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Geothermal Drilling and Completion Technology Development Program Quarterly Progress Report October 1980 - December 1980

James R. Kelsey, Editor

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GEOHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM
QUARTERLY PROGRESS REPORT

October 1980-December 1980

James R. Kelsey
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.

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GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM QUARTERLY PROGRESS REPORT

October-December 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 problems, research goals have been set for the program.

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 an increased emphasis on advanced system development is anticipated as time progresses and resources permit.

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 through contracts with private industries and universities. Many projects are conducted internally by Sandia.

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

2. HIGHLIGHTS

- Stratapax™ Bit Field Test -- On 18 and 19 October 1980, the final scheduled Stratapax™ bit field test was carried out at The Geysers, California, using a type S-2B Stratapax™ bit. The test results were negative. The outer portion of the bit cutting structure wore severely, and there was no measurable penetration during the test. Several possible failure mechanisms were proposed, and a program was established to identify the principal cause of the failure.

- Wellbore Inertial Navigation System (WINS) -- This project was initiated early in the first quarter of FY81. The objective of this project is to provide a system that is capable of making an accurate positional survey of a wellbore. The first field test of WINS is scheduled for July 1981 at the Nevada Test Site.

- Nitrogen/Drill Pipe Corrosion Test -- During the drilling of Baca Well No. 22 in November 1980, air and nitrogen were used alternately as the principal components of the drilling fluid. The results from the corrosion rings that were installed at tool joints inside the drill pipe indicated that the corrosion rates were at least an order of magnitude lower when nitrogen was used.

- Cavitation Descaler Field Test -- The cavitation descaler tool was field tested at Imperial Magma's Woolsey No. 1 Well, Niland, California, in November 1980. The following conclusions were reached as a result of the field test:

1. The lead sulfide scale could be removed successfully from the casing walls using the tested technique.
2. The minimum operating pressure utilized during this test to remove the scale was 34 MPa (5,000 psi).
3. Even at the 34-MPa (5,000-psi) operating pressure, an injection rate of 1.5 m/min (5 ft/min) could be maintained. This injection rate corresponds to a cleaning rate of 0.957 m²/min (10.3 ft²/min).

- Completion Technology Life Cycle Cost Model -- This project was initiated late in the first quarter of FY81. Its objective is to provide a model that will evaluate the cost of current completion technology, the areas needing development, and the cost benefit of new technology.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

3. MANAGEMENT

Systems Analysis

The following lists several of the systems analysis activities that were completed this quarter:

1. A paper, Geothermal Well Costs and Their Sensitivities to Changes in Drilling and Completions Operations (SAND80-1724C), summarizing the study of geothermal well costs, was submitted for presentation at the International Conference on Geothermal Drilling and Completion Technology in January 1981.
2. The trouble-free representative well models were completed for the principal geothermal resource areas. The work on these models was done primarily by Livesay Consultants.
3. The survey of future geothermal drilling requirements was completed, and a draft report was submitted. G. Brown of BDM, Albuquerque, New Mexico, was the principal investigator.
4. The analysis of erosion drilling was concluded by Foster-Miller Associates. A draft report of this work has been received.

A number of major on-going activities continued through this quarter, including the following:

1. Analyzing new technologies from the standpoint of estimating the progress the program is making toward achieving its goals.
2. Modeling and characterizing the impacts of drilling and completion problems on well costs.
3. Studying the economic ramifications of various wellbore descaling techniques. A draft report submitted by Resource Technology, Inc., during the previous quarter was reviewed by Sandia and by outside consultants. New material was gathered from sources in the Imperial Valley this quarter, and the expanded economic comparison should be completed in the next quarter.
4. Analyzing the performance of potential systems and components for percussion drilling for geothermal resources. Preliminary results obtained in previous quarters are being updated.

Two significant activities were begun this quarter.

1. BDM and Keplinger and Associates were funded to model the life-cycle costs and benefits of various geothermal completion methods and technologies and
2. Resource Technology, Inc., has begun an investigation of the techniques for and the economics of flexible-pipe drilling.

