circulation Detector into commercial use. Eliminating these three tools results in a list of currently available "best" tools for mapping lost circulation zones as follows:

<u>Rank</u>	<u>Tool</u>
1	Sound-Temperature Survey
2	Spinner-Temperature Survey
3	Spinner Survey
4	Straddle Packers
5	Radioactive Tracer Log
6	Temperature Log
7	Impresssion Packers
8	Downhole Camera
9	Borehole Televiewer

Preparation of the final report was in process as the fiscal year ended. The report will be published separately and will include descriptions of each tool evaluated and the detailed scoring process on each tool. The preliminary conclusions resulting from the assessment of the capability of equipment and methods to map and quantify lost circulation zones in geothermal wells are:

1. Several methods are available to map lost circulation zones in geothermal wells at temperatures to 275°C (527°F); higher in some cases. No single tool is capable of completely mapping lost circulation zones. Rather, multiple tools, usually two, are required to obtain sufficient information.
2. No single method is the best in all cases. However, the new combined Sound-Temperature Log has been used successfully in several diverse applications and is the single most promising tool.
3. Tools that measure more than one parameter generally reinforce one another and tend to provide better results than single measurement tools.
4. The choice of a tool must be dictated by the type of information required and the downhole environment's influence on the performance and reliability of the tools being considered.
5. No radically new design approaches for mapping lost circulation zones were found. The development trend appears to be focused on increasing the capabilities of existing technologies.
6. Presently available systems can improve lost circulation understanding, treatment, and control.

7. Future availability of high-temperature geothermal logging tools having 260° to 288°C (500° to 550°F) and limited 316°C (600°F) capacity appears promising with several companies currently updating existing technology, or developing new technologies, for use in high-temperature environments.
8. Several tools beneficial in mapping lost circulation zones, e.g. Lost Circulation Detector, are not available. Feasibility studies on high-temperature versions of these tools as well as cost/benefit analysis could determine if the introduction of these tools into commercial use would significantly increase the number of useful alternatives.
9. Further research on electrical resistivity devices is needed to determine conditions favorable for their use, develop better interpretation techniques, and establish the possibility of new applications.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 79

★

LEGEND:

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

7.4 Lost Circulation/Cementing Test Facility

Sandia National Laboratories

Technical Consultants: J. Kelsey (505) 844-6968

V. Behr (505) 844-0301

Project Objective

The objectives of this project are to

1. Design and fabricate a facility for testing lost circulation materials and cementing techniques at simulated geothermal well conditions,
2. Evaluate lost circulation materials, and
3. Evaluate cement displacement techniques for effectiveness prior to field tests.

Project Status

The existing lost circulation/cementing testing facilities have been evaluated. Based on this evaluation, it was decided that a new facility is needed for accurate simulation of geothermal well conditions. The design of this facility is continuing.

FY80 Progress

A substantial portion of the cost associated with drilling and completing a geothermal well can be attributed to lost circulation problems and poor cement displacement. Lost circulation that occurs during drilling may increase the drilling costs by 30% or more, while incompetent cementing jobs can result in loss of the well.

Evaluation of Existing Facilities — The following companies were visited and their lost circulation/cementing testing facilities evaluated:

- Halliburton
- Dowell
- Amoco
- Shell
- Exxon
- NL Baroid
- Magcobar

Of the companies visited, only Halliburton had a facility similar to that needed for this project. Unfortunately, this facility is scheduled for use by a major oil company for the next three years. This facility also has an operating temperature of less than 121°C (250°F), which is below the temperatures that may be encountered in geothermal wells.

Because of the lack of availability and the limited testing temperature, it was concluded that a new, high-temperature facility was required.

Facility Design -- The lost circulation/cementing test facility will experimentally evaluate lost circulation materials and cement displacement practices at simulated geothermal well conditions. The characteristics of the test facility are listed in Table 7-8. A flow schematic of the facility is shown in Figure 7-17.

Table 7-8

Characteristics of the Lost Circulation/Cementing Test Facility

<u>Parameter</u>	<u>Range</u>
Pressure	0.1 to 41.4 MPa (15 to 6 000 psi)
Temperature	21° to 204°C (70° to 400°F)
Flow Rate	No flow to 6.3 m ³ /s (100 gpm)
Length	91.4 cm (3.0 ft)
Bore Diameter	5.1 to 30.5 cm (2.0 to 12.0 in.)

Laboratory space for this facility has been allocated and detailed design is nearing completion.

Figure 7-17. Lost Circulation/Cementing Test Facility Flow Schematic

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT	★												END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>LOST CIRCULATION DRILLING TECHNIQUES MAURER</u>													
DEFINE PERFORMANCE SPECIFICATIONS												●	OCT 80
DESCRIBE TECHNIQUES TO BE EVALUATED												●	NOV 80
DOCUMENT AND EVALUATE PAST PERFORMANCE													START OCT 80
CITE AND EVALUATE NOVEL TECHNIQUES													START DEC 80
IDENTIFY PREFERRED TECHNIQUES													JAN 81
FINAL REPORT													FEB 81

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

7.5 Evaluation of Techniques and Hardware for Drilling Through Lost Circulation Zones

Contractor: Maurer Engineering, Inc.
Principal Investigator: D. Daring (713) 683-8227
Contract Period: 1 September 1980 to 1 March 1981
Contract Number: 62-7201 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to evaluate the techniques and hardware that enable drilling through lost circulation zones in geothermal wells. Techniques and hardware, including

1. Concentric drill pipe,
2. Low density drilling fluids, and
3. Fluid aeration through a parasite string

will be evaluated on the basis of performance, risk, cost, and availability.

Project Status

Work was initiated to define performance specifications and to describe the techniques to be evaluated.

FY80 Progress

The majority of techniques for drilling through lost circulation zones have been catalogued and preparation of detailed descriptions are in progress. A generic well is being defined. The various techniques will be evaluated against the generic well.

8. 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 under way 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; 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; to evaluate elastomers for use in geothermal applications; and to extend laboratory 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. The use of the code is continuing for calculating stresses in the PDC 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 transient wellbore temperatures for compressible fluids in the single-phase flow regime.

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 at Sandia. DRL at Salt Lake City has been modified to provide torque capabilities to 13 600 N•m (10 000 ft•lb) and rotary speeds to 500 rpm.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

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

8.1 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 the 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 and provide measurements of bottomhole pressure gradients, cutter heat transfer coefficients, and chip removal ability.

Project Status

A program plan and technical investigation procedure have been formulated. The design, assembly, and fabrication of the test facility have been completed. A defective drive shaft has delayed the start of the full-scale bit hydraulics studies until October 1980. A small-scale water channel has been constructed, however, for the purpose of measuring single cutter heat transfer coefficients and flow patterns. These tests are currently underway.

FY80 Progress

The FY80 milestone schedule for the Bit Hydraulics Studies Project was revised to reflect more realistic estimates for the fabrication and check-out of the test stand. Also, more detail concerning specific studies was added to the schedule to reflect refinements and additions to the program plan since the original milestones were proposed in January 1979. These study additions are the result of the increased capability designed into the test stand. The fabrication of the test stand has taken longer because of the more stringent structural and tolerance requirements imposed by this increased capability. The ability of the test stand to withstand full-scale flow rates has led to the inclusion of a flow similarity study in the program plan. This study will assess the validity of Reynolds number scaling by comparing the flow patterns across the bit face that result from full-scale flow rates with those that result from flow rates reduced according to scaling laws.

The Lexan material for the simulated borehole was delivered, and a task was undertaken to machine the material to the required dimensions. The borehole consists of two parts, a cylinder and a bottom plate. The Lexan cylinder, with an o.d. of 30.5 cm (12 in.), was bored with conventional machining methods to the 16.5-cm (6.5-inch) bit diameter. The bottom of the simulated borehole consists of a circular Lexan plate that fits against the bottom of the cylinder and is sealed with a static O-ring.

In order to simulate the actual shape of the borehole to the greatest possible extent, a decision was made to attempt to cut the bottomhole pattern of a stud-mounted PDC bit into the Lexan plate. To accomplish this, the plate and bit were chucked into a lathe. The bit was forced into the plate while the latter was rotated. Although there were initially some doubts about the ability of the bit to successfully cut smooth patterns in such a plastic material, the results were excellent. Individual cuts within the bottomhole pattern were smooth enough that the clarity required for flow visualization experiments was easily achieved.

During this machining test, observations revealed that the cutting action of individual cutters could be clearly seen through the opposite face of the Lexan plate. This discovery raises the possibility of studying the mechanical cutting action of the bit, as well as hydraulics, with high-speed photography during a simulated drilling operation. Although drilling in Lexan would not accurately simulate rock drilling, the relative engagement of individual cutters into the material and the effects of this engagement on hydraulics performance can be studied. These studies could lead to improvements in cutter placement and hydraulic configuration.

The test stand also provides for a cutter heat-transfer study. In this study, the convective heat-transfer coefficient for the various cutters in the bit will be measured under a variety of test conditions. The measurements will be taken with thin-film, temperature-dependent resistors. These resistors, similar to strain gages in size and shape, can be mounted at various positions on the cutter faces and studs. By using electronic circuitry to maintain the resistors at a constant temperature above the ambient fluid and by measuring the current passing through each resistor, the convective heat transfer coefficients can be calculated. These values, together with theoretical and experimental heat generation values ascertained for cutting, can be used to compute cutter temperatures. This will allow an assessment of the ability of the hydraulics to effectively cool the cutters.

During the 1980 fiscal year, 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.

The assembly of the bit hydraulics test facility was completed in May 1980. The Safe Operating Procedures manual was submitted and approved, and the facility was successfully pressure tested. However, a problem with rotation of the bit was encountered. The facility is designed to provide bit rotation by rotating the drive shaft that supplies hydraulic fluid to the bit. This shaft is supported by two bearing assemblies. Fluid is sealed by rotary O-rings at four points along the shaft. Because these seals require a smooth rubbing surface, the shaft was plated along its entire length.

To begin the testing, the shaft drive motor was engaged to test the bit rotation capability. Initially, the system worked well, and rotation to approximately 400 rpm was achieved without supplying full power to the motor. After approximately 1 minute of operation, however, the torque required to rotate the shaft increased significantly, eventually reaching the point at which the motor could no longer rotate the shaft. The motor was disengaged, and the test stand was disassembled so that the components could be examined. It was found that the plating on the shaft had begun to flake due to a poor plating job. Although flaking was widespread over the surface, localized flaking at the seal interfaces had caused the problem. The resultant surface roughness had torn the elastomeric seal surfaces, thereby increasing friction and torque.

The shaft was inspected to determine the feasibility of replating. Based on the inspection, a decision was made to order a new, stainless-steel shaft. The extruded pipe was received in August 1980 and placed in Sandia's machine shop for machining to the required dimensions. This operation is expected to be completed in early October. Assuming that assembly of the facility proceeds as planned, initial hydraulics studies should begin in late October.

The small water channel shown in Figure 8-1 was designed and built for single-cutter hydraulic studies. A single stud, instrumented with heat transfer gages, is shown mounted in the channel. Water enters the channel and flows past the stud before exiting through the port at the rear of the channel.

The angle between the face of the stud and the flow velocity vector can be changed by rotating the stud about a vertical axis to the desired position. Water flow velocities immediately upstream of the stud are measured with a pitot-static tube. This permits correlation of the measured heat transfer coefficients with velocity as a function of flow impingement angle. This data will be used for interpreting full-scale data obtained in the bit hydraulics test facility.

In addition, dye can be introduced through several ports upstream of the stud in order to study flow patterns around studs. This study will allow identification of zones of flow stagnation and separation. This will be helpful in guiding placement of nozzles relative to studs in bit optimization studies planned for the future.

The single cutter tests were started in September 1980 and will be run concurrently with full-scale tests in the bit hydraulics test facility.

Figure 8-1. Water Channel Device for Single-Cutter Heat Transfer and Flow Pattern Studies

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8.2 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 H₂S environment without large sacrifices to its mechanical properties or cost.

Project Status

An Internal R&D research report was issued. The test facility design was completed, and the facility will be built by the time test specimens are ready for testing. Compositional changes to the drill stem material were defined, and conventional drill stem material suitable for the corrosion fatigue study was identified. Unavoidable delays in the delivery of the steel for test specimens delayed the inception of the test program. However, the dual-phase steel alloys have now been made and the conventional drill stem material delivered. Processing of the dual-phase alloys has been completed, and fabrication of specimens for the heat treatment experiments is proceeding. Fatigue tests in dry air and in a 5% brine solution have been conducted using Grade E drill stem material to establish baseline data.

FY80 Progress

Silicon-based, dual-phase steels were vacuum-induction melted and cast by the Sandia Melting Laboratory. The steels were made in two separate runs: the first on 12 October 1979 and the second on 17 October 1979. Each run contained about 227 kg (550 lb) of steel and was split between two compositions. Table 8-1 lists the alloy designations and compositions.

Table 8-1

Silicon-Based Dual-Phase Steel Alloys

Run	Alloy Designation	Alloy Composition		
		Fe plus (by weight percent)		
		Si	C	V
1	V-12-1	2.0	0.1	--
	V-12-2	2.0	0.1	1.0
	V-12-3	2.0	0.1	1.0
2	V-13-1	2.0	0.1	0.1
	V-13-2	2.0	0.1	0.2

As-cast ingot material from each alloy was tested for hardness. Table 8-2 shows the hardness and the corresponding approximate tensile strength for each of the alloys.

Table 8-2

As-Cast Hardness and Tensile Strength of Alloys

Alloy Compositions	Hardness R_B	Approximate Tensile Strength	
		MPa	(ksi)
Fe - 2.0 Si - 0.1 C	78.1	482.6	(70.0)
Fe - 2.0 Si - 0.1 C - 0.1 V	79.8	498.5	(72.3)
Fe - 2.0 Si - 0.1 C - 0.2 V	83.4	533.7	(77.4)
Fe - 2.0 Si - 0.1 C - 1.0 V	83.0	528.8	(76.7)

NOTE: Alloys listed in order of increasing vanadium content

The hardness values indicate tensile strengths in the 483- to 538-MPa (70- to 78-ksi) range for the as-cast alloys. These values are below that required for Grade E pipe, which is approximately 655 MPa (95 ksi). This result is expected, because the alloys have not undergone mechanical processing or heat treatment.

Samples of the as-cast ingots of the silicon-based, dual-phase steels were cut, and some initial heat treating studies were performed. Because the samples were from the ingot, a number of problems with this initial characterization may exist. These possible problems include macrosegregation and nonhomogeneity in the ingot. Thus, the samples taken from one particular area may not be representative of the overall composition. The as-cast material also has a large grain size compared to forged or worked material. The large grain size may affect the strength as well as the time response to the various heat treatments. In spite of these possible problems, an indication of heat treat response of these alloys can be gained through work on as-cast ingot material.

Figures 8-2 through 8-5 show the hardness of alloys V-12-1 (Fe-2.0Si-0.1C) and V-13-1 (Fe-2.0Si-0.1C-0.1V) as a function of heat treatment. Figure 8-2 shows the hardness (as well as the approximate ultimate tensile strength) as a function of the austenitizing temperature for samples of alloy V-12-1 in the as-quenched condition as well as in the quenched and tempered condition. The samples were tempered at 550°C (1022°F) for 1 hour. Figure 8-3 shows the same information for alloy V-13-1. Each of these alloys behaves as expected; the hardness and strength increase as the austenitizing temperature increases, because more carbides are dissolved at higher temperatures. Consequently, on quenching, an increased amount of carbon is released for hardening of the martensite.

Figure 8-2. Hardness and Approximate Tensile Strength of Alloy V-12-1 as a Function of the Austenitizing Temperature

Figure 8-3. Hardness and Approximate Tensile Strength of Alloy V-13-1 as a Function of the Austenitizing Temperature

Figure 8-4. Hardness and Approximate Tensile Strength of Alloy V-12-1 as a Function of Various Inter-critical Annealing Temperatures

Figure 8-5. Hardness and Approximate Tensile Strength of Alloy V-13-1 as a Function of Various Intercritical Annealing Temperatures

The tempering, after quenching, allows carbides to form in the fully martensitic matrix. The carbon level in solid solution decreases, thus decreasing the hardness but increasing the toughness of the alloy. The addition of 0.1 vanadium to the base composition increases slightly the strength of the alloy in both the as-quenched and the quenched and tempered conditions.

When samples of the alloy are given intercritical annealing treatments after austenitizing and quenching, the final hardness again depends on the temperature of the initial austenitizing treatment. Hardness as a function of various intercritical annealing temperatures is shown in Figures 8-4 and 8-5. The irregularity of the curves may have resulted in large part from the use of as-cast ingot material. The general trend of these curves indicates that, in both alloys, the samples that are austenitized at the lower temperature have the highest hardness after the intercritical anneal treatment. The cause of this phenomenon was not immediately determined, but the effect seemed to be connected again with the amount of carbide dissolved during the austenitizing treatment. The higher austenitizing treatment puts more solute of C, Si, and V, if present, back into solid solution. In this state, the hardening, primarily in the ferrite, is not as great as that provided by the V-carbides and/or Si-carbides. The prime factor for determining the hardness differences produced by the different austenitizing temperatures seems to be the strength of the ferrite. Verification of this explanation will require transmission electron microscopy studies of the samples in various heat treat conditions.

The particular intercritical annealing temperature determines the fractions of ferrite to martensite. The higher the intercritical anneal temperature is, the higher the fraction of martensite in the quenched alloy will be. The hardness of the alloy is determined by the ratio of the amount of martensite to the amount of ferrite, as well as by the strength ratio of martensite to the ferrite. Although the amount of martensite increases as the intercritical anneal temperature increases, the hardness of that martensite decreases because it contains less carbon in solid solution. At lower intercritical anneal temperatures, the smaller amount of martensite formed on quenching contains significantly more carbon in solution and makes the martensite harder. Thus, a self-compensating effect occurs that keeps the alloy from changing hardness drastically as the intercritical annealing temperature is changed. Specific changes should more easily be determined on fully homogenized and hot-worked alloy material.

An important point to note is that both of these alloys are capable of achieving the required strength through quenched and tempered as well as quenched and intercritically annealed heat treatments. The existence of two types of heat treatments provides the opportunity to compare attendant mechanical properties, such as toughness and fatigue resistance, and chemical-mechanical properties, such as corrosion fatigue, on samples having the same composition and the same strength level but having a variety of microstructures.

The heat treatment studies on the as-cast ingot material were continued. The initial heat treatment and metallography studies were designed to help determine the heat treatments that should be used for the corrosion fatigue test samples. The initial metallography on the heat treated ingot material was completed.

The optical metallography was designed to define the fractions of martensite and ferrite as well as the particular morphology. A representative selection of micrographs is shown in Figures 8-6, 8-7, and 8-8. In Figure 8-6, the microstructures are shown for steel alloy samples of Fe-2.0Si-0.1C-0.1V that 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 previously reported; the alloy that is austenitized at the highest temperature exhibits the highest hardness due to an increased amount of martensite. Figure 8-7 shows microstructures of this same alloy upon tempering after quenching. Figure 8-8 shows microstructures of the alloy upon intercritical annealing and quenching after austenitization and quenching. Figure 8-7 also shows the tempered microstructure that 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 8-8, is comprised of areas of proeutectoid ferrite (relatively large, 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 presence of 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 8-8, is not clear-cut after the sample's surface has been etched in 2% Nital. Alternate etching procedures were pursued to allow the various phases to be clearly distinguished from each other.

A modified, dual-phase heat treatment was 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 8-9. 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 8-10. The modification to this heat treatment is schematically depicted in Figure 8-11. 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 8-12) obtained from this modified heat treatment shows a dramatic difference from the microstructure obtained from standard heat treatment (Figure 8-10). 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

Figure 8-6. 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 8-7. 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.

100x

500x

Figure 8-8. 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.

(a)

(b)

Figure 8-9. Standard Duplex Ferritic-Martensitic Heat Treatment of an Iron-Carbon-Silicon Alloy; (a) Phase Diagram and (b) Heat Treatment Schematic

Figure 8-10. 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 8-11. Modified Duplex Ferritic-Martensitic Heat Treatment of an Iron-Carbon-Silicon Alloy; (a) Phase Diagram and (b) Heat Treatment Schematic

Figure 8-12. 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

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 8-12) that are present.

Investigations continued on the significance of the modified heat treatment to the properties of the alloy. The hardness of the specimens as a function of intercritical annealing temperature is shown in Figure 8-13. 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.

Studies on the effect of tempering after the dual-phase heat treatment were continued. Hardness as a function of annealing temperature after tempering at 540°C (1004°F) for 1 hour is shown in Figure 8-14. The tempering treatment decreases the hardness of the samples that underwent the modified heat treatment more than it decreases the hardness of the 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. The remelted ingots were homogenized by heating them to 1150°C (2102°F) in argon for 16 hours. Then the low-alloy, dual-phase steels designed for resisting corrosion fatigue in an H₂S-containing environment were sent to the Rocky Flats Plant for fabrication. These steels contained 2.0 weight percent silicon, 0.1 weight percent carbon, and 0 to 1.0 weight percent vanadium as the main alloying additions.

At the Rocky Flats Plant, the ingots were double hot-forged. First, each ingot was heated to 1050°C (1922°F), laid on its side, and steam hammered to about 8.26 cm (3.25 in.) in thickness. The resulting slabs were then reheated and positioned to deform the material in a direction perpendicular to the first forging operation. The final forging thickness for each steel was about 7.6 cm (3.0 in.); the steels were air-cooled to room temperature from their hot-forging temperature.

During the hot-rolling operation, the forged slabs were preheated to 955°C (1751°F) for 2 hours and were then rolled to plate in approximately eight passes. The temperature of the final pass on each steel was in the 800° to 850°C (1472° to 1562°F) range, and the deformation induced by the final pass was about 40%. This amount of deformation at temperatures in

Figure 8-13. Hardness versus Intercritical Annealing Temperature (at Temperature for 20 min) for Dual-Phase Heat Treatments (Standard and Modified)

Figure 8-14. 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)

the 800° to 850°C (1472° to 1562°F) range should produce steel plate with a very fine grain size, particularly for those steels that contain vanadium additions. A fine grain size in these steels should enhance the resistance to corrosion fatigue in H₂S and, additionally, improve mechanical properties such as strength and toughness. The final thickness of the as-rolled plates was 1.334 cm (0.525 in.). The as-rolled material was cleaned and shipped to Sandia, and heat treating studies and mechanical test specimen preparation initiated.

Mechanical testing of Grade E drill pipe began in May 1980. The test program includes tensile tests; impact testing of both pre-crack and notched but not pre-cracked Charpy specimens; and fatigue tests on compact tension specimens. The effect of sample orientation with respect to the parent material is monitored in both the tensile and impact tests. The specimens are machined from actual Grade E drill stem (manufactured by Wheeling-Pittsburgh) that has been sectioned and flattened into small plates approximately 12.7 by 12.2 cm (5 by 6 in.).

The fatigue portion of the program involves testing in several environments, including dry laboratory air, the NACE-standard brine solution, and the brine solution saturated with H₂S. These tests can alternatively be called corrosion fatigue tests, but it is only in the H₂S-saturated brine that an appreciable effect of corrosion is expected to be observed in these short duration tests, each of which lasts only about 8 hours. It is through the corrosion fatigue tests in the H₂S solution that the suitability of various alloys for use as drill stem can be most adequately gaged by laboratory-scale tests. The other mechanical tests are considered important for determining the suitability of various steels for application in rotary drilling.

The Drill Stem Corrosion Program presently has three specific steels that are being tested as outlined above. The first material is the conventional Grade E drill pipe, which is a medium carbon, i.e., approximately 0.4 weight percent carbon, with approximately 1.5 weight percent manganese and 0.15 weight percent molybdenum as the main alloying additions. The second alloy under test is the dual-phase steel with silicon and vanadium. Progress in the development of this alloy was described earlier and is continuing. The third material being tested is a modified 4120 steel that has been developed by the Climax Molybdenum Research Center. Metallurgists at the Center, Ann Arbor, Michigan, have developed the modified 41xx* 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 is being tested for corrosion fatigue in this program. A special heat of about 22.7 kg (50 lb) of this alloy has been provided by the Climax Molybdenum Research Center.

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

Other alloys are presently being sought for the testing program and will be included when suitable sources of material are identified.