Visit by Representatives of Shell Oil Company

J. Smith, Supervisor of Drilling Research, and W. Bingman, Chief Drilling Consultant, Shell Development Co., visited Sandia National Laboratories (SNL) on 18 and 19 November 1980 to discuss Sandia's drilling research program. Sandia's staff presented a review of the entire program, and the Shell visitors were very complimentary about the thrust and quality of the program. The visitors indicated that they knew of no other programs in the industry that overlap Sandia's program. A special interest was shown in the Stratapax™ bit development activities and the well-bore thermal simulator code, GEOTEMP. Shell had planned to develop a similar code, but, as a result of the visit of their representatives, the company has decided not to enter into this development but to obtain a copy of Sandia's model for Shell's use. J. Smith presented an overview of Shell's drilling research activities. The total Shell/United States effort in drilling research comprises 14 people and \$1,500,000 for 1981. Shell is concentrating on the design of tubular goods for hostile environments containing H₂S, drilling characteristics of shale, oil-based mud research, and the problems of the differential sticking of drill pipe. In addition, noninvading pressure coring fluids are being developed. Sandia staff members involved in the coring fluid work will visit Shell Development Co. in the near future to further explore this topic.

Department of Energy (DOE)/ENEL Workshop

S. Varnado and R. Salzbrenner of SNL attended the Second DOE/ENEL Workshop on Geothermal Research, which was held in Berkeley, California, 20 and 21 October 1980. ENEL is the electric power organization in Italy. DOE signed a cooperative agreement on geothermal research with the Italians in 1975, and the agreement recently was renewed. At the meeting in Berkeley, the session on deep drilling was devoted to a discussion of the problems that are being encountered by the Italians in drilling at depths below 3,000 meters (914 feet) and at temperatures in excess of 400°C (752°F). Presentations on drilling problems in The Geysers were made by United States representatives. The main problems encountered by the Italians involve drill pipe corrosion at these extreme depths and temperatures. A program for future cooperative R&D was outlined by the United States and Italian chairmen. The program will involve mutual studies of the corrosion of drill pipe steels in simulated downhole conditions, of lost circulation control methods, and of the fabrication and testing of experimental drill bits. This joint research activity will involve the exchange of reports, papers, and other information and, possibly, reciprocal visits between the United States and Italian members.

Drilling Hardware

Laboratory and Field Tests of Stratapax™ Bits -- On 10 August 1980, two 22.2-cm (8-3/4-in.) General Electric (GE)/Smith Stratapax™ bits designed by GE, Schenectady, New York, and built by Sii Smith Tool, Irvine, California, under DOE funding were tested in a well at Union's Baca location No. 1 in Sandoval County, New Mexico. Over a period of several hours, the two bits drilled only 7 feet into a volcanic tuff formation. Close examination of the bits revealed that the 14 center cutters were not protruding far enough from the bit body to achieve a high penetration rate. This condition was due to a manufacturing error. Two new bits modified to correct this error were manufactured. One of the bits from the Baca test and one of the new modified bits were laboratory tested in Carthage marble at Terra Tek, Inc., Salt Lake City, Utah, on 8 September 1980. As expected, the new modified bit drilled 8 to 11 times faster than the old bit under identical drilling conditions. Therefore, the lab test confirmed that the problems encountered in the Baca field test were indeed caused by the incorrect standoff of the 14 center cutters.

On 19 October 1980, the modified GE/Smith 22.2-cm (8-3/4-in.) diameter Stratapax™ bit was field tested at The Geysers in Union Geothermal's LF-30 well. The test was conducted in a graywacke formation at 2,042 meters (6,700 feet), using air as the drilling fluid. The bottomhole temperature was about 260°C (500°F). The bit reamed approximately 7.6 meters (25 feet) of hole to reach bottom and then stopped drilling. A preliminary inspection of the bit indicated that 16 of the 18 outer Stratapax™ cutters had become detached and that the carbide studs had been worn down to the steel bit body. A comprehensive failure analysis will be conducted by Sandia and GE to determine the cause of the loss of the cutters. Currently, it is believed that either the GE LS-braze was weakened by the temperature or that the braze was not properly applied.

Dyna-Drill Turbo Drill Test at Fenton Hill -- Two 17.8-cm (7-in.) diameter downhole turbines manufactured by Dyna-Drill, Irvine, California, were tested in the 31.1 cm (12-1/4 in.) segment of the EE-3 hole being drilled by Los Alamos National Laboratory at Fenton Hill. The 7.3-meter (24-foot) long directional turbine was run at about a 1,950-meter (6,400-foot) depth. The turbine demonstrated its capability to drill in the formation using a carbide-button rock bit by drilling about 3.0 meters (10 feet) at a rate of 3.7 m/h (12 ft/h). Drilling was limited to 3.0 meters (10 feet) because the steering "EYE" tool manufactured by Scientific Drilling Control was not functioning properly. At a depth of 2,560 meters (8,400 feet), the 14.6-meter (48-foot) straight-hole turbine was placed in the hole. This turbine reamed about 30.5 meters (100 feet) of hole but never actually reached bottom because of tight hole conditions. The stabilizer mounted on the turbine by Los Alamos caused the assembly to bind in a tight area that was more than 305 meters (1,000 feet) 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 the request of Los Alamos at a depth of approximately 3,048 meters (10,000 feet). Sandia is providing these turbines for Los Alamos under a lease agreement with Dyna-Drill to obtain data on turbine performance.

Drilling Fluids

Foam Drilling Fluid in Underpressured-Gas Formation -- Three pressure cores were successfully taken from a west Texas underpressured-gas formation at a 3,048-meter (10,000-foot) depth and an 8.62-MPa (1,250-psi) pressure using a foam drilling fluid. This was the first time that a pressure coring operation used foam to reduce wellbore pressure overbalance. Many oil and gas reservoirs are underpressured. The use of foam should give better estimates of in situ fluids. A Sandia-designed core bit with polycrystalline diamond compact (PDC) cutters was used in this operation. The bit cut at rates up to 30 cm/min (1 ft/min) in dolomite rock. A bromide-brine-based, low-invasion coring fluid, another Sandia development, was also used for the first time while these cores were taken. This fluid does not alter the core chloride content, and the bromide may be used as a tracer.

University of Oklahoma (U of O)

Mud Flow Loop -- Two reports presenting data obtained in the flow loop are being prepared. These reports will show

1. That the flow loop is well-designed and is capable of stabilizing the drilling fluid and subjecting it to the desired flow conditions and operating temperatures, currently up to 288°C (550°F), and
2. That, when comparisons are made between the fluid rheological properties measured in the flow loop and those measured in a Fann rheometer, large differences are evident.

Item 2 demonstrates the importance of testing fluids at conditions that approximate those encountered downhole. Consequently, the publication of these reports will make potential users aware of the flow loop's capabilities and of the importance of testing drilling fluids under downhole conditions.

A suggestion was made that the mud flow loop be moved to a location at which there is a stronger emphasis on drilling fluid research. The DOE maintains that, in order to move the loop, the following requirements must be satisfied:

1. A program must be established for the use of the loop to justify the move,
2. The loop must be made available to industry, and
3. The required maintenance must be guaranteed.

Because a program does not exist that satisfies these requirements, the loop will stay at the University of Oklahoma.

In order to insure that the flow loop is available on a timely basis, it was recommended that Sandia write a small contract with U of O that will allow U of O to maintain the loop. The cost of this contract will be

\$6,000 to \$10,000 per year. As part of the maintenance contract, improvements could be made in the loop. E. Blick of the U of O staff believes additional efforts are needed to improve the reliability of the pressure measuring system in the tube viscometer. The readings in the present system are erratic at times. Also, he believes the method of calibrating the pressure transducers should be examined and possibly improved. Both of these efforts could be conducted as part of the maintenance contract.

L. Carney recently cycled mud samples through the flow loop at Magcobar in Houston, Texas. The Magcobar loop was capable of heating the drilling fluid to 218°C (425°F). Carney indicated that he may want to repeat this experiment at higher temperatures. To achieve a higher temperature, the U of O flow loop would have to be used. These programs point out the importance of having a flow loop available to outside users on a quick-turnaround basis.

Advanced Drilling Systems

Flexible Drill Pipe Program -- A recent trip was taken to Coflexip in Houston, Texas, to discuss activities directed at upgrading the temperature capability of their flexible drill pipe. A French Coflexip technical consultant reviewed the testing method Sandia is using to screen existing elastomeric products used with Coflexip pipe that has geothermal applications. The French are interested in cooperating in Sandia's development activities.