The machined test specimens of the Grade E drill stem include flat tensile bars, compact tension specimens, and Charpy specimens. The flat tensile bars, of two orientations, have been tested. Figure 8-15 shows a typical engineering stress-strain plot generated during a tensile test. A compilation of the test results are shown in Table 8-3. The average values for the yield and ultimate strengths are nearly the same for the transverse and longitudinal orientations; the longitudinal sample is parallel to the axis of the drill pipe, while the transverse is at right angles to it. The elongation is slightly better for the longitudinal samples than for the transverse samples. The lack of a large difference in strength with orientation, that is a lack of anisotropy, indicates that the crack growth during a fatigue-type test should remain in the proper plane.

Table 8-3

Tensile Test Data for a Joint of Grade E Drill Stem Manufactured by Wheeling Pittsburgh and Reheat Treated*

Sample	Yield Strength		Tensile Strength		Elongation %
	MPa	(ksi)	MPa	(ksi)	
Transverse 1	712.9	(103.4)	787.4	(114.2)	21
Transverse 2	692.2	(100.4)	772.2	(112.0)	22
Transverse 3	696.4	(101.0)	770.8	(111.8)	23
Transverse 4	695.0	(100.8)	772.2	(112.0)	23
Average	699.1	(101.4)	775.7	(112.5)	22.3
Longitudinal 1	706.0	(102.4)	776.4	(112.6)	26
Longitudinal 2	703.3	(102.0)	776.4	(112.6)	28
Longitudinal 3	703.3	(102.0)	776.4	(112.6)	26
Longitudinal 4	707.4	(102.6)	781.9	(113.4)	26
Longitudinal 5	707.4	(102.6)	780.5	(113.2)	25
Longitudinal 6	703.3	(102.0)	768.1	(111.4)	27
Average	705.3	(102.3)	776.4	(112.6)	26.3

* Water quenched from 860°C (1580°F) and tempered at 650°C (1202°F) for two hours

The test results of a preliminary fatigue test in dry air are plotted in Figure 8-16 as da/dn (crack growth rate) versus ΔK , where a is the crack length in inches, and n is the number of fatigue cycles through a ΔK , which is $K_{max} - K_{min}$. K is the stress intensity in the crack plane and is given in units of $ksi \sqrt{in}$. The dry air test was done in the same chamber being used for the tests in the brine solution and in the H_2S -saturated brine solution. The interaction between dry air and the Grade E specimen during

Figure 8-15. Typical Tensile Test for a Joint of Grade E Drill Stem
Manufactured by Wheeling-Pittsburgh and Reheat Treated:
Water Quenched from 860°C (1580°F) and Tempered at
650°C (1202°F) for 2 hours

Figure 8-16. Fatigue Curve in Dry Air for the Grade E Material
Taken at a Frequency of 5 Hz with $K_{\min} = 0.1 K_{\max}$

the test was minimal; thus, the dry air tests provide a baseline set of data to which tests in other environments can be compared. The dry air test was also conducted to establish a correlation between the crack length and the compliance of the sample during testing. In air, it is possible to measure the crack length optically with the aid of a microscope. The crack length can then be correlated with the compliance. Once this correlation is firmly established, the crack length may be determined without a visual observation of the crack. This capability is important during testing in the brine solutions, with and without H_2S , because a general surface corrosion film is formed that obscures the crack during testing in these solutions. Figure 8-17 graphically shows the correlation between crack length and compliance for a fatigue test in dry air.

Additional fatigue tests both in dry air and in a 5% brine solution have been performed. Dry air fatigue tests on the Grade E drill stem material were run to improve the testing procedures as well as to arrive at a reliable baseline fatigue behavior. The dry air fatigue curve is shown in Figure 8-18, where the crack growth rate, da/dn , is plotted versus a measure of the stress intensity, ΔK . The additional data yielded a much smoother curve for da/dn versus ΔK than that shown in Figure 8-16. Additional data were also taken to allow a correlation between compliance and crack length. As previously indicated, these data allow the crack length to be determined without visual measurement, permitting measurements to be made in other environments, such as brine and brine saturated with H_2S gas. The relationship between crack length and compliance for the Grade E material is shown in Figure 8-19.

Figure 8-20 shows the results of a fatigue test of Grade E material in brine. A comparison of Figure 8-20 and Figure 8-19 shows that the brine environment has a negligible effect on the fatigue behavior of the Grade E material.

Tests were also run in the 5% brine solution with 0.5% acetic acid to lower the pH; this is called the standard NACE brine solution. The fatigue behavior was also observed in the standard NACE brine solution which had N_2 gas bubbled through it in order to decrease the oxygen content. Additionally, some data points were taken while air was bubbled through the solution in order to raise the O_2 level of the solution. All of the fatigue behavior in these various environments produced curves of crack growth rate versus stress intensity level which were essentially coincident. Specifically, there was no effect on the fatigue behavior produced by varying the environment as described above. However, this statement is valid only for the specific conditions of these tests, i.e., room temperature and a frequency of 5 Hz. For other conditions, specifically higher temperatures and lower frequencies (0.1 to 1 Hz), the variation of these environments may cause a change in fatigue behavior. The data for various experiments are shown in Figure 8-21.

Figure 8-22 shows a smooth curve drawn through the data in Figure 8-21. Also, shown in Figure 8-23 is a curve representing the fatigue crack growth rate for a normalized 4140 alloy in air or brine. The crack growth rate is lower for the 4140 alloy compared to the rate in the Grade E material. The primary differences may be due to a variation in composition or to differences in inclusion content. The Grade E material is currently being analyzed for composition and inclusion content.

Figure 8-17. Correlation Between the Compliance and the Crack Length during a Fatigue Test in Dry Air for Grade E Material

Figure 8-18. Fatigue Curve in Dry Air for a Grade E Material at a Frequency of 5 Hz with $K_{\min} = 0.1 K_{\max}$

Figure 8-19. Correlation Between Compliance and Crack Length for Grade E Material

Figure 8-20. Fatigue Curve in 5% Brine Solution for Grade E Material at a Frequency of 5 Hz with $K_{\min} = 0.1 K_{\max}$

Figure 8-21. Fatigue Data for Grade E Material in Various Environments at a Frequency of 5 Hz with $K = K_{\max} - K_{\min}$ and $K_{\min} = 0.1 K_{\max}$. K = the stress intensity in the cracked plane.

Figure 8-22. Fatigue Curves in NACE Brine for Grade E Material and for 4140 Alloy at a Frequency of 5 Hz with $K = K_{\max} - K_{\min}$ and $K_{\min} = 0.1 K_{\max}$. K = The stress intensity in the cracked plane.

The Safe Operating Procedure for the H₂S Corrosion Fatigue Test has been written and approved. A schematic of the H₂S corrosion fatigue system is shown in Figure 8-23.

The corrosion fatigue chamber has been leak checked with H₂S and minor leaks have been repaired. The scrubbing and vent systems have been checked under a constant flow of H₂S. The system is ready for H₂S corrosion fatigue testing of Grade E material which should be completed during the next reporting period.

Figure 8-23. Schematic of Corrosion Fatigue System

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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8.3 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 on and testing of the chip formation process of rock cutting tools utilizing 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 was initiated. Modeling of the rock/tool interface has begun. Calculations of tool stresses and frictional forces were completed. Calculations of heat input were completed, and wear calculations are continuing. A thermal analysis is being conducted.

FY80

TOODY was used to model the drag-tool/rock interaction for a drag tool with a -20° rake angle. The calculations indicate that 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 tool/rock interface. The tool force histories were similar to those observed for other rake angles. The predominant failure mechanism in the rock was tensile failure. The position and orientation of the cracks in the rock were similar to those calculated for other rake angles. Stress and velocity histories on the bit and rock surface were generated for A. Ortega and used in his frictional heating studies.

It has been determined that rock fracturing occurs in roughly four identifiable steps. Each step influences the tool forces. The four rock fracturing steps are illustrated in Figure 8-24. In the first step (Figure 8-24a), little or no cracking of the rock occurs. The rock is being deformed elastically, and the tool forces are increasing at approximately a constant rate.

In the second step (Figure 8-24b), there is little or no cracking of the rock ahead of the tool. However, a crack forms and runs from the bottom of the tool down into the rock. The rock corner at the front of the tool causes a stress concentration that leads to the tensile fracture. The tool corner at the back of the rock/tool interface causes a stress concentration that also leads to tensile failure. These two cracks tend to coalesce and form one vertical tensile crack. The tool cutting force changes little during the first 30 μ s of this phase. After this period of time, the tool cutting force increases. The tool thrust force continues to increase at the same rate as in the first step.

(a)

Drag-Tool/Rock Interaction Problem, First Step

(b)

Drag-Tool/Rock Interaction Problem, Second Step

(c)

Drag-Tool/Rock Interaction Problem, Third Step

(d)

Drag-Tool/Rock Interaction Problem, Fourth Step

Figure 8-24. Rock Fracturing Steps

In the third step (Figure 8-24c), the crack propagating from the bottom of the tool terminates, and another crack initiates in front of the tool. The gap or V-groove between the rock and tool in front of the tool causes the formation of a tensile-stress region inside the rock in front of the gap. As the loads increase, the tensile stresses increase, resulting in a tensile fracture in front of the tool. In one calculation the gap was eliminated. The tensile region still formed in front of the tool below the surface of the rock. The tool cutting force increases during this step, and the thrust force continues to increase at the same rate as in earlier steps.

In the last step (Figure 8-24d), the crack in front of the tool has propagated to the surface. The tool forces drop very quickly because the fractured rock has little strength. These observations on tool forces are in qualitative agreement with the experimental results.

Table 8-4 shows the times at which each of the four previously described steps occurs. In one case, the vertical crack continues to grow throughout the entire problem. However, its late-stage growth is very slow. The time chosen when the crack "ends" is when the crack dramatically slows down. All four of the runs were stopped because of severe mesh distortion.

Table 8-4

Crack Growth Times for Four Calculation Runs

Run	Vertical Crack Begins	Vertical Crack "Ends"	Horizontal Crack Begins	Failed Rock in Front of Bit
7 by 7 cm/0.5 friction	35 μ s	85 μ s	95 μ s	180 μ s
9 by 9 cm/0.5 friction	35 μ s	110 μ s	90 μ s	125 μ s
9 by 9 cm/0 friction	35 μ s	120 μ s	90 μ s	130 μ s
9 by 9 cm/no gap	35 μ s	205 μ s	230 μ s	245 μ s

All four of these runs use the same drag bit with a -20° rake angle, an initial velocity of 0.5 m/s (1.6 ft/s), and a depth of cut of 5 mm (0.2 in.). The coefficient of friction between the rock and bit was 0.5 in all runs, except for one that was set to 0. In the first run, the rock in the problem was approximately 7 by 7 cm. In the rest of the runs, the rock was approximately 9 by 9 cm. The rock dimensions, 7 by 7 cm (2.8 by 2.8 in.) and 9 by 9 cm (3.5 by 3.5 in.), were chosen large enough to insure that the rock boundaries would have no influence on rock fracture propagation. The second run was identical to the first except for the size of the rock. The geometry of the third run was identical to the second, but the coefficient of friction between the rock and bit was decreased from 0.5 to 0.0. In the fourth run, the small gap between the front of the drag bit

and the rock was eliminated. An earlier analysis indicated that the tool forces will increase dramatically when this gap is eliminated. This implication is confirmed by Run No. 4.

As shown in Table 8-4, the vertical crack begins at the same time in all four runs. The crack continues throughout the 9 by 9 cm/0 friction problem but is essentially formed at 120 μ s. The times for the 9 by 9 cm/0.5 friction and 9 by 9 cm/0 friction runs are almost identical. However, the times for the 9 by 9 cm/0.5 friction runs are different from those for the 7 by 7 cm/0.5 friction or the 9 by 9 cm/no-gap runs. These observations imply that the rock failure process is relatively insensitive to the coefficient of friction but is sensitive to the geometry of the rock.

Figures 8-25 through 8-30 are a set of plots comparing the tool forces of four runs. Figures 8-25, 8-27, and 8-29 are comparisons of thrust forces for the four runs. The thrust force is directed downward into the rock perpendicular to the motion of the bit. The thrust forces are very similar for all four runs and begin to decrease only after the rock has failed in front of the tool. Figures 8-26, 8-28, and 8-30 are comparisons of the cutting force of all four runs. The cutting force is in the same direction as the motion of the bit. Figure 8-26 compares the 9 by 9 cm/0 friction and 9 by 9 cm/0.5 friction runs. The cutting forces are identical up to 120 μ s. There is some deviation after 120 μ s, when the cutting force associated with the 0 friction run continues to increase. Figure 8-28 compares the 9 by 9 cm and 7 by 7 cm runs in which the coefficient of friction was 0.5. The results are practically identical up to 100 μ s. After this time, the forces associated with the 7 by 7 cm run continue to grow. This result is consistent with the data presented in Table 8-4. At 125 μ s, the rock in front of the bit in the 9 by 9 cm calculation has completely failed, and the forces begin to drop. However, in the 7 by 7 cm run, some of the rock in front of the bit remains competent until 180 μ s. This competent rock continues to support an increasing cutting force. The cutting forces of the 9 by 9 cm gap and no-gap runs (Figure 8-30) are very close until approximately 90 μ s. The cutting forces of the no-gap problem continue to grow for much longer. This condition results from the delayed failure of the rock in front of the bit. Once the rock in front of the bit begins to fail, the tool forces drop rapidly.

These calculations are an improvement over earlier calculations, because modifications were made that led to the incorporation of finer zoning, larger rock, and longer run time into the study. Some of the earlier runs used smaller, more coarsely zoned rocks whose stress-free boundaries strongly influenced the stress fields. If larger rocks were used, the details would change, but the four steps identified in this report would remain. The zoning used in these calculations is quite fine, as shown in Figure 8-31, but, due to the unstable nature of tensile fractures, changes in zoning will change the tool loads and details of the fracture. The delayed failure of a few cells can strongly influence the cutting force. These calculations were terminated because of extreme distortion of some of the cells. Some of the earlier runs were terminated on a different criterion before the rock had completely failed.

Figure 8-25. Comparison of Drag Tool Force Histories; Thrust Force

Figure 8-26. Comparison of Drag Tool Force Histories; Cutting Force

Figure 8-27. Comparison of Drag Tool Force Histories; Thrust Force

Figure 8-28. Comparison of Drag Tool Force Histories; Cutting Force

Figure 8-29. Comparison of Drag Tool Force Histories; Thrust Force

Figure 8-30. Comparison of Drag Tool Force Histories; Cutting Force

Figure 8-31. Example of Fine Zoning Used in Calculations

These calculations resulted in the following findings: (1) rock failure occurs in four steps; (2) the thrust forces increase at a steady rate throughout the fracturing process and begin declining in the fourth step; and (3) the cutting force goes through several phases that are strongly dependent on the rock failure mechanisms.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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8.4 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 31 March 1981
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 capability 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 were identified. The design and assembly of the high-speed/high-torque facility were completed. A high-rate, data acquisition, computer program was completed. Conceptual ideas for the high-pressure facility were evaluated, and the design and fabrication of the facility are continuing. An extension of the project is under consideration.

FY80 Progress

Rock Selection and Acquisition — Rock property data from the major geothermal development sites were compiled. Literature on geothermal wells and reservoir rock formations available at Terra Tek's and DRL's libraries and files was gathered. A search to locate all rock property data on geothermal formations generated on other projects was completed. Outside sources of information were sought and data compiled. The rock properties needed for simulation were defined, and a search for sources of surface rock formations to match these properties was completed.

A decision was made to collect and compile data on the following sites: (1) The Geysers, (2) Imperial Valley, (3) Roosevelt Hot Springs, (4) Jemez Hot Dry Rock, (5) Baca, and (6) Coso Hot Springs. The information compiled includes a brief geological description of each site, mineralogic data, and typical physical and mechanical properties for the predominant rock formations at each site. In addition, core samples were sought,

where possible, to allow physical examination, rock mechanics tests as needed, and display. Emphasis was placed on determining certain key parameters for each rock type, including density, porosity, strength, and permeability. These parameters are considered to have a primary effect on rock drillability. A list of potential locations for surface outcroppings of rock that may have properties similar to these sites was also compiled, and the locations were investigated.

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 8-5. The unconfined compressive strength versus axial strain is plotted in Figure 8-32.

Table 8-5

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. DRL is recommending that, if this rock proves useful in the two current Sandia drilling projects, Sandia should 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 simulates formations at the Baca field,

Figure 8-32. Unconfined Compressive Strength of Sandstone versus Axial Strain

New Mexico, geothermal site. Two andesite formations were located in Utah, and hand samples were obtained for evaluation. Physical and mechanical properties of the andesite samples were determined and 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.

Several hand samples of a hard, abrasive sandstone known as Crab Orchard were obtained from a quarry in Tennessee. Physical property tests indicated that one of the rocks has an unconfirmed strength of 257.2 MPa (37 000 psi), a density of 2.490 g/cm³ (155.5 lb/ft³), and a porosity of 9.7%. Two other samples had densities of 2.515 g/cm³ (157.0 lb/ft³) and 2.450 g/cm³ (153.0 lb/ft³) and porosities of 6.2% and 6.7%, respectively. The first rock is available in a block 0.91 metre (3 feet) thick and may be a candidate to simulate the hard, abrasive sandstones at The Geysers. The other two sandstones are not available at this time in blocks thick enough for full-scale laboratory drilling tests.

High-Speed/High-Torque Capabilities — Due to space limitations on the present DRL drill rig, close examination was given to determine the appropriate layout for the new transmission, two 125-hp dc motors, and associated drive trains. The scaled layout selected is shown in Figure 8-33. The components selected allow installation in the available horizontal space. Data on the transmission are given in Table 8-6, and the torque versus speed capabilities of this new drive system are shown in Figure 8-34. The new drive system, which runs from 0 to 500 rpm, was installed on the drill rig and debugged. The system checked out well; however, a few modifications were made. A cost estimate is being prepared to provide a 500- to 1000-rpm, high-speed, all-hydraulic drive system. The proposed high-speed test setup is shown in Figure 8-35.

Table 8-6

Transmission Specifications

Model:	Eaton MT - 509 M 5-speed, twin countershaft design manual shift
Gear Ratios:	1:1, 1.32:1, 1.76:1, 2.67:1, and 5.47:1
Input Torque:	1 220 N·m (900 lbf·ft) maximum
Weight:	194.6 kg (429 lb)
Approximate Dimension:	56 by 56 by 36 cm (22 by 22 by 14 in.)
Delivery:	20 February 1980

Bit Dynamic Data Acquisition -- The high-rate, data acquisition, computer program was completed, debugged, and made operational. The data reduction and plotting routine with capabilities to calculate average and standard deviation values was also completed. Figures 8-36 and 8-37 are

COMPONENTS:

1. DRIVE/DRIVEN SPROCKETS
2. PILLOW BLOCKS
3. PILLOW BLOCKS
4. DRIVE/DRIVEN SPROCKETS
5. COUPLING
6. INPUT SHAFT
7. OUTPUT SHAFT
8. TRANSMISSION
9. MOTORS

Figure 8-33. Scaled Layout of Modified Drill Rig

Figure 8-34. Torque versus Speed of New Drive System

Figure 8-35. Proposed Test Setup for Pressure Drilling at Rotary Speeds Greater Than 500 rpm

GRLPLT X: TIME-SEC Y: UNLOAD XCOL: 3 YCOL: 7
 TESTID:
 " QUICK " FILE 5/ 1/79 13:33:41 TIME: 0.000- 1.000
 RANGE X: 0.0000E-01- 1.0000E+00 Y: 0.0000E-01- 5.0000E+04
 Y (A-D CHNL/ZERO/OFFSET/CAL): 61/-0.057/ 0.000/-6.03776E+03

Figure 8-36. Example of Load versus Time Plot

4DRFLPT X: TIME-SEC Y: UNTOR XCOL: 3 YCOL: 6
 TESTID:
 " QUICK " FILE 5/ 1/79 13:33:41 TIME: 0.000- 1.000
 RANGE X: 0.0000E-01- 1.0000E+00 Y: 0.0000E-01- 2.0000E+03
 Y (A-D CHNL/ZERO/OFFSET/CAL): 59/ 0.102/ 0.000/ 7.76530E+02

Figure 8-37. Example of Torque versus Time Plot

examples of the hard-copy plot of load versus time and torque versus time with calculated average and standard deviation values from an actual drilling test. Figures 8-38 and 8-39 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.

The spectral analysis program was completed and consists of a Fast Fourier analysis. An additional feature of the spectral analysis program not originally planned for was pursued. With this feature, the difference between frequency response data for a given drill bit and the same type of data for a baseline bit can be determined by essentially subtracting one data set from another.

High-Pressure Capabilities -- Conceptual ideas for the high-pressure choke system, pulsation dampeners, and high-pressure rotary seals were considered. The pulsation dampening system was identified as being beyond the present state of the art, and some prototype testing of potential concepts will probably be needed before full-scale equipment is fabricated. Hydrodyne Industries, Inc., has an inventory of dampeners up to 41.4 MPa (6000 psi) and claims to have the technology to build a 103-MPa (15 000-psi) dampener. The company is going to send a dampener to DRL for testing. The tests will involve pressures less than 41.4 MPa (6000 psi) but will provide valuable data for the 103-MPa (15 000-psi) accumulator that Hydrodyne Industries has agreed to build and test.

The small DRL mud pump was removed, the 1600-hp Continental Emsco mud pump was rotated 90°, and the pump was brought back into operation. With this arrangement, the 3-ton pump fluid end becomes accessible so a fork lift can be used to remove and install it. This option was chosen because it will involve a minimal expense compared with the option of providing a large overhead crane or jib crane. This is the first step in providing quick changeover from the standard to the high-pressure fluid ends.

The preliminary design of the high-pressure choke system was completed. A schematic (Figure 8-40) 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.

Investigation into large-volume, high-pressure-drop hardware fabricated by Hitco of Gardena, California, has been initiated in order to reduce the high-pressure fluid to low pit pressures. Information received from Hitco shows pressure drops of up to 27.6 MPa (4000 psi) available; however, they have had no experience with drilling mud as a fluid. These apparatuses may be connected in series or in parallel position to achieve the desired pressure reduction.

A piping manifold skid and a lifting device were designed to minimize the time required to change over from the mud pump standard fluid ends to the high-pressure fluid ends. All modifications to the system for reducing

***DRLPT - "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 8-38. Example of Load versus Frequency Plot.

***KORLPLT - "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 8-39. Example of Torque versus Frequency Plot

the changeover time from standard to high-pressure fluid ends were completed. Some of the final modifications were completed during the setting up for the Hydronautics/Hycalog high-pressure Cavijet® test program in April. The fluid end changeover took between 2-1/2 and 3 days. With all modifications now complete, the changeover time for the next high-pressure program is estimated at 1-1/2 to 2 days. Some of the high-pressure hammer unions and swivel-joint fittings to be used in the high-pressure pulsation dampening and pressure-drop systems were received.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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8.5 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: J. Kelsey (505) 844-6968

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, and
 - 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 in January 1980. The effort to modify the existing GEOTEMP code to handle deviated holes, variable tubing areas, and multiple fluids was completed and checked out. The development of the existing GEOTEMP code is discussed in References 1, 2, and 3. Work is continuing on the compressible flow model.

FY80 Progress

Modification of Existing Code -- The modifications to GEOTEMP were completed. These modifications consist of the following additional capabilities:

1. Variable tubing flow areas,
2. Multiple fluids, separated by interfaces in the wellbore, and
3. Deviated wellbores.

Compared to vertical wells, deviated holes increase 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 8-41 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 8-41. 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, because they act as both initial and boundary conditions.

The two modifications of GEOTEMP, i.e., variable tubing areas and multiple fluids in the wellbore, were initiated in late March. The necessary changes in the input variables have been coded: 10 different tubing sizes and 5 different primary fluids can now be specified. The effect of variable tubing size on grid formulation, as illustrated in Figure 8-42, was fairly straightforward, with the radius of the innermost grid points determined by the smallest tubing size and the radius of the next layer of grid points governed by the largest tubing size. The variation in tubing size results in variable cell size, and further modifications were necessary to account for variable cell conductivities and changes in the flowing stream energy balance due to variable cross sections and multiple fluids.