Lost Circulation Control

Lost Circulation/Cementing Test Facility (LC/CTF) -- Personnel from Halliburton, Inc., were recently asked to comment on the current design of the LC/CTF, which is planned for construction at Sandia's facility in Albuquerque, New Mexico. Critical comments that were made regarding pump capacities, tank designs, and core preparation resulted in the incorporation of design modifications. Halliburton personnel indicated a willingness to continue to participate in reviewing Sandia's design.

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. 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 improvements in materials 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 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 meters (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 meters (41.6 feet); (2) weight on bit, 28 kN (6,400 pounds); and (3) rate of penetration, 1.2 m/h (4.0 ft/h). A second field test was conducted in September 1979, at which time 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, as had occurred in the second field test, a rapid wearing of the chain link cutting surfaces occurred in the third field test, and the bit wore out quickly in the hard granite formation. The chain link seals are suspected of being the cause of the rapid wear and will be studied next quarter. Also, the use of investment castings to make chain link bases and matrix pads is being investigated.

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 1,676 to 1,707 meters (5,500 to 5,600 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 meters (50 feet) each, bit lifetime could not be established. Additional development and testing are planned to quantify and maximize bit lifetime and to optimize the bit design.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

———— ACTIVITY PERIOD
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○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

4.1 Continuous Chain Bit

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

Project Objective

The objectives of this project are 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 the Nevada Test Site (NTS) during the period 5-20 June 1979 (field test I). 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 was made that field repair of the drills could not be accomplished. 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 predrilling, 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). As occurred in field test II, a rapid wearing of the chain link cutting surfaces also occurred in field test III. The chain link seals are suspected of being the cause of the rapid wear and will be studied during laboratory testing in February and March 1981. The analysis of the data is in progress. A parallel effort to develop an all-PDC chain link is continuing. The use of investment castings to make chain link bases and matrix pads is being investigated.

Quarterly Progress

Drilling Performance Investigation -- An in-depth review is being conducted of the three drilling field tests that were carried out at NTS and of the two laboratory tests, one preceding and one following the field tests, that were conducted at the Drilling Research Laboratory (DRL) Salt Lake City, Utah. This review has entailed plotting curves of the most representative drilling test to allow the comparison of such parameters as penetration rate, bit weight, torque, and mud pressure versus drilling depth. Detailed mechanical inspections were completed on the chain links and on the drill bit heads used in the tests. The emphasis in the inspection was placed on the following aspects:

1. The variation in the spherical contour of each drilling surface,
2. The variation in the radial height of each chain link,
3. The clearance between the installed chain links and the wall of the chain link slot on the drilling head, and
4. The variation in the spherical contour of the chain link base that mates to the drilling head.

Through this inspection and data review, it has been determined that design parameters and manufacturing processes for building chain links have allowed the chain link cutting surfaces to move more than is desirable in relation to a theoretical drilling position. This variation from nominal seems to be randomly distributed in the chain link production lots used during the test period considered. Therefore, this variation is not considered the cause of the short drilling life experience in field tests II and III as compared to field test I. It was previously reported from preliminary inspection data that the tested chain links had a nonspherical contour. This information has been found to be incorrect. There was an error in the inspection set-up, which has been corrected.

Adiprene rubber O-ring seals were used in the April 1979 laboratory test and in the first field test for sealing the chain links' fluid passages to the bit head. The drilling results achieved using these seals were excellent. These rubber seals were unfortunately replaced with tungsten carbide inserts to give the chain bit a higher drilling temperature capability for future geothermal drilling applications. (See Figure 4-1.) It is now believed that this design change is the major reason for the reduced drilling life experienced in field tests II and III and in the last laboratory test. Another laboratory drilling test is now scheduled--for the weeks of 23 February and 2 March 1981--to determine what can be achieved with the use of rubber seals. This design change was not a major suspect prior to the last laboratory test for two reasons:

1. Link set No. 18, using carbide inserts, drilled 9.1 meters (30 feet) when tested in field test I.
2. The internal rupture of the two chain bit bodies in field test II seemed to be so serious a matter that the chain link seal problem was overshadowed.

Spinoff from this data review and from the inspection of the chain link has occurred. Changes will be made in the drilling head and in the manufacturing processes for building the PDC chain bit to improve the performance of these components.

PDC Chain Links -- The reworking of the chain bit body and the fabrication of new piece parts that are required to modify the changing mechanism have been completed, and the components are ready for assembly. A new drilling head was designed that will position the cutter pattern within 0.10 to 0.20 mm (0.004 to 0.008 in.) of the nominal drilling position as compared to the 0.33 to 0.69 mm (0.013 to 0.027 in.) that was used previously. Purchase orders are in process for building the bit head and also the matrix pads, which hold the PDCs. Christensen, Inc., Salt Lake City, Utah, has agreed to assemble the chain links if Sandia will furnish the parts. This offer is appreciated because the five major diamond bit

Figure 4-1. Comparison of Chain Link Seals. The side of the chain links shown makes contact with the bit head.

companies did not submit a bid for the previous order to assemble PDC chain links. The chain link assembly activity is considered to be progressing on schedule.

Investment Casting Evaluation -- The use of investment castings to make chain link bases and matrix pads, which hold the natural diamonds or PDCs, looks promising for reducing the manufacturing cost of building chain links. For example, the unit cost for a machined link base is \$177, whereas the estimated cost of an investment cast link for production quantities to include finish machining and tooling is \$60. The use of production quantities creates a savings of \$117 per link base or \$5850 per chain bit. This type of savings will significantly enhance the economic advantages when the cost of using a chain bit is compared with the cost of using a commercial drill bit.

Tooling samples of an investment casting of the chain link base made by Consolidated Casting, Dallas, Texas, have been received and evaluated for dimensions and metallurgical properties. Some reworking of the tooling will be made before limited quantities are run, but, overall, the castings look very promising. A destruction test to evaluate the ultimate strength of the link bases was performed late in this quarter. The results will be reported in the next quarterly report.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>PDC BIT DEVELOPMENT:</u> <u>GENERAL ELECTRIC</u> FIELD TESTING DESIGN MODIFICATION PERFORMANCE AND ECONOMIC ANALYSIS CONTRACTING	<div> </div> <div> COMPLETED </div> <div> <div>EXTENSION</div> </div> <div> <div>EXTENSION</div> </div>												

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 ▼ COMPLETED

4.2 Geothermal Polycrystalline Diamond Compact Drill-Bit Development

Contractor: General Electric Company, Corporate
Research and Development (CRD)
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 30 June 1976 to 31 March 1981
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 the laboratory testing of full bits. Single-cutter tests were run at simulated downhole conditions, and the data were analyzed. Because of the catastrophic failure that occurred during the November 1978 field test, the S-1, modified, bit, was redesigned and fabricated. 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.

Two S-2A bits were designed and fabricated for testing in the Baca field using aerated water as the drilling fluid. Subsequent testing at the Baca location and then in the lab revealed a fabrication error of the S-2A bits.

Two S-2B bits were designed and fabricated for testing in The Geysers, California, using air as the drilling fluid. One of the S-2B bits was lab tested with good results; however, when tested at The Geysers, the other S-2B bit experienced excessive wear. Investigation as to the cause of this wear is continuing.

Quarterly Progress

Baca Field Tests -- On 10 August 1980 the two 22.2-cm (8.75-in.) S-2A Stratapax™* diamond compact bits fabricated by Sii Smith Tool, Irvine, California, were tested in the field at Baca Location No. 1, Sandoval County, New Mexico. Unlike the drilling test performed in the same area in October 1979 with the 21.6-cm (8.5-in.) diameter S-1, modified, Stratapax™ bit, with which very high penetration rates were achieved during the drilling of andesite, the results of these experiments during the drilling of Bandelier tuff were negative. Only about 2.1 meters (7 feet) of hole was made over a period of several hours with two bits, Smith Tool bits Nos. SPX-013 and SPX-014. Many possible reasons for the poor drilling performance were proposed during the period of testing, including differences in fracture characteristics of the volcanic tuff as compared with the fracture characteristics of andesite, pinching of the bit gage, and gage cutter wear that allowed the bit body to bottom out. However, careful examination of the bits showed that the lack of Stratapax™ cutter standoff from the bit body for the 14 cutters in the center of the cutting face was the reason the bits would not drill. Penetration by these cutters, particularly by the No. 1 cutter tangent to the center of rotation, was so limited that the stresses necessary to fracture the formation could not be achieved before the center inverted conical section of the body contacted the rock; this condition effectively limited the applied stress and also blocked any fluid flow through the central nozzle. Thus, the bits rested on a combination of fine rock chips and solid rock confined to the center section of the cutting structure and could not penetrate except by a very slow rock wearing mechanism.