Modifications to allow multiple tubing areas were completed, and preliminary testing determined that the code operated properly. Three principal changes were necessary to allow variable tubing areas: (1) changes to the input routines to allow multiple tubing sizes, (2) changes to the subroutine COND to compute the correct conductivity with multiple tubing, and (3) changes to subroutine COEF to account for the changes in fluid velocity due to tubing area changes. The input routine READ was modified so that no changes were necessary to the mesh generator GRID. The

Figure 8-41. Geometry of Deviated Well

Figure 8-42. Variable Tubing Sizes--Mathematical Cells in Wellbore

revised GEOTEMP code input data format corresponding to the changes made in the main program and subroutine READ is contained in Appendix B.

A sample calculation with variable tubing size is illustrated in Figure 8-43. Two problems were calculated. Case I is the same sample injection problem included in the GEOTEMP user's manual and gives identical results. Case II uses smaller tubing below 610 metres (2000 feet). The temperatures predicted by Case II below 610 metres (2000 feet) are lower than those predicted by Case I below the same level, because the faster moving fluid in the smaller tubing receives less heat from the surroundings. Above 610 metres (2000 feet), the two cases are essentially identical and predict the same temperatures.

Modifications to allow multiple fluids in the wellbore were also completed. The main addition necessary was a subroutine to calculate the positions of the interfaces between the different fluids in the wellbore, based on the injection, production, and circulation histories of the well. This subroutine was tested before being incorporated into GEOTEMP.

The modified code was tested by rerunning previous GEOTEMP test cases and by running special problems that use the new capabilities. The modified code performed well for all these cases. A case copy and a magnetic tape copy of the modified program were delivered on 28 May 1980, and the new capabilities were discussed with Sandia. Details of the modified code and the test cases are presented in this report, Appendix C.

The solution of a fluid flow problem requires the solution of three balance laws: balance of mass, momentum, and energy. By assuming incompressibility for the flowing fluid, the original GEOTEMP only had to solve the balance of energy equation and a simplified version of conservation of mass. The formulation of a compressible flow version of GEOTEMP, however, will require solution of all of the balance equations.

Several simplifying assumptions will be made in the analysis of the compressible flow problem:

1. One-dimensional flow.
2. No inertial effects -- steady flow.
3. Transient heat transfer.

The GEOTEMP thermal simulator will be used to solve the energy equation with only slight modifications, and a fluid flow simulator will be added to solve the mass and momentum equations. The simulators will be used sequentially, rather than simultaneously, to solve the overall flow-heat transfer problem. This is the same solution scheme used in the original GEOTEMP, where flow parameters are updated at each time step. The following procedures from each time step are executed:

1. The momentum and mass conservation equations are solved using the temperatures calculated in the previous time step.
2. The energy equation is solved for temperatures using the flow parameters determined in Step 1.

Because of the relatively high fluid velocities expected, the wellbore temperatures are not expected to vary much between time steps, thus

Figure 8-43. Variable Tubing--Injection Sample Calculation

allowing this sequential calculation. If, during testing, this assumption is not verified, then a method for simultaneous solution of Steps 1 and 2 may be necessary.

The implementation of the compressible flow simulator will be taken in four steps:

1. Prediction of flow properties in a constant area duct with friction and transient heat conduction.
2. Addition of solids in the gas flow in the annulus.
3. Inclusion of area change effects of flow parameters.
4. Simulation of flow conditions at the bit nozzles -- including choked flow and stationary shocks.

Figure 8-44 illustrates a control volume for deriving the one-dimensional balance laws for compressible fluid flow. The fluid enters the volume with a given density, velocity, enthalpy, pressure, and temperature through area A_1 and exits with different values of these variables through area A_2 . Forces F_W are exerted on the fluid by the walls of the control volume, and heat $\dot{Q}$ is conducted into the volume. The balance laws for this volume will be written for steady-state flow, although transient heat flow will still be considered. Conservation of mass requires

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 = \dot{m} = \text{mass flow rate}.$$

Conservation of momentum requires

$$A_2 (p_2 + \rho_2 v_2^2) - A_1 (p_1 + \rho_1 v_1^2) = F_B + F_F + F_W,$$

where F_B is the gravity force, F_F is the viscous force, and F_W is the wall force. Conservation of energy requires

$$\dot{Q} = \dot{m} [h_2 - h_1 + 1/2 (v_2^2 - v_1^2)].$$

Solution of these equations requires equations of state for pressure and enthalpy and a constitutive equation for the viscous force.

The details of the compressible flow formulation proposed for GEOTEMP were presented to Sandia in late May 1980. The information is contained in Appendix C. The consensus at the Sandia briefing was that the compressible flow model was somewhat unconventional, although promising, and that suitable testing against analytical solutions was called for.

Additional analysis work on the compressible flow model revealed that, if the variation in velocity, ΔV , and the variation in temperature, ΔT , between the top and bottom of a cell are small, then the momentum and energy equations can be linearized and solved simultaneously:

$$\text{Momentum: } a_1 \Delta V + a_2 \Delta T = a_3.$$

$$\text{Energy: } b_1 \Delta V + b_2 \Delta T = \dot{Q}.$$

F_W = FORCES EXERTED BY WALLS

$\dot{Q}$ = HEAT

ρ = DENSITY

v = VELOCITY

h = ENTHALPY

p = PRESSURE

T = TEMPERATURE

A = FLOW AREA

Figure 8-44. 1-D Balance Laws for Use with Compressible Flow

$$a_1 = 1/2 G - \frac{\rho_1}{V_1} \frac{\partial p}{\partial \rho}(\rho_1, T_1) + \frac{G f' \Delta z}{4D} - p_1 g \frac{\cos \theta}{2V_1} \Delta z .$$

$$a_2 = \frac{\partial p}{\partial T}(\rho_1, T_1) .$$

$$a_3 = - G \frac{f' \Delta z}{2D} - 2 \rho_1 g \cos \theta \Delta z .$$

$$b_1 = - \frac{\rho_1}{T_1} \frac{\partial h}{\partial \rho}(\rho_1, T_1) + V_1 .$$

$$b_2 = \frac{\partial h}{\partial T}(\rho_1, T_1) .$$

Given the inlet temperature, velocity, and mass flow rate, the system of linear equations given above can easily be solved for the exit temperature and velocity. The solution of the linearized equations can then be used in the momentum and energy equations to check the accuracy of the grid size used in the analysis, with the grid refined where necessary.

The linearized equations given previously will be tested against known analytic solutions over the next few months. Assuming that this formulation gives satisfactory results, the linearized equations can be incorporated into GEOTEMP in the following way. The momentum equation can be used to eliminate ΔV from the energy equation. The resulting energy equation depends only on ΔT and can easily be inserted into the present GEOTEMP code.

Equations of state and correlations for friction factor, viscosity, and thermal conductivity were investigated. The thermodynamic equations of state most commonly used by industry are the Soave-Redlick-Kwong equations⁴ and the Benedict-Webb-Rubin equations.⁵ The use of either set of equations would allow GEOTEMP to deal with very general gas mixtures over a wide range of temperature and density. These equations of state are formulated as functions of density and temperature. In the typical analysis of compressible flow, these equations must be inverted so that pressure can be used as the independent variable. This analysis is accomplished by generating tables of numbers and using an interpolation routine, because numerical inversion is much too slow. The strongest motivation for using velocity as an independent variable is that these equations of state can be used directly. The Soave equations will be used in the GEOTEMP formulation, though the code will be written to allow easy substitution of other thermodynamic equations of state.

The most commonly used friction factor relationship is taken from the work of Colebrook.⁶ Unfortunately, the empirical relationship determined

by Colebrook must be solved numerically for the friction factor. A subroutine for this calculation was written and currently is being tested.

Two viscosity correlations have been found: Watson's correlation⁷ is recommended by Zucrow⁸ for use in gas dynamics applications. Coefficients are given for air, N₂, and a number of other gases. Reid, Prausnitz, and Sherwood⁹ recommend the Chapman-Enskog viscosity equations.¹⁰ The advantage of the Chapman-Enskog equations is that coefficients are available for a wide variety of gases and gas mixtures. For air drilling applications, the Watson correlations are probably the best choice.

The Eucken relationship¹¹ is recommended in References 8 and 9 for calculation of the thermal conductivity of gases. The Prandtl number, Pr, is given by

$$Pr = \frac{4\gamma}{9\gamma - 5},$$

where γ is the ratio of specific heats. The thermal conductivity is thus calculated from

$$K = C_p \mu / Pr.$$

The general compressible flow model was programmed on the computer. To test the performance of the model, three analytic solutions for compressible flow were used as bench marks:

1. Adiabatic, ideal gas, with friction,
2. Isothermal, ideal gas, with friction, and
3. Frictionless, ideal gas, with heat input.

Adiabatic, Ideal Gas, with Friction — The comparisons with bench mark Test 1 are summarized in Figures 8-45, 8-46, and 8-47. The problem presented in these figures is the adiabatic flow of an ideal gas with friction through a circular duct 5000 metres (16 400 ft) long with a 1-m² (10.8-ft²) cross-sectional area. The inlet pressure is 700 kPa (102 psi), the inlet temperature is -26.9°C (-32.7°F), and the inlet velocity is 15 m/s (49 ft/s).

Figure 8-45 shows the flow velocity from the inlet to the end of the duct. Two model results are compared to the bench mark. The triangles represent the use of the flow model with a very coarse mesh; each element of the mesh is 2500 metres (8200 ft) long. Figure 8-45 shows that the model slightly underpredicts the bench mark at 5000 metres (16 400 ft), predicting 17.1 m/s (56.1 ft/s) compared to 17.0 m/s (55.8 ft/s), for an error of about 0.6%. A finer mesh with 1000-metre (3280-ft) elements reduces the error to about 0.3%. A mesh with 100-metre (328-ft) elements was computed to give accuracy to 1 part in 10 000.

The underprediction of velocities is characteristic of finite element techniques in general. When a continuum of variables is reduced to a finite set, e.g., the nodes of the mesh, the degrees of freedom of the system are reduced. In effect, constraints are imposed on the system that make it less responsive; thus it tends to underpredict.

Figure 8-45. Flow Velocity: Adiabatic Compressible Flow With Friction

INLET CONDITIONS

PRESSURE = 700 kPa (102 psi)
TEMPERATURE = 26.85°C (80.33°F)
DENSITY = 8.128 kg/m³ (0.5074 lb/ft³)
FLOW RATE = 121.9 kg/m²·s (24.97 lb/ft²·s)
VELOCITY = 15.0 m/s (49.2 ft/s)
darcy F = 0.0200

Figure 8-46. Flow Temperature: Adiabatic Compressible Flow With Friction

Figure 8-47. Flow Pressure: Adiabatic Compressible Flow with Friction

Figure 8-46 compares flowing temperatures from the bench mark to the model temperature predictions. As with the velocities, the temperature changes were underpredicted; in this case model temperatures were slightly higher. Figure 8-47 compares pressures from the analytic solution to the model predictions. The model pressures are computed as a function of the predicted velocity and temperatures and show an equivalent degree of accuracy.

Isothermal, Ideal Gas, with Friction — Figure 8-48, 8-49, and 8-50 give the flow velocity, density, and duct pressures for isothermal flow of an ideal gas with friction. The adiabatic flow in bench mark Test 1 was nearly isothermal, and so the results of Test 2 are quite similar to Test 1. The same degree of accuracy and convergence of Test 1 was matched for Test 2, i.e., for flow cells of a size typical of GEOTEMP applications, the energy and momentum equations are solved within much less than 1% error.

Frictionless, Ideal Gas, with Heat Input — Figures 8-51 to 8-54 give flow temperatures, velocities, densities, and pressures for frictionless ideal gas flow with heat transfer. The flow response in this model is quite different from Tests 1 and 2. Tests 1 and 2 were very nearly isothermal with large pressure drops in the duct. Test 3 shows large changes in flow temperatures with a very small pressure drop in the duct. The general flow model was more accurate for Test 3 than Tests 1 and 2. This result is considered favorable because the intended application of the compressible flow model is in heat transfer applications in GEOTEMP, and Test 3 is primarily a heat transfer model.

Tubing Area Changes — In the current version of GEOTEMP, the flowing fluid is incompressible and the effect of area change on fluid velocity is determined through the continuity equation. In compressible flow, however, continuity, momentum and energy equations must be considered simultaneously to determine the effect of area change on flow properties. These equations take the following form for the situation illustrated in Figure 8-55:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \dot{M} \quad (1)$$

$$A_2 (P_2 + \rho_2 V_2^2) - A_1 (P_1 + \rho_1 V_1^2) = P_b (A_2 - A_1) \quad (2)$$

$$h_2 - h_1 + 1/2 (V_2^2 - V_1^2) = 0 \quad (3)$$

where friction and heat transfer have been neglected for this very short section of duct, and

- ρ = density
- V = velocity
- P = pressure
- A = duct cross-sectional area
- h = enthalpy
- $\dot{M}$ = mass flow rate
- Subscript 1 denotes inlet properties
- Subscript 2 denotes exit properties

If G is defined as $G = \rho_2 V_2$, and $P_b = P_1$ from subsonic flow is used, then:

Figure 8-48. Flow Velocity: Isothermal Flow with Friction

Figure 8-49. Flow Density: Isothermal Flow with Friction

Figure 8-50. Duct Pressure: Isothermal Flow with Friction

Figure 8-51. Flow Temperature: Heat Transfer - No Friction

Figure 8-52. Flow Velocity: Heat Transfer - No Friction

Figure 8-53. Flow Density: Heat Transfer - No Friction

Figure 8-54. Duct Pressure: Heat Transfer - No Friction

Figure 8-55. Tubing Area Changes

$$P_2 + G V_2 = P_1 + G V_1 = P^\circ \quad (4)$$

$$h_2 + 1/2 V_2^2 = h_1 + 1/2 V_1^2 = h^\circ \quad (5)$$

Eqs. (4) and (5) are simultaneous non-linear equations in independent variables T_2 , V_2 and have to be solved by an iterative technique (ρ_2 is related to V_2 through the continuity equation). An initial guess for the iteration could use the relations

$$P_2 \approx (P_1/\rho_1 T_1) \rho_2 T_2 = Z^1 G T_2/V_2 \quad (6)$$

$$h_2 \approx C_p T_2 \quad (7)$$

which, when used in Eqs. (4) and (5), gives the following quadratic equation in T_2 :

$$(GZ^1 T_2 + 2G(h^\circ - C_p T_2))^2 = (P^\circ)^2 (2h^\circ - C_p T_2) \quad (8)$$

The velocity can then be determined from Eqs. (5) and (7) and the iteration procedure repeated to convergence. For an ideal gas, this initial guess is the exact solution to the problem.

Cutting Transport Model — The cuttings transport model presented below is the simplest possible application of continuum mixture theory. The mixture is defined as a compressible gas intermixed with solid particles. The first simplification is that the solid particles cannot be converted into gas, so there is no coupling of the continuity equations:

$$\bar{\rho}_s V_s = G_s = \dot{M}_s/A \quad (9)$$

$$\bar{\rho}_g V_g = G_g = \dot{M}_g/A \quad (10)$$

where $\bar{\rho}_s$ is the "in-mixture" density of the solids, V_s is the velocity of the solids, and G is the mass flux density of the solids. Similarly, the subscript g refers to the gas phase. The densities are in-mixture densities, i.e., the densities used are volume average densities of the mixture components, not the actual microscopic densities of each phase. To make this idea concrete, the variable ϕ , called the volume fraction, is introduced and defined as:

$$\phi = \lim_{u \rightarrow 0} \frac{U_s}{U} \quad (11)$$

where U_s is the volume of the solids in volume U of the gas-solid mixture. The "in-mixture" densities to the microscopic densities can now be related by the equations:

$$\bar{\rho}_s = \phi \rho_s \quad (12)$$

$$\bar{\rho}_g = (1 - \phi) \rho_g \quad (13)$$

where ρ_s is the actual density of the solid particles and ρ_g the actual gas density, e.g., the density used in thermal and caloric equations of state.

Since two continuity equations are needed, Eqs. (9) and (10), two momentum equations are also needed:

$$\Delta(\bar{\rho}_s V_s^2) = F_{sg} + F_{sf} + \hat{P} \quad (14)$$

$$\Delta(P + \bar{\rho}_g V_g^2) = F_{gg} + F_{gf} - \hat{P} \quad (15)$$

where F_{sg} = gravity force on solids

F_{sf} = friction force on solids

F_{gg} = gravity force on gas

F_{gf} = friction force on gas

$\hat{P}$ = drag force on solids by the gas

Eqs. (14) and (15) look like conventional momentum equations except for two differences. First, Eq. (14), the momentum equation for the solids, does not have a pressure term in the left hand side of the equation. The reason for this exclusion is that the solid particles are not connected to each other, and hence, there is no pressure in the mixture sense. Of course, the solids do feel an internal pressure, which has negligible influence on the density ρ_s . The second difference in the momentum equations is the term $\hat{P}$. This term represents the force exerted on the solids by the flowing gas due to their relative velocities. This term can be determined from the extensive literature on particle settling velocities, which is the special case of zero gas velocity. The final equation needed to solve the mixture problem is the energy equation:

$$\bar{\rho}_s V_s \Delta(e_s + 1/2 V_s^2) + \bar{\rho}_g V_g \Delta(h_g + 1/2 V_g^2) = \dot{Q} \quad (16)$$

where e_s is the internal energy of the solid per unit mass, h_g is the enthalpy of the gas per unit mass, and $\dot{Q}$ is the rate of heat input. A single energy equation is used to further simplify this model. The form of Eq. (16) implies that the two components of the mixture are at thermal equilibrium with each other at temperature T . An alternate interpretation is that heat transfer between components is being ignored and that T represents a heat capacity weighted temperature for the mixture. This approach is justified because the heat transfer process between phases is not of sufficient interest to justify the additional complexity of two energy equations. The internal energy for the solid phase is used in the energy equation because the "in-mixture" pressure is zero.

Development of the cuttings transport model with emphasis on numerical techniques applicable to GEOTEMP is continuing. The compressible flow model with area changes will be incorporated into GEOTEMP during the next reporting period.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

8.6 Evaluation of Elastomers

Sandia National Laboratories
Technical Consultant: C. Arnold (505) 844-8728

Project Objective

The project objectives are to determine (1) the effect on the life of elastomeric seals of coating the seals with Parylene C, a polymer, or with tetrafluoroethylene (TFE), (2) the chemical stability of various elastomer liner candidates for flexible drill pipe, and (3) the effect of H₂S on elastomeric seals.

Project Status

The experiments on coated elastomeric seals were completed. Two coating techniques were used. A 0.037-mm (0.0015-in.) thick film of Parylene C was deposited onto elastomers by Union Carbide's vapor phase, pyrolytic method, while a 0.038-mm (0.0015-in.) 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 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. TFE proved to be the more successful coating in dynamic applications. Dynamic wear tests showed that TFE-coated O-rings did not delaminate, ran cooler than non-coated rings, and exhibited improved abrasion resistance. Chemical stability studies of elastomer liners for flexible drill pipe and the investigation of the effects of H₂S on elastomeric seals were initiated.

FY80 Progress

The study of the coating of elastomeric seals was completed with an analysis of the effect of coatings on the coefficient of friction. Certain types of abrasive wear can be minimized by encapsulating the elastomers with a low-coefficient-of-friction coating such as Teflon. Teflon-coated seals are commercially available. However, when these seals were evaluated under simulated geothermal conditions, the Teflon took a set and leaked after a few hours of service. In addition, the hoop stresses inherent in this nonhomogeneous seal could not be adequately relieved as the drilling cone rotated, and, as a result, the coating buckled.

In contrast, enhanced service-life was realized with seals on which plasma-polymerized tetrafluoroethylene had been deposited. For example, uncoated Parker EPR seals failed after 9 hours at 150°C (302°F) following a 2-hour presoak at 288°C (550°F). The presoak simulated tripping-in when there is no circulation. In contrast, the TFE, plasma-coated seal lasted

34 hours. Similar results were obtained with TFE, plasma-coated, Parker Viton seals. Studies of friction affirmed that plasma-coated TFE did, on a short term basis, reduce the coefficient of friction (see Figures 8-56 and 8-57).

Planning for the evaluation of elastomer liners for flexible drill pipe and for the investigation of the effect of H_2S on elastomeric seals was completed. The acquisition of equipment for conducting the studies is under way.

Figure 8-56. Effect of Plasma Treatments on the Frictional Coefficients of Buna N

Figure 8-57. Effect of Plasma Treatments on the Frictional Coefficients of EPR

9. ADVANCED DRILLING SYSTEMS

Advanced and innovative drilling systems will be 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 under way to (1) improve downhole motor bearings and seals, (2) evaluate the potential of percussion drilling devices for use in the geothermal environment, (3) assess the performance potential and economics of erosion drilling systems, (4) optimize the design of cavitating-jet nozzles for use with rock cutting bits, (5) develop high-pressure fluid delivery systems compatible with fluid-jet drill bits and downhole motors, and (6) demonstrate that high-temperature/high-pressure polymers are compatible with flexible drilling pipe. The objectives of these projects are to develop and demonstrate hardware incorporating these concepts so that increased rates of penetration and longer downhole drilling periods may be achieved. The projects to design, fabricate, and demonstrate a water-jet erosion drilling underreamer and to design, fabricate, and laboratory test a pressure-pulsing device for use with cavitating jets were completed in FY80. The status and progress of these activities are described within this section.

A field test of a hybrid, high-pressure-water-jet/roller-cone bit has been completed. The test demonstrated that the optimum penetration rate in dolomite was achieved with a 1.8-mm (0.07-in.) 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 test 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 that 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 is under way.

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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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD
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PLANNED COMPLETION
 COMPLETED

9.1 Characterization of High-Pressure Jet Drilling Systems

Contractor: Foster-Miller Associates, Inc. (FMA)
Principal Investigator: A. Guzdar (617) 890-3200
Contract Period: 1 August 1979 to 31 October 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 was completed. Coordination was made to assure a proper interface between the study output and the Sandia Well Cost Simulation Model. An erosion drilling information computer search was made. Detailed data were obtained from company files on the high-pressure projects conducted by Gulf Oil Company and Exxon Production Research. Some data were obtained from Shell Research on their high-pressure experience, and they reported that most of their data were available in public literature. A request was made to Hughes Tool Company, but they declined to make available their company data on high-pressure drilling. The assessment of all available data was completed, and system cost estimates based on the data were made.

FY80 Progress

The state-of-the-art study of erosion drilling was completed. The computer search at the University of Tulsa of the recent literature concerning erosion drilling showed that little relevant information exists.

A meeting was held with J. Fair of Gulf Research and Development Company (GR&D). The purposes of the meeting were to get an in-depth view of the Gulf abrasive-jet drilling system and to obtain Gulf reports covering the work. The meeting was successful in both areas.

Fair made a 3-hour presentation covering the following key items:

1. History of the Gulf abrasive-jet drilling program,
2. Equipment specifics,
3. Potential market for abrasive-jet drilling,
4. Economics of abrasive-jet drilling, and
5. Major problem areas still existing at the completion of the Gulf program.

The meeting provided insight into the Gulf work and initiated a dialogue between FMA and Gulf on this subject. Gulf made available to FMA many of Gulf's internal reports for assessment of their system. These reports are company confidential and were returned.

Gulf provided a large amount of information, and the assessment process required a significant amount of effort. The initial appraisal of the information was as follows:

1. The information is thorough and well organized,
2. The material provided contains most of the information needed for input to the Sandia computer program,
3. The costs are 7 years out of date, and
4. The technique is still in the developmental stage.

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.

Included in the data collecting efforts were the following:

1. Three operating oil rigs were observed in Oklahoma. Two of these rigs were located near Chickasha and the third near Duncan. Tripping operations were observed, and photographs were taken.
2. Halliburton, Inc., was visited. Halliburton is a major supplier of high-pressure intensifiers. These intensifiers are considered critical components of the Gulf abrasive-jet drilling system. An unsuccessful effort was made to persuade Halliburton to assist in the development of costing estimates on their own equipment. In lieu of this assistance, limited data from other sources were used, together with engineering judgement and costing experience, to estimate high-pressure intensifier capital, operation, and maintenance costs.

3. A written request was made to Shell Research in the Netherlands for information on their high-pressure drilling experience. Shell responded with answers to specific questions and indicated that most of their data already appear in the literature.
4. An agreement to obtain Exxon's jet-drilling data was reached, and selected data were obtained for evaluation.
5. A request was made to Hughes Tool Company for information on their laboratory testing of high-pressure drill bits. The request was declined.
6. Equipment costs were discussed with drilling consultant, R. Rinaldi.

Technical evaluation of the data for the Gulf, Exxon, and Shell systems provided performance data and determination of areas of needed improvements, required technology and hardware development, and additional analytical, experimental, and field work requirements.