The reduction in cutter standoff for the center 14 cutters resulted from a fabrication error. The type S-2A bit design was a modification of the successful type S-1, and relatively extensive changes were made, including the cemented tungsten carbide stud design and the rake angle design for cutters Nos. 15 through 39 on the cutting face, a slight reduction in standoff for these cutters, and the addition of two types of Stratapax™ diamond compact gage trimmers and of 16 diamond compact gage wear pads. However, no design changes were intended for the central conical section of the bit. This cutting structure was supposed to have remained identical to the structure of the type S-1, modified, design. Unfortunately, the incorrect cutter structure was not recognized until after the field test.

The bit tested before the first Stratapax™ bit was a Smith Tool 22.2-cm (8.75-in.) diameter carbide-button rock bit, type 5GA. This bit drilled 161 meters (529 feet) in approximately 16 hours rotating time, or approximately 9.8 m/h (32 ft/h), at 70 rpm with 22,700 kg (50,000 lb) of weight on the bit. The drilling fluid was water pumped at 1.15 m³/min (304 gal/min) and air pumped at 29.7 m³/min (1,050 ft³/min). The bottom-hole assembly included a three-point reamer immediately above the bit, a monel collar, three stabilizers, a shock sub, and 16 drill collars each 16.5 cm (6.5 in.) in diameter. The total string weight at 1,331 meters (4,367 feet), when this bit was removed, was 56,700 kg (125,000 lb). The

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same bottomhole assemblies, with new three-point reamers, and the same hydraulics were used for both Stratapax™ bits, except that the shock sub was removed before the testing of the second experimental bit.

The 5GA rock bit was under gage between 3.18 and 6.35 mm (0.125 and 0.25 in.) after use. One cone was frozen, and the other two were very loose due to bearing wear. Consequently, the first Stratapax™ bit, No. SPX-013, had to ream the final 110 meter (360 feet), which is equivalent to 12 joints of drill pipe, to reach bottom at 1,331 meters (4,367 feet). Reaming was done at 40 rpm with the weight on bit varying but restricted to a maximum of 2,270 kg (5,000 lb). Almost 6 hours were required in order to ream, including a 15-minute period of rotation with no bit weight, when circulation was temporarily lost. Initially, torque was 150 relative, on a scale of 500, and increased to 200 for the last hour.

The original plan for testing the first Stratapax™ bit was to try several rotary speeds, varying the bit weight to identify a near optimum rpm/weight combination, and then run the bit at this condition for 8 to 10 hours. The bit would then be removed and examined. However, the penetration was so slow and sporadic that no rpm/bit-weight/penetration rate relationships could be determined. A total of 19 rpm/bit-weight combinations was tried, covering an rpm range from 40 to 80 and a bit weight range from 2,270 to 13,600 kg (5,000 to 30,000 lb). The torque varied from 140 to 240, relative, but there was no correlation with rpm or the weight on the bit. After about 1.5 meters (5 feet) total penetration, this bit was removed for examination. The bit was approximately 3.2 mm (0.125 in.) under gage due to the wearing of the four principal gage cutters. Other than this wear, apparently due to the reaming of 110 meters (360 feet) before bottom was reached, there was no obvious damage. The bit was essentially in a "green" condition.

Because it was not clear at the time of the test why the first bit did not drill effectively, the second Stratapax™ bit, Smith Tool No. SPX-014, was put in the hole. For this test, the shock sub was removed from the bottomhole assembly. The trip in had to be halted 61 meters (200 feet) from the bottom, a distance equivalent to almost seven joints of drill pipe, to attach the kelly, start circulation, and commence reaming. After reaming for approximately 15 minutes, the Union drilling engineer decided to try to push the bit down the hole. After rotation and circulation were stopped, the remainder of the first joint and three additional joints were dropped into the hole, using up to 11,300 kg (25,000 lb) of weight on bit. However, bottom could not be reached with this procedure. Rotation and circulation were reestablished, and the final 27 meters (90 feet) were finished by reaming at 50 rpm and 2,270 to 4,540 kg (5,000 to 10,000 lb) weight.