The development of cost estimates included the following activities:

1. Cost estimates of the low-pressure and high-pressure subsystems of the Gulf abrasive-jet drilling system were completed.
2. Cost estimates for the downhole equipment used in the Gulf abrasive-jet drilling system were completed.
3. A cost estimation for expendable materials, e.g., mud and abrasive, used in the Gulf abrasive-jet drilling system was completed.
4. A preliminary report on costs of the low-pressure system, downhole equipment, and expendable materials needed for abrasive-jet drilling was prepared.
5. Costing of rig equipment required for abrasive-jet drilling was completed.

The evaluation of data from Exxon and Shell was completed, and cost data for these systems were obtained by determining which components of the Gulf system would be required for the former two systems.

Due to the difficulty of obtaining drilling system data, a no-cost extension of the period of performance was provided. The work is now scheduled for completion by 31 October 1980. All technical and economic evaluation of the systems have been completed, and the final report is currently being written.

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> SEAL TESTING BEARING/ SEAL PACKAGE TESTING FULL-SCALE MOTOR TESTING	CONTINUING AS REQUIRED													
	○---													

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.2 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 were developed to test seals and bearing/seal packages at the geothermal downhole conditions of 300°C (572°F) and 34.5 MPa (5000 psi). Selected standard seals were tested to determine baseline performance. New seals, designed in cooperation with the seal industry, were tested in the laboratory. A bearing/seal package for downhole motors was designed and is being laboratory tested in the Bearing/Seal Package Test Facility. Seal testing and evaluation are continuing.

The lubricant screening program was completed, and test results were published. The lubricant test facility remains available for new testing as required.

FY80 Progress

Seal Testing and Evaluation — Tests DMT-029 through DMT-048 were completed during this reporting period and are summarized in Table 9-1.

Test DMT-029 was a repeat of test DMT-028. The seal tested was Grafoil® with 0.76-mm (0.030-in.) preformed rings of yellow brass. The total running time was 3.17 hours. The test ended abruptly when the spline at the bottom of the seal test machine shaft disengaged from the torque cell. The shaft was removed and the spline was repaired. It should be noted that the seal did not fail during this test and therefore probably would have had a longer running time had the test machine not malfunctioned.

Tests DMT-030, DMT-031, and DMT-033 tested the first-generation, 127-by 152-mm (5- by 6-in.) canted seal. The canted seal assembly consists of two seal rings held in place by a three-piece backup system made of 9C aluminum bronze. The three parts of the backup system are pinned together. The seal material in DMT-030 was Buna-N and cotton duck, and the seal material in DMT-031 and DMT-033 was lubricated Buna-N, cotton, and nylon.

Table 9-1
Completed Seal Tests

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	ΔP MPa (psi)	rpm	Duration h	Chrome Shaft Coating Finish (rms) μm (min.)	Diametral Clearance: Shaft to Backup Rings mm (in.)	
028	II Grafoil®-bronze	3	SAE 660 bronze	10.3 (1 500)	412	2.92	0.1 to 0.2 (4 to 8)	0.025	(.001)
029	II Grafoil®-bronze	3	SAE 660 bronze	10.3 (1 500)	412	3.17	0.1 to 0.2 (4 to 8)	0.02	(.001)
030	Canted, 31A material	2	9C aluminum bronze	10.3 (1 500)	412	0	0.1 to 0.2 (4 to 8)	0.203	(.008)
031	Canted, 42DR material	2	9C aluminum bronze	10.3 (1 500)	412	0	0.1 to 0.2 (4 to 8)	0.203	(.008)
032	RD-199 graphite-metal matrix	3	SAE 660 bronze	10.3 (1 500)	412	8.57	0.1 to 0.2 (4 to 8)	0.025	(.001)
033	Canted, 42DR material	2	9C aluminum bronze	10.3 (1 500)	412	0.72	0.1 to 0.2 (4 to 8)	0.203	(.008)
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	3.71	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 Backup ring 4.32	(0.001) (0.170)
035	Grafoil®-phosphor-bronze	3	Backup III w/4 0.4-mm (0.016-in.) leaves	10.3 (1 500)	412	34.6	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 Backup ring 4.32	(0.001) (0.170)
036	Canted Buna-N	2	9C aluminum-bronze	10.3 (1 500)	412	0	0.2 to 0.3 (8 to 12)	0.203	(0.008)
037	Grafoil®-phosphor-bronze	3	Backup I SAE 600 bronze	10.3 (1 500)	412	aborted	0.1 to 0.2 (4 to 8)	0.025	(0.001)
038	Hybrid assembly SF design	3	SAE 660 bronze	10.3 (1 500)	412	8.0	0.2 to 0.3 (8 to 12)	0.127	(0.005)

Table 9-1 (Continued)

Completed Seal Tests

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.)	
039	Hybrid assembly V design	3	Backup III w/4 ea 1/64 leaves	10.3 (1 500)	412	3.8	0.1 to 0.2 (4 to 8)	Flexing leaves 0.025 (0.001) Backup ring 4.32 (0.005)	
040	HTCR SF design	3	SAE 660 bronze	10.3 (1 500)	412	53.28	0.2 to 0.3 (8 to 12)	0.127 (0.005)	
041	Variseal® (double spring)	1	SAE 660 bronze	10.3 (1 500)	412	5.33 (aborted)	0.2 to 0.3 (8 to 12)	1.60 (0.063)	
042	Variseal® (single spring)	1	SAE 660 bronze	10.3 (1 500)	412	4.25 (aborted)	0.2 to 0.3 (8 to 12)	1.60 (0.063)	
043	Mesh matrix copper wire	3	Sintered graphite	10.3 (1 500)	412	0.75	0.1 to 0.2 (4 to 8)	0.203 (0.008)	
044	Mesh matrix glass fiber	3	Sintered graphite	10.3 (1 500)	412	0	0.1 to 0.2 (4 to 8)	0.203 (0.008)	
045	Variseal® (double spring)	1	SAE 660 bronze	10.3 (1 500)	412	164.75	0.2 to 0.3 (8 to 12)	0.127 (0.005)	
046	HTCR SF design	3	SAE 660 bronze	10.3 (1 500)	412	71.8	0.2 to 0.3 (8 to 12)	0.406 (0.016)	
047	Variseal® (double spring)	1	SAE 660 bronze	10.3 (1 500)	412	10.25	0.2 to 0.3 (8 to 12)	0.127 (0.005)	
048	Hybrid assembly SF design	2	SAE 660 bronze	10.3 (1 500)	412	6.04	0.2 to 0.3 (8 to 12)	0.406 (0.016)	

Two important findings concerning the canted seal installation resulted from these tests:

1. To function, canted seals must be mechanically loaded. However, this procedure is very difficult to carry out in the seal test machine. One solution was to preload the canted seal assembly and then install the assembly as a cartridge unit in the seal tester.
2. A modification to the seal tester was needed to prevent damage to the lip of the canted seal during installation of the shaft. A small taper of approximately 0.51 mm (0.020 in.) was put on each end of the shaft sleeve.

In tests DMT-030 and DMT-031, the canted seals and spacers were installed in the seal tester. The seals were preloaded, and finally the shaft was installed. The test was started, and the seals in both tests leaked immediately. The seal tester was disassembled, and the seals were inspected. Scratches on the outside of the canted seal backup system showed that the seals had rotated in the seal tester.

F. Pippert from Utex Industries, the manufacturer of the canted seal, visited Terra Tek on 25 October 1979. He supervised the installation of the canted seals for DMT-033. The seals were installed in the same manner as in DMT-030 and DMT-031, except that the canted seal backup systems and the spacers were all pinned together inside the seal tester.

Test DMT-032 tested the RD-199 graphite-copper matrix seal. The total running time was 8.57 hours. The backup system used was the same system used in test DMT-024--the bronze backup ring with flexing lip. The seal did not begin to leak until the end of the test, when seal failure was catastrophic. Examination of the seals after the test showed a loss of graphite from the matrix.

On Pippert's recommendation, the test was run without heating the vessel. A reverse differential pressure was put across the seals to shock the lip on the lower seal pack into place. The seals held a differential pressure for approximately 45 minutes before they started leaking.

DMT-034 was the first test of the zero clearance backup system III (flexing leaves) with a nonelastomer seal. This system is shown in Figure 9-1, and details are found in the report "Deflections in Rotary Seal Backup 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-in.) thick phosphor-bronze rings and a bottom backup ring with a radial clearance of 2.154 mm (0.0848 in.) 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

Figure 9-1. Flexing Seal Backup Rings

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; $\Delta P = 12.1$ 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-in.) 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; $\Delta P = 10.3$ MPa (1500 psi).
The test was resumed and run until 1 gallon of lubricant had leaked past the test seal.

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

DMT-035 was completed, and the total duration was 34.6 hours. The test seal consisted of three Grafoil®-phosphor-bronze seal rings with back-up system III. Based on the experience from DMT-034, the stiffness of the

flexing leaves was reduced for DMT-035 by making the leaves from 0.4-mm (0.016-in.) thick material. Details of the test conditions are shown in Table 9-1. Some of the observations made from this test are as follows:

1. There was a high torque initially, due to the wear-in of the flexing leaves. After a couple of hours, the torque dropped to below 136 N·m (100 lbf·ft), where it remained for the duration of the test.
2. The seal leaked very slowly and periodically. The test was terminated when 0.004 m³ (1 gal) of lubricant had leaked past the test seal.
3. Inspection of the seals after the test showed that much less Grafoil® had been lost from the seal cavity in Test No. 035 than in previous tests with Grafoil® seals.
4. Inspection of the seal sleeve after the test showed much more wear than in previous tests with Grafoil® seals. The flexing leaves had worn a groove in the seal sleeve, but the failure appeared to be due to the flexing leaves wearing out.

DMT-036 was also completed (see Table 9-1). The test seal was the generation II canted seal, Buna-N. This seal would not hold pressure, and the test was terminated. Inspection of the seals after the test showed that the outside diameter and height of the seals had shrunk slightly and would not seal properly.

DMT-037, of the Grafoil®-phosphor-bronze seal with zero clearance backup system I, had to be aborted (see Table 9-1). Two attempts were made to run this test. In each attempt, a new set of backup rings was machined to a 0.025-mm (0.001-in.) diametrical clearance with the shaft sleeve. Rotation was attempted after both test setups, and the seal tester was shut down immediately after torques in excess of 678 N·m (500 lbf·ft) were noted. These torques were caused by the seizure of the backup rings on the shaft. A detailed analysis of the test was presented in the Phase IV Semi-Annual Report.¹

DMT-038 tested the hybrid assembly SF design, shown in Figure 9-2. This seal pack contained three pressure rings; the top ring was a high-temperature corrosion-resistant (HTCR)* cloth seal, the middle ring was a graphite homogeneous seal, and the bottom ring was an HTCR homogeneous seal. The test duration was 8.0 hours. Inspection of the seals after the test showed a considerable material loss from the middle and bottom rings.

DMT-039 tested the hybrid assembly V design, shown in Figure 9-3. Zero clearance backup system III with four 0.40-mm (1/64-in.) thick leaves was used. The seal pack contained three pressure rings; the top and bottom rings were Grafoil®-phosphor-bronze seals, and the middle ring was an HTCR homogeneous seal. The test duration was 3.8 hours. Inspection of the

* HTCR material is an elastomeric material.

Figure 9-2. Hybrid Assembly, SF Design

Figure 9-3. Hybrid Assembly, V Design

seals after the test showed a considerable loss of Grafoil® material from the top and bottom rings, possibly indicating that the zero clearance system did not flex properly.

DMT-040 tested the HTCR cloth seal. This seal pack contained three HTCR cloth seal rings with SAE 660 bronze adapters. The test duration was 53.28 hours, the third longest test to date. As shown in Figure 9-4, the plot of temperature versus time for the lower seal, the thermocouple read as high as 296°C (565°F) and above 232°C (450°F) for a large part of the test. Because the thermocouple is approximately 6.5 mm (0.26 in.) from the shaft/seal interface, the seal temperatures are even higher than the thermocouple reading. Inspection of the seals after the test showed very little degradation of the seals. Excessive wear of the chrome surface on the shaft sleeve was also noted. It appears that the shaft surface wore out before the seals and allowed the lubricant to leak past the seals. Also, the high shaft/seal temperatures caused some degradation of the standard test lubricant, Texaco EP 85-90.

DMT-041 tested the Variseal® (double spring), and DMT-042 tested the Variseal® (single spring). Each seal pack contained one seal ring. DMT-041 lasted 5.33 hours, and DMT-042 lasted 4.25 hours. Both tests were aborted after catastrophic failure of the dummy seal. It was learned after the tests that the backup rings supplied by Maurer Engineering had a diametrical clearance of 0.157 to 0.175 cm (0.062 to 0.069 in.), which is much larger than the manufacturer recommends. This clearance allowed the Variseal® to extrude between the shaft sleeve and backup ring. Maurer Engineering recommended that these tests be aborted, that two new backup rings with a diametrical clearance of (0.004 to 0.008 in.) be machined, and that a new test be run with a fresh set of Variseals®.

DMT-043 and DMT-044 were tests of seal rings made from a proprietary, nonelastomeric compound molded around a copper-mesh matrix, for DMT-043, and a glass-fiber-mesh matrix, for DMT-044. Each seal pack consisted of three pressure rings comprised of the mesh matrix with sintered graphite backup rings. DMT-043 lasted 0.75 hours, and DMT-044 would not hold a change in pressure. Inspection of the seals after the tests showed that the female, sintered, graphite backup rings had fractured and that the seals showed almost no wear.

DMT-045 was a test of the Variseal® (double spring). The test duration was 164.75 hours, the longest running test to date. Following is a brief description of the test.

a. 0 to 84 hours

The test ran smoothly during this period, and there was very little leakage both in test and dummy seals. At 84 hours, there was a catastrophic failure of the dummy seal. The dummy seal was replaced with a new seal, and the test was resumed.

b. 84 to 156 hours

The test ran smoothly during this period, and there was very little leakage both in test and dummy seals. At 156 hours, there was a catastrophic failure of the dummy seal. The dummy seal was replaced with a new seal, and the test was resumed.

Figure 9-4. Temperature and Leakage Rates for DMT-040

- c. 156 to 164.75 hours

At 164.75 hours, there was a catastrophic leak failure of the test seal, and the test was terminated.

DMT-046 was a test of the HTCR. The test duration was 71.8 hours, the second longest running test to date. This test was run to establish repeatability of the test results from DMT-040, the first HTCR test, which lasted 53.3 hours. Following is a brief description of DMT-046.

- a. 0 to 12 hours

The test ran smoothly during this period. The test seal pack consisted of three pressure rings, and the dummy seal pack consisted of two pressure rings. At 12 hours, the dummy seal pack failed. The dummy seal pack was replaced with a seal pack consisting of three pressure rings and the test was resumed.

- b. 12 to 51.7 hours

The test ran smoothly during this period. At 51.7 hours, the dummy seal pack failed. The dummy seal pack was replaced, and the test was resumed.

- c. 51.7 to 71.8 hours

At 71.8 hours, the test seal failed, and the test was terminated.

The following seal test matrix was established for seal tests subsequent to DMT-046.

1. A repeatability test will be run on the Variseal®.
2. One test will be run on each of the following seals:
 - a. Mesh matrix-copper wire with SAE 660 bronze backup rings,
 - b. Mesh matrix-glass fiber with SAE 660 bronze backup rings,
 - c. Hybrid assembly SF design,
 - d. Grafoil®-horizontal laminates with zero clearance backup system III, and
 - e. Canted HTCR.
3. A repeatability test will be run on any seal in list number 2 that looks promising.

DMT-047 tested the Variseal® (double spring). The test lasted 10.25 hours. Following is a brief description of the test.

- a. 0 to 5.48 hours

The test ran smoothly during this period. At 5.48 hours, there was a catastrophic failure of the dummy seal. Inspection of the dummy seal showed that the heel of the Variseal® had cracked. The dummy seal was replaced with a new seal, and the test was resumed.

- b. 5.48 hours to 10.25 hours

The test ran smoothly during this period. At 10.25 hours, there was another catastrophic failure of the dummy seal. An attempt to pressurize the system showed that the test seal would not hold

pressure and had failed catastrophically. The test was terminated. Inspection of the second dummy seal and the test seal showed that the heel of both seals had cracked. Thus, the failure mode of the test seal and both dummy seals appeared to be the same.

DMT-048 tested the hybrid assembly SF design. This seal pack consists of two pressure rings, an HTCR-homogeneous ring on the high-pressure side and an HTCR-fabric ring on the low-pressure side. In DMT-038, the hybrid assembly SF design was first tested with the addition of a homogeneous graphite ring sandwiched between the two HTCR rings. Based on the test results from DMT-038, Utex Industries recommended that the homogeneous graphite ring be deleted from DMT-048. Following is a brief description of the test.

- a. 0 to 4.00 hours
The test ran smoothly during this period. The test seal ran at higher than normal temperatures, as is the case with HTCR seals.
- b. 4.10 hours to 4.57 hours
The O-rings located under the test sleeve failed due to the high temperatures. This failure required that the test be stopped and the O-rings replaced.
- c. 4.57 hours to 5.40 hours
The test continued until a water leak developed. The test was stopped to correct the leakage problem.
- d. 5.40 hours to 6.04 hours
Shortly after restarting the test, the water leak again occurred. The test machine was disassembled for the third time and the leak repaired. A static ΔP was applied to the seals before restarting. It was found that the seals would not maintain this pressure.
- e. Examination of the seals revealed that the cotton and HTCR seal was badly worn. Significant amounts of the seal had degraded and washed out.
- f. The homogeneous seal showed signs of wear and had developed cracks in the sealing lips.

Failure Analysis — A separate contract has been placed with Failure Analysis Associates (FAA), Phoenix Division, to assist Sandia in identifying the seal failure modes and in generating new seal designs. The contract runs from 7/80 through 3/81 and has a goal of using the information from analyzed failures to design, manufacture, and test an improved seal assembly.

As the first part of this analysis and design, a selection of 27 failed seals was sent to FAA for intensive examination. After the examination is complete, FAA will report their conclusions on failure modes and will assist Sandia and Terra Tek in consideration of new seal designs.

Seal Tester Modifications — A new torque cell preamp was fabricated that provided greater sensitivity.

Several minor changes were made to the seal tester shaft, including the completion of a preliminary design modifying the ends of the shaft sleeve to make the installation of the shaft easier. Also, minor changes were incorporated into the shaft. The 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.

A major modification to the seal tester was made that involved the complete redesign of the heating system for the tester. The downhole motor seal tester was originally designed for a maximum operating temperature of 316°C (600°F). This high-temperature requirement resulted in a design heat capacity for the tester of 30 kW. This high heat capacity prevented the use of band heaters in the original design because of the limited power density that can be obtained from this type of heater. As a result, the heater system incorporated 30 1-kW cartridge heaters in a heater carrier that surrounded the main vessel seal carrier.

There is an inherent problem in using cartridge heaters in the seal tester. Space is limited inside the tester vessel, and the leads from the cartridge heaters must be bent at the junction with the heater in order to fit. The bend causes cracking of the ceramic insulation, which allows the heaters to short.

A seal test run temperature of 121°C (250°F) was established after the original design of the seal tester. Thus, the original design heat capacity of 30 kW is no longer required. To solve the problem with the cartridge heaters, the heater carrier was removed from the main vessel seal carrier, and a band heater system was designed to fit directly around the main vessel seal carrier. These heaters have a power density of 5.4 W/cm² (35 W/in.²) and are 3.8 cm (1.5 in.) wide. There are a total of six band heaters, and the total heat capacity is 8.2 kW. Surrounding the band heaters is a blanket of insulation.

The control system for the band heater system was also redesigned. The old controller was a phase-angle-fired SCR power controller. This type of controller has some inherent problems for the seal tester heater system. A phase-angle controller can cause radio frequency interference (RFI), which will affect all of the other instrumentation in the seal tester. Also, the phase-angle-fired controller is complicated and difficult to troubleshoot. This type of controller is used in a situation in which the resistance of the heater changes with temperature. The band heaters do not change resistance with temperature.

A zero-voltage-switched SCR power controller was ordered and installed in the new heater system. This type of controller turns on when the waveform is near the zero voltage point, eliminating the RFI problem connected with the phase-angle-fired controller. Also, the zero-voltage-switched controller is simpler and easier to troubleshoot than the phase-angle-fired controller.

The new band heater system and zero-voltage-switched SCR power controller should increase the number of tests that can be performed in the seal tester and will allow completion of all of the testing scheduled for this program. The equipment was installed and is functioning properly.

The seal tester drive train was also overhauled. The following over-haul procedures were carried out:

1. The drive belt for the 20-hp motor was replaced,
2. The slip ring was rewired, and new contacts were installed,
3. The right-angle drive was rebuilt, and worn seals and bearings were replaced, and
4. A new coupling was installed between the right-angle drive and the slip-ring assembly.

The beneficial effects of these modifications and the installation of the new shaft were evident during test DMT-035. This test was completed without disassembling the seal tester during the test. Thus, the test seals were not disturbed during the test.

One observation about the seal tester that was made during DMT-045 is that the vessel seal packs have a life of approximately 50 hours. The present vessel seals are Johns-Manville Uneepac® seals (Buna-N). Terra Tek is replacing them with seal packs, acquired from Utex Industries, that consist of top and bottom adapters made of SAE 660 bronze and two pressure rings made of HTCR. This modification will be used for the first time for DMT-049 and should extend the time between vessel seal replacements.

The seal tester main vessel seal carrier for 3/4-inch cross-sectional seals has been made operational for installation in the seal tester after completion of DMT-052. The new seal carrier will allow the testing of the 3/4-inch cross-sectional canted seal and face seals. In addition, the new seal carrier will permit the installation of a seal adapter to simulate the arrangement of the seals in the bearing/seal package and will allow the testing of candidate seals in abrasive mud.

Bearing/Seal Package Testing and Evaluation — A number of modifications were made to the completed Bearing/Seal Package Test Facility.

The cartridge heaters with insulated leads were installed in the geothermal vessel, and the vessel was reinstalled in the pit.

The electronic cables were inspected and overhauled. The purpose of overhauling the cables was to facilitate the hookup of the electronic instrumentation console to the Bearing/Seal Package Test Facility when the console is moved from the downhole motor seal tester.

New cabling was received for the Bearing/Seal Package Test Facility controls. This cabling is shielded and will reduce noise signals such as those experienced during the last full-scale test of the bearing/seal package.

A preamp was constructed for the load and torque cells that will give greater sensitivity to the cells. 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. The incorporation of the transformer should make the downhole motor instrumentation more reliable.

A spare seal sleeve, Part No. 78-416, for the bearing/seal package was ordered and received from Maurer Engineering.

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.

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

Recommendations for arrangement of the seals in the bearing/seal package were solicited from Utex Industries and Maurer Engineering. Utex recommended that the HTCR seals be placed with the lips of the seals facing away from each other. Maurer Engineering recommended that the Variseals® be placed with the lips of the seals facing into each other. It was decided to test the HTCR seals with both recommendations. The adapters for the HTCR seals have been ordered from Utex, and the adapters for the Variseals® are being detailed by Maurer Engineering.

The new electrohydraulic flow control valve for the hydraulic drive motor was received. The new control valve has a maximum flow capacity of 0.004 m³/s (60 gpm), which is double the flow capacity of the existing flow control valve. New hoses and fittings for the hydraulic-drive-motor servovalve were installed to accommodate the larger flow rate of the new hydraulic and servovalve system.

• Hot Water System

The hot water system, shown schematically in Figure 9-5, uses the geothermal vessel equipped with cartridge heaters to heat the water. The water is piped from the geothermal vessel to the Bearing/Seal Package Test Facility. Inside the test facility there is an insulated metal jacket, the hot water jacket, that surrounds the bearing/seal package. The hot water jacket keeps the bearing/seal package surrounded with hot water and prevents the hot water system from being contaminated by the drilling mud inside the test facility.

An air intensifier is used to pressurize the hot water system, which must be pressurized to keep the hot water from flashing to steam. The pressure on the inside and outside of the hot water jacket must be balanced to prevent failure of the jacket.

• Test Results

Six tests using the hot water system were run in the Bearing/Seal Package Test Facility. These tests demonstrated the following:

HAND VALVE -- CLOSED
DURING HOT WATER
SYSTEM OPERATION

Figure 9-5. Hot Water System Schematic

1. The torques on the bearing/seal package were relatively low, below 136 N·m (100 lbf·ft),
2. There may be high temperatures generated in the area of the floating piston in the bearing/seal package, and
3. It is difficult for the water in the hot water system to flow without a circulation pump.

• Bearing/Seal Package

A new floating piston was designed. The new piston is required because of the high temperatures observed during the tests and the damage that occurs to the floating piston during assembly and disassembly of the bearing/seal package. Figure 9-6 shows a cross section of the new piston, which is a bidirectional lip seal. Proposed and manufactured by Utex Industries, the piston is a one-piece molded seal made of RD-239 HTRC elastomer. The piston was recently received from Utex Industries.

Figure 9-6. New Floating Piston

Several new floating piston designs were considered before the bidirectional lip seal was selected. These designs included using Grafoil® seals and Variseals® on the inside diameter and O-rings on the outside diameter. All of these designs were thoroughly evaluated, and Technical Services personnel from Parker Hannifin Corporation, Packing Division, Salt Lake City, were consulted on the designs using O-rings. They did not recommend using O-rings on the floating piston, because contamination problems from the drilling mud would cause the O-ring seal to fail. It was decided that the bidirectional lip seal offered the best promise because of the simplicity of construction, ease of installation, and potential problems that exist with the O-rings on the other designs.

• Reduced Flow System

A reduced flow system was designed and tested during this reporting period in an attempt to maintain the temperature of the bearing/seal package. The system is shown schematically in Figure 9-7. The fluid flows from the Triplex mud pump through a flow divider, part of the fluid flowing through the test facility and the other part of the fluid flowing through the adjustable choke. The fluid flowing through the test facility passes through two nozzles; one nozzle is located in the nozzle sub, and the second nozzle is located in the flow restrictor. By varying the nozzle sizes, the flow rate through the test facility can be adjusted.

The reduced flow system was successfully operated, but it did not keep the bearing/seal package at the elevated temperature. Following the test of this system, a survey of pump manufacturers was performed to locate a circulating pump for the hot water system. The design conditions for the pump were

- Maximum operating temperature: 260°C (500°F)
- Maximum operating pressure: 34.5 MPa (5000 psi)
- Flow rate: $6.3 \times 10^{-4} \text{ m}^3/\text{s}$ (10 gpm)
- Fluid: water

The Thomas Register was used to obtain the names of pump manufacturers to contact. In addition, the chemical process, oil and gas, boiler, and nuclear industries were all consulted for pump recommendations.

The extreme temperature and pressure requirements for the pump eliminated most pumps from consideration. Two pumps were located that would meet the specifications. Both of these pumps are magnetically driven and have no shaft seals. One pump is manufactured by Autoclave Engineers, Inc., Erie, Pennsylvania, and the other pump is manufactured by The Kontro Company, Inc., Orange, Massachusetts.

Although both pumps met the specifications, it was not practical to use either pump, because both carry high prices and long delivery times; the two pumps are not stock items and would have had to be specially built for the Bearing/Seal Package Test Facility.

• Self-Generation of Heat Test

The seal testing program demonstrated that the test seals generate a considerable amount of heat. In fact, there are times when the heat generated by the test seals is sufficient to keep the seal tester at the 121°C (250°F) test temperature without the heater system operating.

The initial test of the self-generation of heat by the seal in the bearing/seal package was completed. This test was run without the use of the hot water system to establish baseline data for the self-generation of heat by the seal.

The following lists the test conditions:

1. Seal type: Utex style 701

Figure 9-7. Reduced Flow System

2. Number of pressure rings: 3
3. Backup rings: SAE 660 bronze
4. ΔP : 5.5 MPa (800 psi)
5. rpm: 400
6. Finish on chromed shaft: 0.2 to 0.3 μm (8 to 12 $\mu\text{in.}$)

The test duration was 2.5 hours. The starting temperature of the thermocouple at the o.d. of the seal was 26.7°C (80°F); during the test the steady-state temperature was 60°C (140°F).

Lubricant Testing and Evaluation -- Two lubricant tests, Tests 162 and 163, were performed on Pacer PLX-014 mixed with a small amount of water to check for water effects on lubricant performance. The tests used the same procedure as that used in previous tests and were run at 204°C (400°F) so that comparisons could be made with the previous tests on Pacer PLX-014. The test results were as follows:

<u>Test No.</u>	<u>Average Wear Scar Width</u>
162	4.42 mm (0.174 in.)
163	2.74 mm (0.108 in.)

Previous Pacer PLX-014 tests, Nos. 103 and 104, also run at 204°C (400°F), showed wear scar widths of 1.78 mm (0.070 in.) and 2.21 mm (0.087 in.), respectively.

Since the initial lubricant screening tests, Pacer Lubricants submitted several new lubricant samples for testing in the Terra Tek high-temperature lubricant tester. These new samples were aimed at optimizing the PLX-014 formulation, which was the best lubricant sample tested in the initial screening tests. The testing of these new lubricant samples was performed under the project "Seal and Lubricant Development for Geothermal Rock Bits," Section 4.2. The main conclusion that can be drawn from these tests for the downhole motor project is that Pacer PLX-014 is still the best candidate lubricant for use in the bearing/seal package.

References

1. Gordon A. Tibbitts et al, Phase IV, Semi-Annual Report, Program for the Improvement of Downhole Drilling Motor Bearings and Seals, TR80-53 (Houston: Terra Tek, Inc., May 1980).

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

9.3 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. The design of redundant seals and of the areas interfacing with the bearing/seal package is continuing.

FY80 Progress

Motor Interface Parts -- The Dyna-Drill and Eastman Whipstock motor interface parts were completed and sent to the respective motor manufacturers for threading. Dyna-Drill and Eastman completed the threading and delivered the parts to Terra Tek. Terra Tek now has all the parts necessary to mate Dyna-Drill or Eastman Motors to the bearing/seal package.

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

Type I--a single-piece piston that 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 that 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.

Type IV—an alternative designed by Maurer Engineering utilizing a new high-temperature seal known as a Variseal®. The assembly for a 19.7-cm (7.75-in.) floating piston is shown in Figure 9-8.

Both Grafoil® and elastomer seals were 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. Eventually the O-ring seizes on the shaft and fails. To avoid seizure, the manufacturer's recommendations concerning contact surface, tensile force in the O-ring, and percent squeeze should be closely followed. The contact surface, i.e., O-ring size, should vary with the rotary speed. Tension should be avoided, and a maximum squeeze should be determined. 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 seal 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 does not rotate in the outer housing. Then, if a Grafoil® seal is desired on the i.d. surface, the seal can be set before installation is complete. Of the designs described, the Variseal® assembly is now considered the prime candidate. The assembly shown in Figure 9-9 was selected as a low-cost, interim solution. The main objection is the use of all-elastomer seals.

Both floating piston and lower rotary Variseals® were designed previously by Maurer Engineering for use in LASL's geothermal turbodrills. The Variseal® piston worked well in the simulated downhole tests conducted at Terra Tek by Sandia and LASL.

The Ryton floating piston was fabricated and delivered to Terra Tek, along with the Variseals® necessary to outfit the piston. Maurer Engineering personnel assisted in the assembling of this piston at Terra Tek in July 1980. However the piston was damaged during the installation process and was returned to Houston, where it will be modified in order to strengthen the seal retaining system. A steel snap ring was used originally. This ring will be replaced with a threaded Ryton lock ring. The piston will be delivered around the first of November.

Improved Redundant Seals — The following design activities were accomplished:

1. A layout drawing of the redundant seals that utilize a check valve to activate the spare seals was completed.

Figure 9-8. Assembly for a 19.7-cm (7.75-in.) Variseal® Floating Piston Utilizing the Low Friction and Mass Properties of Graphite-Filled Ryton

Figure 9-9. Single-Piece Piston Using All-Elastomer Seals

2. Machine drawings of the redundant seal assembly parts were completed. One set of these parts was manufactured by Maurer Engineering and delivered to Terra Tek in December 1979. Terra Tek will manufacture the expendable parts after those initial parts are used up. Terra Tek also provided the Grafoil® seals used in these tests.
3. Drawings that show two additional types of redundant seals were completed. One design utilizes a porous filter to activate the spare packing, whereas the second design utilizes a floating piston containing small flow ports. With these designs, the spare packing is activated when the porous filter or floating piston parts are plugged by Grafoil® particles or solids in the drilling mud.
4. A drawing that shows the modifications to be made to the existing bearing/pack seal nut was completed. These modifications, which will allow the redundant seals to be used in this bearing pack, were made by Terra Tek.

Additional design sketches were made for several redundant seal concepts. A basic decision that must be made in this area concerns the actual function that will trigger the redundant seal into action. Because automatic operation is desired, the seal could be activated when one of the following events occurs:

1. The leakage rate exceeds a set value,
2. The pressure drop across the redundant seal increases, or
3. A specified volume of lubricant has leaked past the primary seal. Leaked-volume activation can be accomplished by a floating-piston locator or a leak-volume metering system.

Functions were discussed at some length in an earlier report (see Terra Tek TR78-58), but the choice of an activating function should await the choice of a primary seal design.

The decision was made to postpone further work on the redundant seal designs at this time, because the development of a workable system requires more work than is presently feasible.

Improved Rotary Seals -- The possibility of adapting the Variseal® designs to the bearing/seal package is being investigated. Bronze housing rings and spacers were designed and manufactured so that the Variseal® could be tested in the Terra Tek seal tester, but the parts that were sent to Terra Tek allowed extrusion of the Variseal® due to compression yielding during the test. After a consultation with the Variseal® manufacturer, new i.d. clearances were determined. Terra Tek manufactured backup rings to the new specifications, and the Variseal® test was run again. See section 9.2 for the results of DMT-045.

Several other modifications have been made to the Variseals®. The seals have been redesigned with a smoother angle on the i.d. surface to prevent the chipping that occurred during installation. The heel of the Variseal® was lengthened, because the failure mode on previous tests was a

circumferential crack on the heel surface. Maurer personnel have redesigned the bronze carrier rings that fit the bearing/seal package. These rings will accommodate the new Variseal® designs.

Bearing/Seal Package Evaluation -- Maurer Engineering assisted Terra Tek in refitting the bearing/seal package with a preload system using Belleville springs to replace the wire mesh springs.

Work is under way to design parts to outfit the bearing/seal package (lower seal) with Variseals® and with HTCR V-rings. As a part of the design, the heat transfer characteristics of these seals will be examined to establish the capability of inferring seal temperatures from thermocouple measurements.

Considerable effort was spent trying to adapt a one-dimensional heat transfer model of the seal tester to the configuration of the bearing/seal package. Computer runs were made using values for a typical HTCR V-ring setup. It became apparent that very little heat is transferred outward, to the location of the thermocouples. Therefore, only slight increases in thermocouple temperature indicate very large increases in seal temperature. This relationship implies that small errors in thermocouple readings may result in large errors in inferred seal temperature. Two conclusions were reached. The first is qualitative; if the indicated temperature begins to vary more than slightly from the ambient mud temperature, the seal can be assumed to be reaching a very high temperature. The second conclusion is that the new Variseal® configuration is too complex to be analyzed with the one-dimensional model.

Maurer personnel are presently evaluating a new face seal design that would be a radical departure from the seal designs tested thus far. An outside contractor has devised the system, and Maurer will provide input in order to optimize the design.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT													END DATE
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<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

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

9.4 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 was 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 were three primary objectives of this project:

1. Development and demonstration of an erosion drilling underreamer 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

All work under this project was completed. A summary of the results of the investigation is presented in the FY80 progress section, which follows. A final report was prepared and will be published separately.

FY80 Progress

Underreamer — The objective of this study was to determine the feasibility of developing a water-jet system to deeply underream geothermal production and injection wells. The purpose of this operation is to increase the flow rates and, therefore, minimize the number of wells required for each producing field. Specific requirements for the underreamer consist of reaming a 22.9-cm (9.0-in.) borehole to a 1.8-metre (6.0-foot) diameter over a 61.0-metre (200-foot) interval at a depth of 1829 metres (6000 feet).

The approach taken in this study divided the work into two tasks. First, the effects of elevated ambient pressure on the rock cutting ability of high-pressure jets were determined. Tests were conducted with nozzle pressure drops of 68.9 MPa (10 000 psi) against Berea sandstone. It was found that, below 17.2 MPa (2500 psi) ambient pressure, the nozzle standoff distance must be less than 1.7 cm (0.7 in.), and the nozzle diameter must be greater than 1.5 mm (0.06 in.) in order for rock to be cut with pure water. These parameters place definite mechanical constraints on any underreamer unit that would be placed downhole.

It was also found that the addition of polymer to the water in the concentration of 200 ppm increases the maximum allowable nozzle standoff distance to 4.8 cm (1.9 in.). Thus, if polymers were included in the underreaming fluid, the mechanical constraints on the system could be reduced.

Further testing revealed that increasing the ambient pressure from atmospheric to 17.2 MPa (2500 psi) and the confining pressure from 0 to 41.4 MPa (6000 psi) decreases the depth of cut in Berea sandstone by a factor of 10. This result shows dramatically the effect of taking a high-pressure jet from the surface into a 1829-metre (6000-foot) borehole.

The second task in this study was to develop a concept for the mechanical design of the underreamer device, to build a working portion of this device, and to test it at atmospheric pressure.

The concept developed consists of four units mounted on two balanced arms. Each unit consists of a rotary coupling to which a nozzle on an extended tube is mounted. A hydraulic motor causes each nozzle to rotate about its coupling axis. In the downhole configuration, the balanced arms would be rotated about the borehole axis, resulting in the translation of each nozzle unit. Thus, each unit would sweep out an annular area 22.9 cm (9.0 in.) wide, and all four units together would underream a 91.4-cm (3.0-ft) radius hole. The arms could be folded parallel to the borehole axis for tripping-in and tripping-out and could be unfolded downhole to the underreaming configuration.

A single unit of this device was built and tested at atmospheric pressure against Berea sandstone. The test was conducted under non-optimum conditions; i.e., the nozzle rotational velocity was not synchronized with the nozzle axis translating velocity to give complete removal of a thickness of rock in a single pass. In addition, the optimum nozzle standoff distance was not maintained. Under these conditions, a 35.6-cm (14.0-in.) hole was excavated at a rate of 0.46 m/h (1.5 ft/h).

The characteristics of a field-usable water-jet underreamer can be projected from the results of this study and from the results of independent studies found in the literature. The characteristics of major interest relate to the pump and rig requirements as well as to the performance of such a system.

The pump needed for the system would be required to pump water or other non-abrasive liquids at pressures of 68.9 to 82.7 MPa (10 to 12 ksi) and flow rates of $2.2 \times 10^{-3} \text{ m}^3/\text{s}$ (35 gpm). These requirements can be met with commercially available pumps.

The rig required for this operation would be fairly small, with a lifting capacity of approximately $31.8 \times 10^3 \text{ kg}$ (35.0 tons). This capacity suggests that a workover or truck-mounted rig could be used.

The projected performance of this system is an excavation rate of $4.2 \times 10^{-5} \text{ m/s}$ (0.5 ft/h) in Berea sandstone at a depth of 1829 metres (6000 feet); thus, a 61.0-metre (200-foot) underreaming interval would require 15 to 20 days for completion.

The results of this study and the projected system characteristics will be examined in order to determine the benefits of developing an underreamer system for use in geothermal fields.

Hydromechanical Bit -- The objective of this task was to field test a hydromechanical bit developed under an earlier contract. The testing was to be conducted at shallow depths for comparison with conventional bit performance.

The field test program examining field performance of the hydromechanical drill bit was completed during October 1979. In comparison to an air-cleaned tricone bit of equivalent size, the hydromechanical bit was able to penetrate at approximately twice the rate, under similar loading conditions. However, a comparison made with the performance of a conventional tricone bit to which a high-pressure jet was added indicated that, when the jet was directed at the hole gage, the latter system was superior.

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.

More critical to the evaluation of the hydromechanical bit was a problem encountered in drilling the relatively hard dolomite at the test site. The leading water-jet nozzle, which drills the access for the lateral jets, does not drill a "tight" circular hole but rather an irregular hole somewhat larger than the nozzle body. The chipping of the surrounding hole by the drilling cones and the flow of fluid in the current design has the potential for feeding debris into this hole. These rock fragments generate a high degree of wear on the leading nozzle body and could result in premature failure.

At the present time, it is difficult to foresee a simple, practical solution to this problem. Taken with the other test data cited above, it is therefore concluded that no further testing of this concept can, at this stage, be recommended.

Cavitation Test -- The objective of this task was to develop a standard procedure for determining the resistance of rocks to cavitating-jet attack. The purpose of this objective was threefold. First, such a standard could be used to investigate the cavitation damage mechanism. Second, it is hoped that, eventually, a determination may be made concerning the relative resistance of different rock types to the attack of cavitating and, perhaps, conventional jets. Finally, the results of these studies could conceivably be used to develop better methods for utilizing the cavitation phenomenon in geothermal drilling.

Two methods for initiating cavitation damage were investigated. The first of these was the vibratory method using a modified Lichtarowicz cell. An American Society of Testing Materials (ASTM) standard for cavitation testing of metals locates the metal specimen at the tip of an ultrasonic transducer. The specimen is then submerged to a standard depth in water,

and the transducer is vibrated at a frequency of 20 kHz. This vibration induces cavitation at the specimen face, which damages the specimen surface.

The investigation of the application of the vibratory method revealed that the machining of the transducer could not be easily accomplished. A modified procedure was therefore used, in which the rock specimen was held stationary below a vibrating titanium specimen. This arrangement resulted in cavitation inception between the two specimens and subsequent damage to the rock face.

Tests were carried out to determine the optimum conditions, which would be used as the standard. Following this determination, tests were conducted on three types of granite, three types of marble, a sandstone, and dolomite. Cumulative damage as a function of time was determined by measuring the weight loss of the samples after testing and drying for specified time periods. In addition, the damaged zones were inspected under a microscope to determine the characteristic results of cavitation attack on different rock types.

The results of this investigation were inconclusive. It was not possible to identify common characteristics that describe the effects of cavitation on similar types of rock. For example, some of the granites showed a response much closer to that of the marble than to that of the other granites. It was also not possible to correlate the response of rock to cavitation attack with the response to conventional-jet attack. For instance, dolomite is one of the most difficult rocks to penetrate with conventional jets, yet it was the rock most easily eroded by cavitation attack.

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.

A 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 was shown to vary 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. Because 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 $(D_N)^5$.

* (D_N) = nozzle diameter

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

The second method that was investigated for inducing cavitation utilized high-pressure jets in a chamber at elevated ambient pressure. Tests were conducted to determine the optimum nozzle diameter, nozzle pressure drop, and ambient pressure to use as standard conditions. Under these standard conditions, tests were run on a suite of rocks and Plexiglas to provide a standardized sample for comparison with research conducted elsewhere. Again, three types of granite, three types of marble, sandstone, and dolomite were tested.

The results of these tests were more consistent than those conducted with the vibratory method. The cavitating-jet erosion mechanism appeared to be much the same for all samples tested. The cavity shape was similar in most cases, with the central cavity being much larger than the diameter of the impacting jet; in most cases, cracks grew out into the sidewalls of the cavity.

In addition, it was found that the data for mass loss versus jet impact time could be described for each rock type by the equation

$$\text{mass loss} = A(\text{time})^B,$$

where A and B are constants for each rock type. It is possible that further research to determine these constants would allow identification of the cavitation erosion resistance of different rock types. However, the short-term benefits of further research are insufficient to justify further work under this program.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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LEGEND:

<p>———— ACTIVITY PERIOD</p> <p>----- RESCHEDULED</p>	<p>○ PLANNED START</p> <p>● STARTED</p>	<p>▽ PLANNED COMPLETION</p> <p>▼ COMPLETED</p>
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9.5 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 was 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 takes 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 essentially consists of a flow passage immediately upstream of the nozzle. The passage is sized so as to resonate at the vortex-shedding frequency, thereby amplifying the small pressure pulses created by the vortex-shedding phenomenon.

Project Status

The project was completed in FY 1980. Three nozzle concepts were selected, designed, fabricated, and laboratory tested. A final report was prepared and published separately.

FY80 Progress

Meetings — A meeting was held at the University of California at San Diego (UCSD) with A. Ellis on 3 October 1979. At this meeting, various conceptual schemes were discussed, with particular attention directed toward selecting promising simple systems that might be checked out in a relatively short time using available equipment in Professor Ellis' laboratory.

On 5 October, a meeting was held with R. Arndt at the Saint Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis. Dr. Arndt, who has been active in cavitation research for most of his career, has recently been studying the mechanics of noise created by jets, with particular interest in the effects of structured eddies in the jet.

He confirmed Hydronautics' belief that the incipient cavitation number of a submerged water jet could probably be increased by controlled low-energy excitation near its exit at a frequency corresponding to the preferred Strouhal number of 0.3. Dr. Arndt suggested some recent literature describing studies of air-jet noise that might be pertinent to devising an improved cavitating jet.

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.

Cavitation Experiments -- A test apparatus was assembled at UCSD, and tests were conducted to obtain data on the effect of small-amplitude modulation of the supply pressure on cavitation inception using a plain submerged Cavijet®. The data definitely indicate a near-doubling of the incipient cavitation number 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.

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 was 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 were followed by a disc-centerbody nozzle having a disc-string, axial, natural frequency nearly equal to the jet-vortex frequency. Initial tests of such a nozzle showed 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.

A test loop using air was put into operation in February 1980. 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 was used to measure the properties of the jet modulation. When combined with cavitation data obtained in water, these tests provided valuable information as to the feasibility of the various concepts under study.

Summary of Results and Assessment of Feasibility -- The laboratory tests showed that a water jet structures itself into discrete ring vortices when excited near a frequency corresponding to a Strouhal number of 0.3 (as well as 0.6), and the jet incipient cavitation number approximately doubles for an excitation intensity of only 0.02.

Only a few systems have been uncovered that could be applied to deep-hole drilling to achieve a passive oscillation of the jet flow at frequencies near the frequency required to cause discrete ring vortices to form. A number of patented schemes for causing low-frequency, i.e., 100-Hz, pressure oscillations at the hole bottom are apparently being developed by the Hughes Tool Company. Such low frequencies are not capable of structuring high-speed jets, i.e., jets at > 150 m/s (492 ft/s). However, the existence of such a low-frequency oscillator would not impair the performance of the high-frequency, > 7500 -Hz, oscillator that is sought and, in fact, would improve jet cavitation performance during the low-pressure portion of the cycle.

The patented ultrasonic "whistle" has apparently been tried in deep-hole drilling. The principle of operation of this device is similar to the Helmholtz oscillator schemes that were selected as being most promising. However, the device as described uses an eccentrically located jet within the resonant chamber, and the performance relative to an axisymmetric oscillator is not known.

Several concepts incorporating a jet-driven Helmholtz resonator have been preliminarily designed and bench tested both in air and water. Velocity oscillation intensities in the jet of over 60% are easily achieved. Furthermore, a concept for making the device small enough to fit into the small extended arms of tricone roller bits has been shown to cause high pulsations in air experiments. However, initial experiments in water with the oscillator at the nozzle exit have not resulted in the degree of jet structuring observed with active excitation of a plain Cavijet®.

A modification of the jet-driven Helmholtz resonator is the tandem-orifice "Pulser," shown in Figure 9-10. A preliminary design that uses the Pulser concept to feed a single Cavijet® nozzle downstream has been shown to produce high jet pulsation amplitude and should operate cavitation-free within the Pulser. This concept shows promise of providing the same degree of jet structuring as is achieved with active excitation. However, time did not permit testing this concept in water. This concept necessarily introduces an additional energy loss in the system that must be studied and minimized before the concept is finally judged.

Although there are a number of areas that require further research to improve performance, particularly in the range of low cavitation numbers, the concepts uncovered are simple and can be designed to replace conventional nozzles in all types of drill bits. Tests conducted in air show that strong pulsations are achievable in the jet at Mach numbers less than 0.1, so that a similar performance should be expected in water at current operating nozzle pressure drops of approximately 13.8 MPa (2000 psi), if cavitation within the chamber does not greatly alter the effect. Tests in water over a range of nozzle pressures up to 1.4 MPa (200 psi) demonstrated nozzle pressure pulses of 1 to 10% of the mean value. Such tests also show that a Pulser-type nozzle has an incipient cavitation number about twice that of a plain Cavijet® nozzle. Preliminary tests at low cavitation numbers show the Pulser nozzle to be about 20% more erosive than a plain Cavijet®. The latter result is particularly important, because it shows superior performance even when the flow within the Pulser chamber must be cavitating severely. Furthermore, it is doubtful that the Pulser nozzle

Figure 9-10. "Pulser" or Tandem-Orifice, Helmholtz Resonator Concept

tested is even close to an optimum configuration. Therefore, for operating nozzle pressure drops of approximately 13.8 MPa (2000 psi), which are typical of current drilling practice, it is very probable that Pulser nozzle systems can be developed for installation in all types of mechanical drill bits currently in use, with a resulting improvement in drilling performance. The magnitude of improved performance cannot now be estimated and must await further development and trials.

For nozzle pressure drops greater than 13.8 MPa (2000 psi) in water, where the Mach number of the jet is greater than 0.1, air test data indicate that strong pulsations are difficult to achieve in the simple Pulser nozzle configurations studied. However, strong oscillations were achieved in air in a modified Pulser-fed Cavijet® system corresponding to a Mach number of 0.17. It is expected that, with further research, Pulser systems can be designed to produce strong oscillations at pressure drops substantially higher than 34.5 MPa (5000 psi).

The only factor that may compromise the successful development of practical Pulser systems is nozzle erosion caused by either cavitation or solid particle abrasion or both. However, it is anticipated that, with proper nozzle design and material selection, Pulser systems can be designed to have an adequate life.

The downhole pressure-pulsing device will be further developed in a follow-on program.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

9.6 Percussion Drilling Hammers and Bits

Sandia National Laboratories
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to gather data on percussion drilling by testing conventional percussion tools, by designing and testing improved percussion tools, and by surveying existing data from industry and publications. These data will then be used to support an economic analysis of percussion drilling.

Project Status

The testing and analysis of conventional percussion drilling devices was completed, as was the designing of improved percussion systems. The economic analysis of percussion systems has begun.

FY80 Progress

After obtaining general information and specific data on the high-temperature testing of hammers from manufacturers, Sandia purchased three hammers with bits for testing at DRL. These hammers, all with solid head bits, were tested in comparison with a conventional roller bit and a conventional roller bit and hammer. Relative penetration rates over a range of drilling parameters such as weight-on-bit and air supply pressure and flow rate were determined.

The high-temperature endurance of the hammers was investigated using a heated air supply and an insulated shroud to provide a hot test environment. 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 9-11 and 9-12), but these parts could be redesigned in metal or other high-temperature material.

The preparations for a typical percussion drilling equipment test are shown in Figure 9-13. The tests measured penetration rate, hammer frequency, and air flow rate. The penetration tests were conducted in Sierra white granite. The tests compared a conventional tricone insert bit without a 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 9-14).

Figure 9-11. Delrin Air Feed Tube in Top of the Bit Shank of the Epley D-2 Hammer Bit

Figure 9-12. Pieces of Delrin Feed Tube Following Failure after 4 Minutes of Operation at 177°C (350°F)

Figure 9-13. Epley D-2 Hammer Being Set Up to Drill Granite Sample in Penetration Rate Tests

Figure 9-14. Comparison of Rate of Penetration of Drilling Hammers and Rotary Equipment

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. A detailed report on the tests is contained in Appendix D.

Rate of penetration (ROP) data from the previously described tests have been used to estimate cost savings for percussion drilling. For example, if it is assumed

1. that percussion drilling with roller cone bits results in a rate of penetration three times that of conventional rotary drilling,
2. that the life of these bits, in terms of total depth drilled, will be the same for both geothermal and conventional drilling,
3. that, while used, the hammers cost \$30 per hour to rent, and
4. that percussion drilling causes no other changes in the drilling operation,

then percussion drilling could result in savings of up to 15% of the current cost of drilling a geothermal well. The magnitude of this savings is dependent on the specific wells considered and on the portions of those wells that are percussion drilled.

For further economic analysis, more information on bit wear, bit life, and hammer life is required. A contract has been placed with the Colorado School of Mines (CSM) for part of this work, and another contract, with Resource Technology, Inc. (RTI), includes the gathering of data from industry to extend the data base.

The work at CSM will quantify gage wear on solid head percussion bits and predict the percussion drilling performance in hot rock. These activities will be accomplished by a combination of experimentation and compilation of data from the existing literature. The bit-gage study will identify and rank factors affecting gage wear, while the performance study will predict percussion performance in a specific rock at a high temperature, 260°C (500°F), compared to performance in that same rock at a normal temperature.

More tests will be done at DRL in October to provide baseline ROP data on industrial hammers used with foam and on a liquid-powered hammer developed by and borrowed from Amoco Research. An industrial hammer is being modified by replacement of its plastic and elastomeric parts that are not suitable for 260°C (500°F) service. Replacement parts will be made of high-temperature materials such as Kalrez and Vespel. This hammer will undergo an endurance test as part of this same test activity.

Once the data outlined above have been compiled, a reasonably complete economic analysis can be made in order to evaluate the potential benefits of percussion drilling.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

———— ACTIVITY PERIOD

----- RESCHEDULED

○ PLANNED START

● STARTED

▽ PLANNED COMPLETION

▼ COMPLETED

9.7 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 the knowledge of Cavijet® nozzle design principles and to develop Cavijet® nozzles that achieve increased incipient and optimum cavitation numbers.

Project Status

The initial nozzle tests at DRL and the modification of the Hydronautics test facilities were completed. Rock cutting tests and cavitation inception studies were initiated and are continuing.

FY80 Progress

Initial Nozzle Tests — The first task in this project was a test of the effectiveness of existing, full-size Cavijet® nozzles in cutting hard, impermeable rock such as granite. Although similar tests were conducted at the Hydronautics test facility in earlier research, these tests could not be run with full-size nozzles at nozzle pressures greater than 12.4 MPa (1800 psi) due to the limited available pump power. The jets proved capable of cutting granite at this pressure, but the depth of cut was a factor of 20 lower than those obtained in tests at the DRL with Indiana limestone and nozzle pressure drops of 16.6 MPa (2400 psi).

Extrapolated data suggested that obtaining a depth of cut in Georgia granite comparable to those obtained in Indiana limestone would require nozzle pressure drops of 43.4 MPa (6300 psi). This pressure and the required flow rates are within the capability of equipment at DRL. Accordingly, tests were conducted there in April 1980 to determine the validity of this extrapolation. A total of 61 runs was made on two specimens of Sierra white granite: 27 runs on the first specimen and 34 runs on the second.

Upon consideration of the available flows (about 10.1 l/s [160 gpm] at 103 MPa [15 000 psi]), it was realized that only two full-scale nozzles could be simultaneously tested. For this reason, plus consideration of the major changes required in the existing tool to permit operation up to 52 MPa (7500 psi), it was decided to build a new "two-nozzle" tool. The design of this tool was initiated by NL/Hycalog. This new two-nozzle tool was used for these tests, but the remainder of the test configuration was essentially the same as that used during the first phase of this program.

Another change was a vastly improved ratcheting mechanism that was created by DRL especially for the tests because of difficulties encountered during the first phase. This new ratcheting device worked perfectly, completely eliminating the frequent malfunctions in indexing the tool, which occurred throughout the earlier efforts in the wellbore simulator.

To further examine size-scaling effects, the first rock was exposed to hole cutting tests by two Cavijet® cavitating jet nozzles, one having an orifice diameter of 2.6 mm (0.101 in.) and the second 7.2 mm (0.283 in.).

On the second rock specimen, both of the Cavijet® cavitating-jet nozzles had an orifice diameter of 5.2 mm (0.204 in.). One of these had the "plain" Cavijet® nozzle configuration; the other was a new type of Cavijet® nozzle, which consisted of tandem orifices with an intervening, self-excited, resonant chamber. For convenience, the latter nozzle is referred to as the "Pulser," a "nickname" temporarily adopted for this class of Cavijet® cavitating fluid-jet nozzles.

The ranges of the various test parameters were

1. Swivel ($\approx$ pump) pressure: 18.6 to 75.8 MPa (2700 to 11 000 psi),
2. Nozzle pressure drop, Δp : 9.0 to 51.3 MPa (1300 to 7440 psi),
3. Ambient borehole pressure, P_a : 0.8 to 51.2 MPa (122 to 7420 psi), and
4. Cavitation number: 0.02 to 5.58.

It should be emphasized that the foregoing ranges of parameters represent the extreme values achieved during the entire test series and that the maximum values of Δp and P were not utilized during any single test run. Indeed, the maximum swivel^a pressure that could be used was found to be only about 75.8 MPa (11 000 psi), despite the rated pump capacity of 103.4 MPa (15 000 psi). Therefore, since $P_{\text{swivel}} = \Delta p + P_a$, running with any combinations of Δp and P_a that exceeded the system limit of 75.8 MPa (11 000 psi) was precluded. This pressure limit on the DRL system during these tests was found to be at a connection between the aluminum segment of drill pipe, which serves as the load cell for sensing torques and bit weights, and the mating steel drill pipe segment. Twice, when the attempt was made to exceed 75.8 MPa (11 000 psi), this connection began to leak, requiring a shutdown and replacement of the O-ring. It was felt that this problem may have been caused by expansion of the aluminum pipe and could probably be dealt with in any future high-pressure efforts by substituting a steel drill pipe segment. Time restraints prevented an attempt at this solution during the present test series.

Another major problem, which was greatly minimized but not entirely eliminated, was erosion of nozzle orifices by suspended rock particles in the water used for these tests. Because water was selected as the working fluid for these runs to provide direct comparisons with the more extensive tests to be conducted at Hydronautics, and because of the long lead time required to fabricate carbide nozzles, all of the nozzles used in these tests were fabricated from stainless steel. During a first test run, the two nozzles were eroded to about twice their original combined area after less than 1/2 hour of attempts to achieve the desired test pressures and flows. Thus, it was necessary to repair these two nozzles by welding over

the damaged orifices and then remachining to approximate the original configurations. As discussed, these repaired nozzles were subsequently used in the series of runs made on the second specimen of Sierra white granite.

To reduce this nozzle erosion problem, the entire system was thoroughly rinsed with fresh tap water. Outside water was used during the actual testing on a once-through basis instead of being recirculated in the normal fashion. Although this procedure greatly reduced nozzle wear, it was not possible to remove all of the particles of rock from the complex DRL piping and pump system. Thus, measurable wear, which will be factored into the final analyses of the test results, did occur to all four nozzles.

Preliminary examinations of the test results were limited. Estimated hole depths were taken within the intact specimens. Preliminary observations are as follows:

1. Nozzle pressure drops of at least 27.6 MPa (4000 psi) were required to create measurable damage in these Sierra white granite specimens, even at the exposure times of up to 5 minutes that were used for runs at the lower pressures of 10.3 and 17.2 MPa (1500 and 2000 psi).
2. The two plain CaviJet® nozzles having orifice diameters of 2.6 mm and 7.2 mm (0.101 in. and 0.283 in.) produced substantially lower hole-cutting rates at the nominal nozzle pressure drop of 34.5 MPa (5000 psi) when compared to the other pair of 5.2-mm (0.204-in.) plain and Pulser types of CaviJet® nozzles. This enhanced cutting rate for the latter pair of nozzles was observed over the entire test range of cavitation numbers from about 0.2 to 1.3, which were used at the p of 34.5 MPa (5000 psi).

Segments of the two specimens of Sierra white granite were then utilized for "calibration" tests to examine the relative erodibility of these two specimens. Within experimental scatter, there was no measureable difference in the erosion response of the two specimens used in the DRL tests. Thus, it will be valid to make comparisons, not only between tests run on each specimen, but also among the various tests on either rock specimen. A plain CaviJet® nozzle with an orifice diameter of 2.7 mm (0.107 in.) was used for these calibrations. All calibration tests were conducted at Hydronautics in the stationary, submerged mode, with a nozzle pressure drop of 36.9 ± 0.3 MPa (5350 ± 50 psi). In repetitive testing, the 5-second runs produced maximum hole depths that averaged approximately 17 to 18 mm (0.67 to 0.71 in.). The scatter was about ± 1 to ± 3 mm (± 0.04 to ± 0.12 in.) around the average depths, except for one set of runs in which the results were 32 ± 8 mm (1.3 ± 0.3 in.). This set seemed to be anomalous, suggesting a particular region of rock that was relatively easier to erode. Volume removals were typically about 2 cm^3 (0.12 in.^3), with scatter about ± 0.4 to $\pm 0.6 \text{ cm}^3$ (± 0.02 to $\pm 0.04 \text{ in.}^3$).

Flow calibrations were also run on the four CaviJet® nozzles used in the DRL tests. Although each of these nozzles was slightly eroded in the course of the testing at DRL, these calibrations will serve the required purpose of allowing the total flow measured during the DRL tests to be

correctly apportioned between the two nozzles in each test series. The computer program, originally developed during the earlier phase of this program, is now being modified and updated for the final analysis of the DRL nozzle test results.

Facilities Modification -- Three viewing ports were installed in the Hydronautics high-pressure cell (HPC) and were successfully tested to a cell pressure of 20.7 MPa (3000 psi), the current pressure capability of the HPC. These ports afford good visibility of cavitation phenomena during rock cutting, even at lower cavitation numbers. Each port has a circular viewing area 3.8 cm (1.5 in.) in diameter. Two of the ports are opposite one another, on a line passing through the center of the jet flow. A third port, to provide flexibility in lighting, is situated at 90° to the aforementioned line between the other two ports.

To permit detailed viewing of the cavitation phenomena produced by various CaviJet® cavitating-jet configurations, an existing binocular telescope/microscope unit was modified using a new objective lens that has a 20.3-cm (8-in.) focal length. Magnifications varying from 5 to 20X are attainable to facilitate cavitation inception observations.

Various audio methods for detecting cavitation inception have also been examined.

A displacement device for in situ measurements of eroded hole volume was constructed, calibrated, and installed in the chamber. This device significantly increases the rate of data acquisition, because it reduces the number of times the chamber must be opened and the rock removed. The device has proven capable of providing sufficient accuracy and reproducibility and has already saved considerable time during some recent hole-cutting tests. Methods for visual, photographic, and pressure-pulsation data acquisition were installed and are operational.

The modified facility will be used in the fluid-dynamic studies and rock cutting tests conducted at Hydronautics.

Design work related to modifying the Hydronautics' high-speed channel (HSC) to allow studies of large-scale CaviJet® nozzles was begun.

Fluid-Dynamic Studies -- The fluid-dynamic studies will be used to identify changes in nozzle design that improve jet dynamics. Improvements are considered to be those that result in increased incipient cavitation numbers and in the development of more highly structured jets. High-speed still photography will be used to examine periodicity of vortex shedding and cavity size and intensity. Visual and aural detection of cavitation will be used to determine incipient cavitation numbers. Thus, both qualitative and quantitative measures of jet dynamics can be associated with changes in nozzle design in order to rate the relative merit of each change. Increases in incipient cavitation number and jet structure are the desirable results of a nozzle design change because these would increase the depth capability and/or lower the required nozzle pressure for effective rock cutting.

Several nozzle types were tested for cavitation inception over a range of Reynolds numbers from about 0.4×10^6 to 1.5×10^6 . The types tested were plain Cavijet®, Cavijet® with centerbody, vaned Cavijet®, Pulser Cavijet®, and a Smith Tool nozzle. The incipient cavitation number ranged from $\sigma_i = 0.3$ to 1.3 , where the σ_i value depends on the nozzle type, the Reynolds number, and the means of detection. Visual and aural detection of cavitation inception gave comparable results, but these σ_i values were roughly 0.3 of the value that was sensed electronically. In the latter case, cavitation was disclosed by intermittent bursts of high-frequency pressure fluctuations greater than 10 kHz, which were seen as oscilloscope traces from a piezoelectric pressure transducer (PT) that is located in the wall of the HPC. The intensity of the pressure fluctuations sensed by the transducer rises to between 0.69 and 6.9 kPa (0.1 and 1.0 psi), rms, when the onset of cavitation is first perceived by the naked eye or by ear.

A typical photograph of cavitation bubbles viewed in the HPC is shown in Figure 9-15. In this view, a 6.9-mm (0.27-in.) diameter jet is impinging downward on a flat surface that is normal to the jet axis and nominally 22 mm (0.87 in.) from the orifice. The jet is shown at Reynolds number, $Re = 1.0 \times 10^6$, and cavitation number, $\sigma = P/\Delta p = 0.25$, i.e., somewhat below the values for visual (inception) perception, $\sigma_i = 0.35$, and PT perception, $\sigma_p = 0.65$. For this nozzle, the inception of visible bubbles was observed on or near the flat surface and up to about 10 mm (0.39 in.) from the jet centerline. At the lower cavitation number shown in the figure, bubbles are seen to surround the submerged jet and to cover the plate to about a 20-mm (0.79-in.) radius.

A "Pulser-fed" Cavijet® nozzle prototype was designed and built. This prototype nozzle was designed so that it could be studied both within the air testing facility and within the HPC. Therefore the prototype was designed to withstand the full-scale pressure drops in the HPC and also to be modularly assembled for the replacement of various components. This type of assembly will allow easy variation in the nozzle geometry, as suggested by the test results. Testing on this new nozzle was recently initiated.

A laser/photomultiplier system, such as that used by Professor Ellis at UCSD, was assembled for the optical detection of cavitation inception. This instrumentation should prove more sensitive to cavitation inception than aural/visual detection and, unlike acoustic transducer signals, will not be affected by large pressure fluctuations that are created by resonating, pulsed nozzles.

Work on debugging and calibrating the laser/photomultiplier system was completed. The use of direct impingement of the laser on the photomultiplier tube versus scattered light monitoring was examined. The latter approach appears promising, because it seems to be less affected by interference from any impurities in the water. It was found that considerable care had to be taken to thoroughly clean the system and the water to remove rock particles resulting from prior testing. Also, electronic filtration had to be introduced to remove spurious frequencies from the various components that were being used to condition the signal from the photomultiplier tube prior to displaying this signal upon the oscilloscope. Professor Ellis provided guidance during this effort.

DYNAMIC PRESSURE = 5.5 kPa (800 psi)
AMBIENT PRESSURE = 1.4 kPa (200 psi)
ORIFICE DIAMETER = 6.9 mm (0.27 in.)

Figure 9-15. Cavitating Jet in the Hydronautics High-Pressure Cell

Initial Rock Cutting and Final Nozzle Tests -- Nozzle designs identified as improving jet dynamics will be tested for their rock cutting ability. This investigation will consist of measuring the dimensions of cuts produced by the jets in both permeable and impermeable rock specimens.

Due to the limited pump power available at the Hydronautics facility, tests against hard, impermeable rock, which requires higher nozzle pressures, must be conducted with limited flow rates, requiring the use of nozzles that are smaller than full size. To ensure that the size effect does not radically alter the results, tests will be conducted at DRL with higher nozzle pressures and full-size versions of the designs tested at Hydronautics. By conducting the Hydronautics tests first, the test matrix for the DRL tests can be optimized in order to obtain the most useful data in the shortest possible time.

In preparation for these tests, investigations of techniques to calibrate the erosion strength of individual rock specimens are being made. It is anticipated that linear kerfs on the specimens' surface(s) that are cut with a jet at standard conditions of pressure, translation rate, etc., will serve as a calibration standard. Preliminary cuts in Berea sandstone specimens have shown that the variance in penetration depth is less for cuts made with the jet axis normal to the bedding planes than for cuts made with the axis across the bedding planes or in rough alignment with the planes. Hence, holes will be cut in "calibrated" sandstone with jets normal to the bedding plane in order to minimize the standard deviation of future measurements with regard to jet erosivity.

Eighty 15.24-cm (6-in.) cubes of Berea sandstone were obtained for tests in the HPC. Holes were made, and additional holes will be made, with the jet normal to the bedding plane, so that using just two faces of a cube will permit eight test holes to be made per specimen.

Some information on specimen uniformity was developed from repetitive tests on two sandstone specimen faces. Four holes were made in the two faces with each of two different 2.18-mm (0.086-in.) diameter nozzles. Hole depth and volume were measured after 2, 4, 6, 9, and 12 seconds of jet drilling under submerged conditions with $\sigma = 0.105$ and a driving pressure of 6.895 kPa (1000 psig). One sample was observed to be lighter in color and more porous than the others.

The variations in depth and volume that are attributable to specimen non-uniformity and test repeatability are summarized in Table 9-2 for a 9-second drilling.

The holes made in the dark specimen were more uniform than those made in the light specimen, but there was a significantly greater difference in holes between the two specimens than was shown for holes within each specimen. The difference in results between specimens was particularly notable with regard to the volume of material removed, because the volume removal rate was nearly 50% greater in the light-colored specimen. Hence, the need to "calibrate" the specimens to account for variations in erosivity is manifest. Even with calibration, the variation within specimens may not be accounted for completely.

Table 9-2

Variations in Depth and Volume
Attributable to Specimen Non-Uniformity
and Test Repeatability

Sandstone Specimen	Mean Volume			Mean Depth		
	cm ³	(in. ³)	Standard Deviation, %	mm	(in.)	Standard Deviation, %
Dark	7.2	(4.4)	8	14.2	(0.56)	5
Light	10.6	(6.5)	17	17.3	(0.68)	14

The initial rock cutting tests using Berea sandstone specimens indicated that the inherent variability of this rock type may be too large to permit meaningful comparative testing. This rock had been selected for the preliminary runs because it is possible to obtain significant amounts of erosion at rather low nozzle pressures (e.g., 6.895 kPa [1000 psi]). This effect allows the flexibility of making preliminary assessments in a small test chamber and also permits tests up to cavitation numbers of almost one in the HPC while using the Gardner-Denver pump.

Because of the large variations in the erosivity of the Berea sandstone, the testing was delayed so that the decision to use this rock type for preliminary nozzle evaluations could be reassessed. Therefore, alternative approaches are being examined, which include tests on soft metals such as annealed, pure aluminum or lead, plastics, or possibly the development of screening methods that involve changes in the conductivity of a specimen when a protective coating or oxide coating is removed.

Erosion tests on Plexiglas, a surrogate rock, were not encouraging, because the pattern of erosion on this material did not appear to be readily correlatable to the time of exposure of the CaviJet® nozzle action.

The fluid-dynamics studies, along with the initial rock cutting and final nozzle tests, will provide data on the incipient cavitation number and on rock cutting effectiveness against representative permeable and impermeable rock types for each nozzle design tested. Analysis of the results should identify nozzle design changes that significantly improve cutting ability at depth, with the goal being the identification of one or several nozzle designs that incorporate an optimum combination of these changes.

Nozzle Characterization Tests -- The cutting ability of the nozzle designs selected from the previous tests will then be characterized completely in these tests. Several nozzle sizes of each design selected for final consideration will be tested against several rock types at various values of cavitation number and Reynolds number. The rock types selected for these tests will be those that are likely to be encountered in geothermal environments and that have not been previously tested but have characteristics different from those tested in the initial rock cutting and final nozzle tests.

Fluid-Dynamic Studies at UCSD -- The dynamics of jets produced by the selected nozzle designs will also be studied further at UCSD. High-speed motion photography will be used to study jet structures and determine periodicity of vortex shedding and cavity formation. Transient jet-impact pressures and cavitation intensities will also be measured in order to characterize more fully the ability of the jets to cavitate under pressure.

Bit Test -- Conventional mechanical bits will be tested under identical simulated downhole conditions both with conventional and CaviJet® nozzles. The purpose of these tests is to assess the effects on penetration rate of substituting improved CaviJet® nozzles for the conventional nozzles normally used in the field. Conventional, currently available mud flow rates and pressures will be used in these tests. The rock types will be those likely to be encountered in geothermal drilling. Stratapax™ bits will be employed in these tests, which will be the first time that Stratapax™ bits will have been tested with cavitating jets.

Fifth International Symposium on Jet Cutting Technology (5th ISJCT) -- A. Conn attended the 5th ISJCT, presenting a paper entitled "The Fluid Dynamics of Submerged Cavitating Jet Cutting." This paper contrasted some of the results obtained under this and the prior contract (Contract 07-7067) with comparable research results from other investigators. Summarized were the effects of cavitation number, Reynolds number, and nozzle pressure drop on parameters such as optimum standoff distance and cutting rates. Although there are agreements among certain aspects of these studies, it was clear from the discussions at this conference that considerable work, both analytical and experimental, remains to be done before the interactions for all of the parameters that affect the cutting action of submerged cavitating jets can be completely defined.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

PROJECT													END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>FLEXIBLE DRILLING PIPE</u> <u>L'GARDE</u> HIGH - TEMPERATURE POLYMER COMPATIBILITY EXPERIMENTS										●			JUL 81

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.8 Flexible Drilling Pipe

Contractor: L'Garde, Inc.
Principal Investigator: G. Friese (714) 546-4671
Contract Period: 1 July 1980 to 1 July 1981
Contract Number: 62-1247 (Sandia)
Technical Consultant: D. Wesenberg (505) 844-0129

Project Objective

The objective of this project is to demonstrate that high-temperature/high-pressure polymers, such as elastomers and thermoplastics, are compatible with the Coflexip flexible drilling pipe in a downhole geothermal environment.

Project Status

The project was begun in the latter part of FY80. Samples are being prepared to be tested in a test fixture. A high-temperature and high-pressure environment will be designed, and candidate materials will be forced into a simulated Coflexip Z-section gap.

FY80 Progress

The project was divided into four tasks:

1. Fabricate a test fixture to test a flat-polymer/Z-section combination, and test the liner section under high temperature and pressure. See Figure 9-16.
2. Fabricate a test fixture that simulates the stretching of a drill pipe under high temperature and pressure, and subject the liner to cyclic stretching and frictional wear. See Figure 9-17.
3. Evaluate metal and/or plastic reinforcements that are compatible with liner materials.
4. Determine a method of fabricating large liners, 10.2 cm by 4.57 m (4 in. by 15 ft), for testing and evaluation.

Samples of three candidate drilling pipe liners were received. Polyamide II nylon was received from Sandia, and Teflon PFA and Tefzel were received from DuPont. L'Garde, Inc., fabricated elastomer plates Y267 and 291, each 0.635 cm (0.25 in.) thick.

Task No. 1 — The test fixture to test a flat-polymer/Z-section combination was designed to reflect the gap produced by linking Zeta pipe. A sample of 58.2-mm (2.780-in.) i.d. Zeta pipe was provided by Coflexip Services, Inc., for this purpose. Its cross section is shown in Figure 9-18. The test block is being machined. The block will contain slits 0.5,

Figure 9-16. Test Fixture to Test a Flat-Polymer/Simulated Z-Section Combination under High Temperature and Pressure

Figure 9-17. Test Fixture That Simulates the Stretching of a Drill Pipe under High Temperature and Pressure

Figure 9-18. Cross Section of the 58.2-mm (2.780-in.) i.d. Zeta Pipe

1.0, and 1.5 mm (20, 40, and 60 mil) wide that will be cut 6° from the normal. The edges will be rounded to 0.76-mm (30-mil) radii to simulate the Zeta pipe gaps.

For the liner section of the test fixture, Sandia suggested the additional liner candidates GE Noryl and Union Carbide Udel. Glass or graphite-filled PFA is also under consideration. Test specimens are being obtained.

Task No. 2 — the design work on the fixture to simulate the stretching of a drill pipe under high temperature and pressure is continuing. The test objective is to determine whether high-temperature and -pressure polymers are compatible with the Coflexip flexible drilling pipe in the test environments specified in Table 9-3.

Table 9-3

Environments for the Test Fixture that
Simulates the Stretching of a Drill Pipe

Temperature °C (°F)	Pressure kPa (psig)	Duration hours
250 (482)	2 068 (300)	4
125 (257)	68 950 (10 000)	24

The Coflexip Zeta pipe, when fully bent, has a reported maximum gap of 1.52 and 1.02 mm (0.060 and 0.040 in.) for 10.2- and 5.1-cm (4- and 2-in.) i.d. pipe, respectively. The liner must bridge this gap while under temperature and pressure. In addition, during bending, the liner must elastically contract (or expand) about 9% for 5.1-cm (2-in.) i.d. pipe. During this process, some abrasion between the liner and the Zeta pipe is expected. Coflexip has indicated that their standard Polyamide 11 nylon liner would weaken at temperature and enter the gap. Under these conditions, the Zeta pipe wrap would break when the pipe was bent.

The Task 1 tests will be used to screen out poor materials. The Task 2 tests will determine if (1) apparently good materials are adversely affected by abrasion or other dynamic phenomena and (2) apparently marginal materials are good because they may have the elasticity or integrity to be pushed out of the gap.

The proposed test fixture, Figure 9-17, still is considered basically practical. However, a number of changes are being incorporated. The hat will be turned upside down so that air may be bled from the system, and the length difference between the Zeta pipe and the liner hat section will be minimized to the extent practical.

Stainless-steel parts will not be used, because the Zeta pipe is not stainless steel. Coflexip will attempt to define the steel alloy. If they do not, L'Garde will define welding procedures and interfacing steel alloys by experiment.

The Zeta pipe will be surrounded by a close-fitting steel sleeve that will help take the 69-MPa (10 000-psi) pressure. Coflexip wraps flat steel wire radially around the Zeta pipe to get increased pressure capability. Because the pipe will not be bent, a solid sleeve is considered suitable. The interfacing surfaces will be lubricated with a high-temperature, dry lubricant. The sleeve thickness will be minimized, perhaps 6.4 mm (0.25 in.) or less, so that the Zeta pipe takes nearly half the load.

The 4130 steel "bucket" will be moved inboard and the thermal insulation moved outside so that the insulation thickness can be increased. The change will also prevent contamination by oil.

The liner thickness will be reduced to 3.7 mm (0.145 in.). This change is consistent with the Zeta pipe i.d. of 5.8 cm (2.29 in.). Coflexip reports that the Zeta pipe and liner dimensions increase almost proportionally with diameter. A 10.2-cm (4-in.) i.d. Coflexip pipe is reported to have a 6.4-mm (0.25-in.) thick liner and a maximum Zeta pipe gap of 1.52 mm (0.60 in.). These dimensions are comparable to 3.7 and 10.2 mm (0.145 and 0.40 in.), respectively, for a 5.1-cm (2-in.) i.d. Coflexip pipe. A 10.2-cm (4-in.) pipe cannot be tested, so this type of scaling will be used. The scaling problem will be further considered and analyzed when the failure mechanisms, as determined from Task 1, are better understood.

Thermocouples will be mounted on the sleeve near the oil exit to measure and record test section temperature. The pressure system is shown in Figure 9-19. The previously described test section is shown on the left side of Figure 9-19.

The insulated, rigid pipe shown coming from the test section (Figure 9-19) will have enough volume to contain the hot oil that is pumped from and to the test section every cycle. This arrangement not only keeps the hot oil from cooling, but also keeps it off the flexible pipe, which would be operating slightly above its allowable temperature and pressure, 250°C (482°F) and 69 MPa (10 000 psi), respectively.

By test, it was determined that a section of Zeta pipe was compressed at 13.0 cm (5.10 in.) and expanded at 14.1 cm (5.54 in.). The differential volume for the 5.1-cm (2-in.) pipe is therefore 22.9 cm³ (1.4 in.³). Forty-six centimetres (18 in.) of 7.9-mm (5/16-in.) i.d. rigid pipe can contain this amount of fluid.

The flexible, high-pressure hose is necessary because of the movement of the test section. Aminco manufactures 6.1-mm (0.24-in.) i.d. hose rated for 82.7 MPa (12,000 psi) at room temperature and for 65.5 MPa (9500 psi) at 250°C (482°F). The test and burst pressures are two and four times these values. Therefore, this hose is considered safe even if the hose approaches 250°C (482°F).

Figure 9-19. Pressure System

Fluid friction in the hose is negligible. The hydraulic press operates at 10.2 cm/min (4 in./min). The fluid velocity through the flexible hose is therefore only $V(D_1/D_2)^2 = 0.12 \text{ m/s}$ (0.4 ft/s).

The press speed and compression distance result in a cycle time of about 13.2 seconds. Therefore, there will be about 270 cycles/hour, 6500 cycles/24-hour day, and 20 000 cycles per 3 days.

The hydraulic press will be modified to operate automatically. The requirements for this modification follow:

1. The Zeta pipe will be cycled such that its gaps cycle between "fully" closed and open. "Fully" means a cycle position that does not put a large load on the Zeta pipe wrap. Experimentation will be required to determine the correct position.
2. The press will be modified to permit operation in either the manual or automatic mode. Modifications, therefore, should be put in parallel with the existing components, if possible.
3. The press speed in both directions should be as equal as practical.
4. Any failure in the test section or modifications should not damage the basic press. For instance, the system must be shut down if the hydraulic fluid reaches 54°C (130°F). Also, all power to the hydraulic press motor and platens should be shut off in case of a failure.

Systems Analysis — The question, "Will an elastomer liner slowly creep to the bottom of the hole due to its own weight?" was investigated. On the basis of the following simple analysis, a problem does not appear to exist.

If the liner receives no support from the Zeta pipe, the stress at the top of the liner is

$$s = \rho L ,$$

where ρ is the material density and L is the liner length. If $\rho = 1100 \text{ kg/m}^3$ (0.04 lb/in.³) and L is 1500 m (4900 ft), the stress is 16.3 MPa (2360 psi). Without support, then, the elastomer would elongate and break. The ultimate stress and elongation of Y267 EPDM at room temperature are 13.8 MPa (2000 psi) and 200%, respectively.

What internal pressure, then, is needed to firmly hold the rubber to the Zeta pipe by friction? This pressure is represented by the expression

$$P = t\rho/f ,$$

where t is the liner thickness, 6.4 mm (0.25 in.), and f is the steel-to-rubber friction coefficient, which is probably around 1. The required pressure then is 68.9 Pa (0.01 psi), which is considered negligible. For

instance, atmospheric pressure increases by that amount only 6 metres (20 feet) down. Pressures greater than 2 MP_a (300 psi) are expected in the pipe.

With an internal pressure greater than 68.9 Pa (0.01 psi), then, the elastomer in contact with the steel cannot move in any direction. Farther away from this interface, the liner has to support its weight without creeping. The maximum shear stress is

$$s_s = pt = 68.9 \text{ Pa (0.01 psi) .}$$

Under such a load, 267 EPDM should not creep.

Under another program, L'Garde measured compressive creep data for 267 EPDM. These data follow in Table 9-4.

Table 9-4.

Compressive Creep Data for 267 EPDM

Compressive Stress MPa (psi)	Temperature		Creep (in./in.-yr)	Temperature		Creep (in./in.-yr)
	°C	(°F)		°C	(°F)	
0.34 (50)	251	(484)	0.1	361	(681)	11
0.69 (100)	256	(492)	0.2	308	(586)	14
2.07 (300)	259	(499)	1.0	312	(593)	--

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 80

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

9.9 High-Pressure Fluid Delivery Systems

Contractor: Flow Industries, Inc.
Principal Investigator: J. Reichman (206) 872-8500
Contract Period: 13 June 1980 to 31 January 1981
Contract Number: 49-8409 (Sandia)
Technical Consultant: V. Behr (505) 846-0301

Project Objective

The objective of this project is to develop fluid delivery systems that will be compatible, in terms of pressure, with the fluid-jet drilling and downhole motor programs. Two methods of delivering the fluid at pressure to bottomhole will be investigated; one method involves pumping the fluid downhole at the required high pressure while the other considers pumping the fluid down at moderate pressures and using a downhole intensifier to increase the pressure to the required level. When this project is completed, it should be possible to make a decision on which type of system design would function better for a field test.

Project Status

The state-of-the-art review of available high-pressure equipment has been completed. Conceptual design has been initiated on sealing techniques for high-pressure pumps, swivels and drill pipe. A program review was held in September 1980.

FY80 Progress

During the reporting period, a state-of-the-art survey of available commercial pumps, swivels, drill pipe, and downhole intensifiers was completed. The primary evaluation criterion for determining the feasibility of incorporating such equipment in the high-pressure fluid delivery system was the maximum working pressure. The results of this survey indicated the following: a downhole intensifier is not commercially available at this time; swivels and pumps are limited in pressure capabilities by their elastomeric seal limitations; drill pipe needs only minor modifications in the tool joint area to meet the high-pressure requirements; and rotary hoses probably need no modification.

It became evident from this survey that improved sealing techniques were needed in order to meet the high-pressure requirements dictated by the fluid-jet drilling operation, which has a maximum operating pressure of 103 MPa (15 000 psi). Elastomeric seals at these pressures and at the degree of fluid abrasiveness encountered do not seem to offer a feasible solution. Therefore, the idea of a controlled leakage or clearance seal has been introduced for surface equipment. This type of seal will use clean water at a pressure above the fluid working pressure in the seal area; thus, controlled leakage, based on pressure drop and seal clearance, will occur

through the seal, both to the working fluid and to the ambient. This leak rate will be very small compared to the drilling fluid flow rates and thus should not be a problem in relation to the alteration of drilling fluid properties. The seal will be constructed so that the parts moving relative to one another will not touch and will be of very hard materials separated by the leakage water. This construction should lead to a long seal life. This seal concept can be introduced into swivel, pump check valve, and pump plunger seals as shown in Figures 9-20, 9-21, and 9-22.

Work is proceeding on conceptual design of a downhole intensifier. Problems are again being encountered in the seal area and because of geometric restrictions imposed by the downhole requirement. Current considerations include an intensification ratio in the range of 2 to 5. Although the development of a downhole intensifier presents difficult design problems, the potential gain is great. Such a device could make high-pressure drilling more efficient and safer and offer the possibility of using conventional surface equipment with moderate pressures. The device has potential applications in completion as well as drilling operations.

Figure 9-20. High-Pressure Swivel with Clearance Seals

Figure 9-21. Linear Spool Check Valve with Clearance Seals

NOTE: CYLINDER CAP CHECK
VALVES NOT SHOWN

Figure 9-22. High-Pressure Clearance Seal for Pump Plunger

APPENDIX A

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Geothermal Drilling and Completion**

Members of the Advisory Panel
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APPENDIX B

Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Proceedings of Workshop on Geothermal Drilling Fluids, Report No. SAND79-2395, Maurer Engineering, Inc., Houston, Texas; for Sandia National Laboratories, Albuquerque, New Mexico, 9 October 1979.

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SAND79-7122, W. McDonald, L. Remont, and W. Rehm, Maurer Engineering, Inc., and M. Chenevert, Chenevert and Associates, Houston, Texas, Sandia Contract No. 07-7068, January 1980.

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Dareing, Maurer Engineering, Inc., Houston, Texas, Sandia Contract No. 07-7298, January 1980.

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APPENDIX C

Modifications To GEOTEMP: Documentation

**R. F. Mitchell
Eneritech Engineering and Research Co.**

MODIFICATIONS TO GEOTEMP: DOCUMENTATION

GEOTEMP Modifications

The modifications to the single-phase GEOTEMP code have been completed. These modifications give GEOTEMP the following additional capabilities:

1. Variable tubing flow areas,
2. Multiple fluids in the wellbore separated by interfaces, and
3. Deviated wellbores.

A series of test cases were devised to test the modifications, and base cases from the GEOTEMP user's manual were rerun to verify the modified code.

To handle these added capabilities, the input and output formats have been modified, and to illustrate these changes, a sample problem has been run that incorporates all of the input and output modifications. Figure C-1 shows the input data for this example. The first change from the original GEOTEMP input data is the CONTROL card shown on line 52. This control card allows the user to specify

1. The number of tubing sizes in the well,
2. The number of casing sizes in the well, and
3. The number of fluid types to be used in the analysis.

In the example, two tubing sizes, four casing sizes, and two fluids have been indicated. Lines 53 and 54 show the new TUBING card input. The TUBING card has the same general format as the CASING card but with slightly different interpretations. First, the tubing sizes are numbered consecutively from the top of the well to the bottom. With casing cards, the casings are numbered from the smallest to the largest. The setting depth defines the bottom of the interval of tubing, with the top of the interval defined by either the previous interval or the surface. In the output, the top and base of the tubing interval are printed based on this criterion.

The next new card is line 59, the GEOMETRY card. This card replaces the BOREHOLE card used in the original GEOTEMP program. The GEOTEMP card carries the following data:

1. Initial depth (equals total measured depth except when simulating drilling),
2. Total measured depth (i.e., total length of wellbore),
3. True vertical depth,
4. Depth at which well is deviated, and
5. Borehole diameter.

50	GEOTEMP2 TEST DATA : INJECTION				
52	CONTROL CARD	2	4	2	
53	TUBING CARD	1	3.9580	4.5000	2000.0 2000.0
54	TUBING CARD	2	1.9580	2.5000	5000.0 3000.0
55	CASING CARD	1	8.6810	9.6250	5000.0 2200.0
56	CASING CARD	2	12.347	13.37	3000.0 2200.0
57	CASING CARD	3	19.124	20.000	1000.0 1000.0
58	CASING CARD	4	29.000	30.000	100.0 100.0
59	GEOMETRY CARD		5000.	5000.	4500. 2000. 40.00
60	INITIAL TEMPERATURE		70.0	145.00	70. 20.0
61	FLUID CARD	1	10.	15.	5.0 PRIMARY
62	FLUID CARD	2	10.	15.	5.0 ANNULAR
63	INITIAL FLUID	1	1	2	145.00 0.00
64	CHANGE CARD	1 0 1	70.	10.	10.
65	CHANGE CARD	1 0 2	70.	100.	20.

Figure C-1. Input Data for Sample Problem

In this example, the well deviates 30° at a depth of 2000 feet, resulting in a true depth of 4500 feet and a wellbore length of 5000 feet.

The input of fluid properties is changed from the original GEOTEMP through a new card, the FLUID card. All the fluids in the wellbore are now specified by identification numbers. For example, line 61 gives the FLUID CARD for fluid number 1. The entries on this card are

1. Fluid identification (I.D.) number,
2. Fluid density,
3. Plastic viscosity,
4. Yield point, and
5. User-specified name or comment.

The next new card introduced is the INITIAL FLUID card. This card specifies the initial state of the wellbore before calculation begins. The INITIAL FLUID contains the following information:

1. I.D. number of fluid initially in tubing and tubing annulus,
2. I.D. number of secondary flow fluid,
3. I.D. number of packer fluid in casing annuli,
4. Inlet temperature for secondary flow, and
5. Secondary flow rate.

The final change to the input format is a slight modification to the CHANGE card. The new CHANGE card gives the following information at each time to change data:

1. Flow option (same as old CHANGE card),
2. Secondary flow indicator (1=yes; 0=no),
3. I.D. number of fluid injected or produced,
4. Fluid inlet temperature,
5. Fluid flow rate, and
6. Time to change flow parameters.

The following describes in detail the procedure for inputting data to the model. The format for each card is specified, and the variables on the card are defined.

TITLE CARD:

This card allows any title to be printed on columns 1-80. Format (20A4)

Columns 1-80 Title

CONTROL PARAMETERS CARD:

This card inputs parameters necessary to specify the problem. Format (20X, 3I5)

Columns 21-25 Number of tubing intervals
26-30 Number of casing strings
31-35 Number of distinct fluids to be considered (i.e., primary, secondary, annular, etc.)

TUBING SPECIFICATION CARDS:

Each card defines an interval of tubing. Intervals are numbered consecutively from the top of the well to the bottom. Format (20X, I5, 4E10.0)

Columns 21-25 Tubing interval #
26-35 Tubing inside diameter, inches
36-45 Tubing outside diameter, inches
46-55 Bottom of interval, feet
56-65 Length of cement or annulus fluid outside tubing, feet.

CASING SPECIFICATION CARDS:

Each of these cards defines a string of pipe in the well; the order of presentation is immaterial. Format (20X, I5, 4F10.0)

Columns 21-25 Casing identification (I.D.) number (tubing not included)
26-35 Inside diameter, inches
36-45 Outside diameter, inches
46-55 Setting depth, feet
56-65 Interval length of cement or annulus fluid outside casing, feet.

BOREHOLE GEOMETRY CARD:

This card defines borehole dimensions. Format (20X, 5F10.0)

Columns 21-30 Initial depth, feet
31-40 Total measured depth, feet
41-50 True vertical depth, feet
51-60 Depth of well deviation, feet
61-70 Borehole diameter, inches
(outside last casing outside diameter and cement).

Initial and total measured depth are equal for applications other than drilling.

INITIAL TEMPERATURES CARD:

This card defines the initial and boundary temperatures in the well and soil. Format (20X, 4F10.0)

Columns 21-30 Surface temperature, °F
31-40 Bottomhole temperature, °F
41-50 Intermediate temperature, °F
51-60 Intermediate depth corresponding to temperature in columns 41-50, feet.

FLUID PROPERTIES CARD:

This card has the fluid properties as measured at 70°F. Format (20X, I5, 3F10.0, 6A4)

Columns 21-25 Fluid I.D. number
 26-35 Density, lb/ft³
 36-45 Plastic viscosity, centipoise
 46-55 Yield point, lbf/100 ft²
 56-79 Name of fluid or note of your choice.

INITIAL FLUID PARAMETERS CARD:

This card identifies the primary flowing fluid, the secondary flowing fluid, and the annular fluid; the secondary fluid flow rate; and the secondary fluid inlet temperature. Format (20X, 3I5, 2F10.0)

Columns 21-25 Primary fluid I.D. number
 26-30 Secondary fluid I.D. number
 31-35 Annular fluid I.D. number
 36-45 Secondary fluid inlet temperature, °F
 46-55 Secondary fluid flow rate, gal/min.

CHANGING FLOW PARAMETERS CARD:

This card contains flow parameters that are allowed to change at any time during a simulation. As many cards as needed may be used. Format (20X, 3I2, 5F10.0)

Columns 20-21 Flowing option selector
 1 = injection
 2 = production
 3 = forward circulation
 4 = reverse circulation
 22-23 Secondary flow option
 0 = no flow
 1 = secondary flow
 24-25 Primary fluid I.D. number
 26-35 Primary fluid inlet temperature, °F
 36-45 Primary fluid volume flow rate, gal/min
 46-55 Time to read next card for change of variables, days
 56-65 Hole depth at time to change variables, feet, (drilling only)
 66-75 Circulation time per day, hours (drilling only).

Figure C-2 is the summary of the input data printed out by GEOTEMP. The first change is that the tubing configuration is printed separately from the casing program and that the top and bottom of each interval are printed rather than the casing setting depth. The next addition is the well geometry information. The total depth and wellbore diameter are always printed, but the depth of deviation and true vertical depth are printed for deviated wells only. The wellbore fluid properties have been revised to include the fluid I.D. number and the user-designated name. Finally, the wellbore fluids initial state is summarized.

Figure C-3 is the output of the first calculation time interval. This calculation is typical of the type of problem for which the original GEOTEMP was used. The only change in the output is that the fluid injected and the wellbore fluids are now indicated. Figure C-4 is the output of the

GEOTEMP2 TEST DATA : INJECTION

TUBING CONFIGURATION

TUBING	ID, IN.	OD, IN.	TOP, FT.	BASE, FT.	CEMENT, FT.
1	3.958	4.500	0.	2000.	2000.0
2	1.958	2.500	2000.	5000.	3000.0

CASING PROGRAM

CASING	ID, IN	OD, IN	DEPTH, FT	CEMENT INTERVAL, FT
1	8.681	9.625	5000.	2200.
2	12.347	13.370	3000.	2200.
3	19.124	20.000	1000.	1000.
4	29.000	30.000	100.	100.

WELL GEOMETRY

TOTAL DEPTH= 5000. FT.
BORE DIAMETER= 40.000 IN.
NOTE: DEVIATED WELL
DEPTH OF DEVIATION= 2000. FT.
TRUE VERTICAL DEPTH= 4500. FT.

WELLBORE FLUID PROPERTIES

FLUID TYPE NO. 1 PRIMARY

DENSITY= 10.0 LBM/GAL
PLASTIC VISCOSITY= 15. CENTIPOISE
YIELD POINT= 5. LBF/100FT2

FLUID TYPE NO. 2 ANNULAR

DENSITY= 10.0 LBM/GAL
PLASTIC VISCOSITY= 15. CENTIPOISE
YIELD POINT= 5. LBF/100FT2

WELLBORE INITIAL STATE

FLUID # 1 IN TUBING & TUBING ANNULUS
FLUID # 2 IN CASING - CASING ANNULI

Figure C-2. Summary of the Input Data Printed Out by GEOTEMP

SET VARIABLES AT TIME = .000 DAYS
 FLOWING OPTION = INJECTION
 FLUID # 1 INJECTED INTO TUBING
 FLUID # 1 IN WELL
 INLET TEMPERATURE = 70. F
 FLOW RATE = 10. GAL/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 1

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.0	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.1	70.8	72.4	72.7	72.9	73.0
400.	70.4	71.9	75.2	75.8	76.1	76.4
600.	70.9	73.2	78.0	78.8	79.4	79.7
800.	71.6	74.4	80.9	82.0	82.6	83.1
1000.	72.5	75.8	83.8	85.1	85.9	86.4
1200.	73.5	77.7	86.5	88.1	89.1	89.8
1400.	74.7	79.5	89.4	91.3	92.4	93.1
1600.	76.1	81.4	92.4	94.4	95.6	96.5
1800.	77.6	83.3	95.3	97.6	98.9	99.8
2000.	79.3	85.4	98.2	100.7	102.2	103.1
2200.	80.8	90.2	102.2	104.1	105.2	105.9
2400.	82.2	92.1	104.3	106.3	108.0	108.7
2600.	83.6	94.1	107.4	109.5	110.7	111.5
2800.	85.1	95.8	110.0	112.2	113.5	114.3
3000.	86.7	97.9	112.7	114.9	116.2	117.1
3200.	88.3	100.6	115.0	117.5	118.9	119.9
3400.	90.1	102.7	117.7	120.2	121.7	122.7
3600.	91.9	104.9	120.3	122.9	124.5	125.5
3800.	93.8	107.1	123.0	125.6	127.2	128.3
4000.	95.7	109.4	125.6	128.4	130.0	131.0
4200.	97.6	111.7	128.3	131.1	132.8	133.8
4400.	99.6	114.0	130.9	133.8	135.5	136.6
4600.	101.7	116.3	133.6	136.6	138.3	139.4
4800.	103.8	118.7	136.3	139.3	141.1	142.2
5000.	105.9	121.0	139.0	142.0	143.8	145.0
5200.	147.8	147.8	147.8	147.8	147.8	147.8
5400.	150.6	150.6	150.6	150.6	150.6	150.6

Figure C-3. Output of the First Calculation Time Interval

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = INJECTION
 FLUID # 2 INJECTED INTO TUBING
 FLUID # 1 IN WELL
 INLET TEMPERATURE = 70. F
 FLOW RATE = 100. GAL/MIN
 TIME TO CHANGE DATA = 20.000 DAYS

FLUIDS IN WELL UPDATED AT TIME= 10.010 DAYS
 FLUIDS IN TUBING
 FLUID # 2 FROM 0. FT. TO 3034. FT.
 FLUID # 1 FROM 3034. FT. TO 5000. FT.
 FLUIDS IN ANNULUS
 FLUID # 1 FROM 0. FT. TO 5000. FT.

FLUIDS IN WELL UPDATED AT TIME= 10.060 DAYS
 FLUIDS IN TUBING
 FLUID # 2 FROM 0. FT. TO 5000. FT.
 FLUIDS IN ANNULUS
 FLUID # 1 FROM 0. FT. TO 5000. FT.

TIME = 20.000 DAYS

ITERATIONS = 2

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	.0	.3	1.7	3.3	5.5	50.0
-0.	70.0	70.0	70.0	70.0	70.0	70.0
200.	70.0	70.7	72.3	72.6	72.8	73.0
400.	70.0	71.5	74.9	75.5	75.9	76.4
600.	70.1	72.3	77.5	78.4	79.1	79.7
800.	70.2	73.0	80.1	81.4	82.2	83.1
1000.	70.3	73.7	82.9	84.4	85.4	86.4
1200.	70.4	74.9	85.3	87.2	88.5	89.8
1400.	70.5	75.7	87.9	90.2	91.6	93.1
1600.	70.7	76.6	90.5	93.1	94.8	96.5
1800.	70.9	77.5	93.2	96.1	98.0	99.8
2000.	71.1	77.0	94.9	98.5	100.9	103.1
2200.	71.3	83.7	100.1	102.7	104.4	105.9
2400.	71.5	84.8	102.5	105.2	107.0	108.7
2600.	71.7	85.9	104.8	107.8	109.7	111.5
2800.	71.9	86.8	107.3	110.4	112.4	114.3
3000.	72.1	88.1	109.6	113.0	115.1	117.1
3200.	72.4	90.1	111.6	115.3	117.7	119.9
3400.	72.6	91.4	114.0	117.9	120.4	122.7
3600.	72.9	92.6	116.3	120.4	123.1	125.5
3800.	73.2	93.8	118.7	123.0	125.8	128.3
4000.	73.5	95.1	121.1	125.6	128.5	131.0
4200.	73.8	96.3	123.5	128.2	131.2	133.8
4400.	74.2	97.6	125.9	130.7	133.9	136.6
4600.	74.5	98.8	128.2	133.3	136.6	139.4
4800.	74.9	100.1	130.6	135.9	139.3	142.2
5000.	75.2	101.4	133.0	138.5	142.0	145.0
5200.	147.8	147.8	147.8	147.8	147.8	147.8
5400.	150.6	150.6	150.6	150.6	150.6	150.6

Figure C-4. Output of the Second Time Interval

second time interval. This calculation is more typical of the enhanced capability of the new version of GEOTEMP. First, note that fluid #2 is being injected into the wellbore filled with fluid #1. At the first time step, 10.01 days, fluid #2 has displaced fluid #1 to the depth of 3034 feet. At the end of the second time step, 10.06 days, fluid #2 has completely displaced fluid #1, and no further updates are necessary. By using CHANGE cards, any wellbore fluid arrangement can be generated. The ability to change the wellbore fluid at any time is an especially useful consequence of the program's multiple fluid feature. For example, a drilling problem can be studied with greater accuracy by changing mud properties as the drilling progresses. For another example, the simulation of well production with changing flow rates and fluid composition can be accommodated.

Test Cases

Several test cases were run to verify that the modified GEOTEMP code was running properly. The first test was to rerun all of the test cases given in the GEOTEMP user's manual to show that the basic code still works properly. The results of these tests were satisfactory, and the output of these test runs is included in Appendix 2 of the documentation.

Two cases were run to test the variable tubing flow area. The first test, illustrated in Figure C-5, used three cases:

Case I--single 4.5-inch tubing

Case II--4.5-inch tubing to 2000 feet.

2.5-inch tubing from 2000 feet to 5000 feet.

Case III--single 2.5-inch tubing.

The expected result of this test is that the temperatures predicted for Case II should fall between those of Cases I and III and, further, that Case II and Case I should be indistinguishable above 2000 feet and that Case II should approach Case III at depth. The results shown in Figure C-5 indicate that these trends are verified. The output for Cases I, II, and III are included in Appendix 3 of the documentation.

The second study used to test the variable tubing area used a "stacked" production model to simulate the variable area model. Both models were intended to solve the following boundary value problem:

Fluid is produced at 10 gal/min through 2.5-inch tubing from 5000 feet to 3000 feet, where the tubing changes to 4.5 inches from 3000 feet to the surface. The bottomhole temperature is 145°F. How does the fluid exit temperature vary with time?

The stacked model is constructed by first running a single 2.5-inch tubing from 5000 feet to the surface. The temperatures predicted by this model at 3000 feet are then used as the inlet temperatures for another model--a single 4.5-inch tubing from 3000 feet to the surface. The exit temperatures from this model should be close to the exact solution. Figure C-6 compares the results of these two models. A particularly interesting result is that the transient response of the two models from 0.1 hour to 2.0 hours is nearly identical. Beyond 2.0 hours, the model approaches a nearly steady state, and the stacked model stays about 1°F below the

Figure C-5. Multiple Tubing Area Test: Injection
Tubing Fluid Predicted Temperatures

Figure C-6. Multiple Tubing Area Test: Production Fluid Exit Temperatures

multiple area model. This discrepancy is explained by the vertical heat transfer that is neglected by the "stacked" model. The complete "stacked" model output is included in Appendix 4 of the documentation.

The last case run tested the multiple fluid capability of the program. Water was circulated in the wellbore for 30 days, and then two shut-in cases were studied:

1. Water in tubing and annulus and
2. Water in tubing, cement in the annulus.

The expected results were that the initial temperatures would be equal, that the temperature of the water in the annulus would rise faster than in the cement annulus, and that, long term, the temperatures would be equal. Figure C-7 shows the expected short-term results, and Figure C-8 shows the expected long-term results. The output from these test cases is included in Appendix 5 of the documentation.

Program Modifications

Four new subroutines and internal modifications of existing subroutines were necessary to accomplish the Task 1 modifications. The following new subroutines were added:

FUNCTION KTUBE

This function subroutine determines the tubing interval, given the depth.

SUBROUTINE UPFLOW

This subroutine circulates fluid interfaces upward, given the volume of fluid produced or circulated.

SUBROUTINE DWNFLO

This subroutine circulates fluid interfaces downward, given the volume of fluid injected.

SUBROUTINE FDROP

This subroutine determines the fluid types in a given depth interval and returns the appropriate fluid properties.

The main program and subroutines READ, PROP, GRID, COND, COEF, and WELL have internal modifications. A complete listing of the modified program is included in Appendix 1 of the documentation. The interface subroutines UPFLOW and DWNFLO were extensively tested before incorporation into GEOTEMP. These test results are included in Appendix 6 of the documentation.

Figure C-7. Multiple Fluids in Wellbore Tests:
Annulus Temperature at 4200 Feet

Figure C-8. Multiple Fluids in Wellbore Test:
Annulus Temperature at 4200 Feet

APPENDIX D

Report on Percussion Drilling Tests

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REPORT ON PERCUSSION DRILLING TESTS

Introduction

This report describes tests of percussion drilling tools that were done at DRL, Salt Lake City, Utah, during February 1980. The purpose of the tests was threefold: (1) to compare the penetration rates of different hammers with each other and with conventional rotary drilling, (2) to measure and compare the hammer pulses at normal and high temperatures, and (3) to establish hammer life and failure modes at high temperature. The qualitative results were good for (1), poor for (2), and mixed for (3); a description of each part of the test follows.

Rate of Penetration (ROP)

For the ROP measurements, two "oil field" hammers were rented and three "industrial" hammers were bought. Both types function according to the principle of a reciprocating piston striking an anvil, but the oilfield tools are threaded to accept a conventional roller bit, while an industrial tool uses a one-piece solid bit with tungsten carbide inserts. General descriptions of the hammers are given in Table D-1. The Ingersoll-Rand (I-R) DHD 360 is considerably smaller than the other hammers, because it is designed to be used primarily with a 15.2- or 16.5-cm (6- or 6.5-in.) bit. This hammer is available with a 21.6-cm (8.5-in.) bit; however, this combination provides a performance comparison of a hammer that is smaller than normal for this size hole.

The baseline for the comparison of hammer penetration was the data from a Reed M-70, 20.0-cm (7.875-in.), insert bit run without hammer over a range of weights on bit and rotary speeds. These baseline data are plotted in Figure D-1. Each of the hammers was then run in samples of the same granite. The oilfield hammers used the same Reed bit as the baseline tests, and each of the industrial hammers used the bit with which it was equipped by its manufacturer.

Because the mechanism of rock breakage is slightly different for the two types of hammers, the test variables were also slightly different. The bits used in the industrial hammers are one-piece steel bodies with hemispherical tungsten carbide inserts (Figure D-2). The inserts are quite strong in compression but not in shear, so they can withstand heavy blows from the hammer but not high torques imposed by high weight on bit (WOB). The WOB was held constant at 22 241 N (5000 lb), the manufacturers' approximate recommendation for all three industrial hammers, and the air supply pressure and rotary speed were varied. The inserts in the roller bit do not experience the same kind of shear loading, so these assemblies can be run at higher WOB values. For the roller-bit/hammer tests, the rotary

Table D-1

General Descriptive Data on Hammers

<u>Hammer</u>	<u>Hammer Diameter cm (in.)</u>	<u>Bit Diameter cm (in.)</u>	<u>Length with Bit cm (in.)</u>	<u>Length without Bit cm (in.)</u>	<u>Weight kg (lb)</u>	<u>Operating Air Pressure Range kPa (psi)</u>	<u>Air Consumption at 1 724 kPa (250 psi) (Blank Choke) m³/s (ft³/min) (standard)</u>
TRW - Mission A63-15	16.2 (6.375)	20.3 (8.0)	159.9 (60.2)	139.7 (55.0)	159 (350)	690 to 1 724 (100 to 250)	0.51 (1 090)
TRW - Mission Hammerdrill	17.2 (6.75)	20.0 (7.875)		177.8 (70.0)	259 (570)	690 to 2 413 (100 to 350)	0.49 (1 040)
Ingersoll-Rand DHD 360	13.7 (5.375)	21.6 (8.5)	129.5 (51.0)		98 (215)	1 034 to 2 413 (150 to 350)	0.27 (570)
Ingersoll-Rand DHD 2076	16.8 (6.625)	20.0 (7.875)		193.4 (76.1)	238 (525)		
Epley D-2	17.2 (6.75)	20.3 (8.0)	144.8 (57.0)		145 (320)	690 to 1 724 (100 to 250)	0.50 (1 070)

Figure D-1. Baseline Data from Reed 20-cm (7.875-in.), M-70, Tungsten Carbide Insert Bit: Rock--Sierra White Granite; Air Flow Through Bit--0.38 m³/s (800 ft³/min, Standard)

Figure D-2. Bits Used in Industrial Hammers: Left to Right--
Mission, Ingersoll-Rand, Epley

speed was held constant at 45 rpm, and the air supply pressure and WOB were varied. The rates of penetration are plotted for different conditions in Figures D-3 and D-4.

In general, the behavior illustrated by the curves is consistent with theoretical predictions; however, a few anomalous points should be discussed. Figure D-3 shows that the ROP of the oilfield hammers increased only slightly for large increases in bit weight. This result occurs because the force of the hammer blows is greater than the steady bit weight, and the change in bit weight is small compared to the total force of hammer blow plus bit weight. This behavior is also consistent with manufacturers' recommendations to operate the hammers with relatively low WOB.

Large changes in ROP are seen in Figure D-3 when the pressure of the air supply to the hammers is increased. When the pressure is raised, both the hammer-blow frequency and the energy per blow are increased. If it is assumed that there is a specific energy required in order to break a unit volume of rock, then the ROP should increase as the $3/2$ power of the air pressure; with one exception, the curves in Figure D-3 show good agreement with this ratio. The exception is the 1896-kPa (275-psi) line for the I-R hammer, which shows a lower ROP than does the 1379-kPa (200-psi) line for the same tool. The reason for this result is not known, but a tentative explanation is suggested by the failure of this hammer in the next phase of testing. When an attempt was made to run the I-R 2076 against a load cell, the hammer would not operate. When apprised of the problem, the hammer rental company suggested that an internal air valve in the hammer probably had malfunctioned. The hammer was not disassembled to verify this suggestion, but it is possible that, whatever failure mode was involved, the mode had already begun during the 1896-kPa (275-psi) ROP test.

The average ROP of the hammers at 1379 kPa (200-psi) and 88 964 N (20 000 lb) WOB was approximately 4.6 m/h (15 ft/h); this rate compares with a ROP of 1.5 m/h (5 ft/h) for the same bit run without percussion at the same WOB and rotary speed.

It is commonly stated that hammers reduce drill string vibration in rough drilling conditions. There is considerable field experience in highly faulted formations that verifies this assumption, but the assumption is apparently not true in competent rock such as the granite samples used in these tests. Tables D-2 and D-3 show the high-frequency variations in torque and axial force measured by the strain-gaged sub in the DRL drill string. In general, the standard deviation of each variable is higher with the hammer than without. This result seems reasonable for the laboratory situation, but faulted formation and a longer, more flexible drill string might produce a more favorable comparison.

The penetration rates of the industrial hammers are shown in Figure D-4, plotted as envelopes of operating conditions. At each air supply pressure, penetration rates at different rotary speeds are plotted, and curves are drawn through the minimum and the maximum points. This format provides an envelope for each tool that shows its penetration rate as well as its sensitivity to rotary speed.

Figure D-3. Penetration Rates of "Oil Field" Hammers with Reed 20-cm (7.875-in.), M-70 Bit; Run at Varying Air Pressure and Weight on Bit; Rock--Sierra White Granite

Figure D-4. Rates of Penetration for Industrial Hammers; Operating Envelopes Show Variance in Rates of Penetration Over Range of Air Pressure and Rotary Speed; Rock--Sierra White Granite

Table D-2

Comparison of Axial Force and Torque in the Drill String
Operating with and without Hammer at Equal Weight on Bit
and Rotary Speed

Nominal Weight on Bit N (lb)	M-70 without Hammer 40 rpm	Mission with Hammer, 40 rpm		
		Air Pressure, kPa (psi)		
		862 (125)	1 379 (200)	1 896 (275)
		Measured Weight on Bit, N (lb)*		
44 482 (10 000)	44 731/6 632 (10 056)/(1 491)	44 536/18 914 (10 012)/(4 252)	39 429/27 112 (8 864)/(6 095)	39 291/29 367 (8 833)/(6 602)
88 964 (20 000)	88 867/9 799 (19 978)/(2 203)	87 639/25 840 (19 702)/(5 809)	86 500/37 401 (19 446)/(8 408)	72 035/32 530 (16 194)/(7 313)
Torque, N•m (lbf•ft)*				
44 482 (10 000)	305/123 (225)/(91)	388/128 (286)/(94)	480/243 (354)/(179)	697/285 (514)/(210)
88 964 (20 000)	629/209 (510)/(154)	898/420 (662)/(310)	1 192/224 (879)/(165)	1 199/350 (884)/(250)

*Values = Linear Intercept/Standard Deviation

Table D-3

Comparison of Axial Force and Torque in the Drill String
Operating with and without Hammer at Equal Rate of Penetration:
5.5 m/h (18 ft/h)

	Mission Hammerdrill	M-70 without Hammer 40 rpm ** 177 929 N (40 000 lb)	M-70 without Hammer 70 rpm ** 133 447 N (30 000 lb)
Axial* Force N (lb)	72 035/32 530 (16 194)/(7 313)	175 665/12 740 (39 491)/(2 864)	135 738/18 954 (30 515)/(4 261)
Torque* N·m (lbf·ft)	1 199/350 (884)/(258)	1 969/365 (1 452)/(269)	1 196/258 (882)/(190)

*Values = Linear Intercept/Standard Deviation

**Nominal weight on bit

As Figure D-4 shows, the industrial hammers have considerably higher penetration rates than do the oilfield hammers running at about the same air supply pressures and flow rates. This difference is primarily due to the more efficient transfer of energy from the reciprocating piston to the rock through the solid, one-piece drill bit. In the oilfield hammer, the piston blow is transmitted to the driver sub, then through a threaded connection to the bit body, and finally through the bit bearings to the cones. This system is much less rigid and therefore less efficient than the solid bit.

It is also apparent that there is a wide variation in penetration rate with rotary speed for some drilling conditions. The variation is also inconsistent, because the penetration rate does not always increase with rotary speed. The reason for this apparent inconsistency is not completely clear, but it seems to be a function of the penetration per revolution, the angular spacing of the gage carbides, and the formation being drilled. Since gage carbide wear also varies with rotary speed, the field practice is to establish some speed that will give an acceptable compromise between gage wear and penetration rate.

Figure D-4 also shows that, contrary to the prediction of theory, the penetration rate of the industrial hammers does not increase as the $3/2$ power of the air supply pressure. The penetration rate, and blow frequency, below theoretical values are primarily caused by the increasing back pressure at the piston exhaust position. The flow restriction imposed by the air passage through the bit shank becomes more important as flow rate increases and, therefore, raises the pressure into which the piston exhausts. The increased pressure reduces the amount of work which the piston extracts from the air, and the energy per blow is reduced.

Figure D-5 is a comparison of the penetration rates of the hammers at a theoretical air compressor horsepower. Assuming that the air compressor inefficiencies are the same for all tests, the pressure and flow rate were used to calculate a theoretical power at each test point. The curves then give some indication of how efficiently each hammer and bit transform the energy of the compressed air into the energy of breaking rock. When the curve for the I-R 360 is inspected, three things should be remembered: (1) there may be an erroneous datum point that gives the curve a concave-upward shape; (2) this hammer is actually designed for a smaller hole than the other industrial tools; and (3) the I-R 360 bit was 21.6 cm (8.5 in.) compared to 20.3 cm (8 in.) for the Mission and Epley tools.

Pulse Measurement Tests

The objectives of this part of the testing were to compare the pulses of the industrial and the oilfield hammers and to compare the pulses of the industrial hammers at high and at normal temperatures. These data would have shown the actual force of the blows delivered to the rock and would have shown whether the performance of the hammers changed significantly at high temperature.

The test setup had a strain-gaged load cell beneath the bit (Figure D-6) and accelerometers mounted on the bit head (Figure D-7). One

Figure D-5. Penetration as a Function of Theoretical Air Compressor Horsepower

Figure D-6. Load Cell Stack: Top to Bottom--Bit with Accelerometer, Adapter Plate, Water-Cooled Extension, Load Cell

Figure D-7. Kistler 805A Mounting Block with Accelerometer

oil field and two industrial hammers were run in this setup. The net results were the destruction of two load cells and five accelerometers and the collection of essentially no useful data. The primary reason for this set of mishaps was the unexpected magnitude of the loads on the transducers. These high loads were apparently caused by the dynamic separation of the bit and the load cell plate and their subsequent impact as they rebounded back together. Some of the broken accelerometers were rated for 50 000 g service, so the loads imposed on them must have been considerably higher than that.

In general, it appears that the data desired can be had by redesigning the test apparatus, but the value of the data does not now justify the time and expense.

High-Temperature Tests

The objectives of this part of the testing were to verify the high-temperature operation of the industrial hammers and to identify any failure modes unique to the high temperature. The test setup was similar to that for normal rock drilling, except that the drilling target was a cast-iron billet and the air supply was heated by passing the air through a gas-fired heat exchanger. An insulated sub and swivel were used above the hammer, an insulated exhaust can surrounded the bottom part of the hammer, and the in-line oiler was filled with high-temperature Pacer lubricant. The test plan was to operate the hammers for 8 hours at 28°C (50°F) temperature increments from 177° to 260°C (350° to 500°F). At the end of each 8-hour operating period, the air supply temperature would be cycled to ambient and back to hot, with the hammer off bottom, to simulate tripping.

The first hammer tested was the Mission A63-15. The bit was placed against a cast-iron billet, and hot air that was passed through the hammer during a 1-hour period brought the A63-15 to 177°C (350°F). The rotary was then turned on, and the hammer was loaded to close the bit and begin drilling while maintaining the hot air flow. After about 4 minutes the hammer stopped; it was cooled by passing ambient air through it and was then disassembled. The Delrin foot valve in the top of the bit had shattered into approximately 10 pieces, causing the piston to stop reciprocating.

The Ingersoll-Rand DHD 360 was tried next, assuming that, because it had a metal foot valve, it would last longer at high temperature. The same starting procedure was used, and the I-R tool drilled for approximately 3 minutes before stopping. When the hammer was disassembled, the foot valve was found to be crushed and could easily be lifted out of the bit. Apparently the valve is held in place by some material that melted or softened enough to let the valve tube become misaligned and then be crushed by the piston.

While the I-R test was being prepared, the DRL machine shop made an aluminum (6061-T6) tube to replace the part in the Mission A63-15. This part was installed in the bit and was retained in place by dimpling the aluminum tube into the groove inside the bit. The hammer was assembled and the test repeated; the hammer ran for 52 minutes before stopping. The problem was once again the foot valve. It apparently had fatigued, because

it had parted cleanly just at the point at which the o.d. increased to form a positioning feature on the tube. This problem may have been aggravated by a tool mark on the tube, because the machined finish was rough.

At this point in the testing, it was concluded that plastic parts were not usable at the test temperature, so the Epley hammer, which has a plastic feed tube inside the piston as well as a plastic foot valve in the bit, was not run at 177°C (350°F).

During each of the high-temperature tests, the air temperature was measured at the hammer intake and exhaust. The exhaust air became significantly cooler once hammering began, and the air expansion in the piston replaced the orifice expansion of the temperature soak period. Both hammers produced expansion cooling of approximately 27°C (48°F), which could be significant in keeping the operating temperature low in a hot wellbore.

Although drilling time was short, the use of a cast-iron target appeared to have no effect on the bit. The bit penetrated approximately 15.2 cm (6 in.) into the billet and showed no visible wear on any of the carbides.

These test results indicate that off-the-shelf industrial hammers will not operate at geothermal temperatures but that there is no fundamental obstacle to their modification. Replacing the plastic valve parts with something else is not a trivial problem, because it is very important that the parts have the kind of fatigue-resistant resilience that the plastic gives. This design work can be done if a study of drilling economics shows that the high penetration rate of percussion justifies further development.

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