Bit No. SPX-014 behaved exactly like bit No. SPX-013 when drilling was commenced. Very slow, intermittent penetration was observed. Seven combinations of rpm and bit weight were tried, with the rpm being varied from 50 to 70 and the weight being varied from 6,800 to 12,700 kg (15,000 to 28,000 lb). The torque varied from 140 to 200, relative, again with no correlation with rotary speed and weight on bit. After a total penetration of about 61 cm (2 ft), the bit was pulled.

There was extensive fracture damage to the gage cutters and studs and to several cutters just inside the cutting structure periphery. There were also relatively severe damage to the gage trimmer cutters and noticeable vertical score marks on the surfaces of the junk slots. This damage apparently had been caused by the attempt to force the bit into the hole without rotation or circulation. There was no damage to the center portion of the cutting structure and no significant diamond compact wear, only the fracture damage noted above.

Design Correction for the Type S-2B Bits -- Two additional bits were fabricated by Sii Smith Tool for this program. These bits, targeted for testing at The Geysers, California, and designated type S-2B, have a cutting structure identical to that of the type S-2A bits. The two types of bits differ primarily in gage wear protection design features. The fabrication of these bits was stopped before the Stratapax™ cutters were interference fitted, and the central conical section of the bit bodies was remachined so that the cutter standoff for cutters Nos. 1 to 14 were identical to the standoff used in the type S-1, modified, bit design.

Laboratory Drilling Tests with Types S-2A and S-2B Stratapax™ Bits -- One of the type S-2A bits, bit No. SPX-013, that did not drill effectively during the field test at Baca Location No. 1, Sandoval County, New Mexico, in August 1980 was shipped by Sandia Laboratories to the Drilling Research Laboratory, Terra Tek, Salt Lake City, Utah. One of the new type S-2B bits, No. SPX-016, with the central cutter standoff design corrected was also sent to Terra Tek.

On 8 September, both bits were tested drilling Carthage marble at atmospheric pressure and using water as the drilling fluid. As expected, the type S-2A bit performed poorly, and the type S-2B bit, with the stand-off distances of the central cutters restored to the correct values, performed well. Table 4-1 gives the performance of the type S-2A bit, and Table 4-2 gives the performance of the type S-2B bit. The poor performance of the type S-2A bit drilling Carthage marble, which prior experience has shown to be easily drilled at atmospheric pressure in the laboratory, supports the conclusion that the error in the fabrication of the bit prevented the bit from performing effectively in the field. The cause of the poor performance apparently was not the Bandelier tuff formation.

The Geysers Field Test of the Type S-2B Stratapax™ Bits -- On 18 and 19 October 1980, the final scheduled Stratapax™ bit field test for this program was carried out at The Geysers, California. This test was performed with the permission and assistance of Union Oil Co., Geothermal Division, Santa Rosa, California. The test results were negative because the outer portion of the bit cutting structure wore severely during the test. Only one of the two available bits was tested; the other was shipped to the Drilling Technology Division--4741, Sandia Laboratories, Albuquerque, New Mexico, to be held there pending a decision on an alternative testing site. A brief summary of The Geysers field test and speculation on possible failure mechanisms are given below.

Table 4-1

Type S-2A Stratapax™ Bit, Bit No. SPX-013,
Drilling Carthage Marble at Atmospheric
Pressure, with Water

Fluid Flow m ³ /s (gal/min)	rpm	ROP* m/h (ft/h)	Bit Weight kg (lb)	Torque N·M (lb·ft)
0.019 (300)	50	<0.3 (<1)	2,270 (5,000)	678 (500)
		0.3 (1)	2,270 (5,000)	719 (530)
		0.9 (3)	3,400 (7,500)	1,329 (980)
		1.2 (4)	3,400 (7,500)	1,464 (1,080)
		1.2 (4)	3,400 (7,500)	1,608 (1,186)
		2.1 (7)	4,540 (10,000)	2,034 (1,500)
		1.8 (6)	4,540 (10,000)	2,034 (1,500)
		3.7 (12)	6,800 (15,000)	3,932 (2,900)
0.019 (300)	100	0.6 (2)	2,270 (5,000)	658 (485)
		1.5 (5)	3,180 (7,000)	1,085 (800)
		2.4 (8)	4,540 (10,000)	1,464 (1,080)
		4.3 (14)	5,670 (12,500)	1,885 (1,390)
		6.7 (22)	6,800 (15,000)	4,337 (3,200)
0.025 (400)	100	0.6 (2)	2,270 (5,000)	624 (460)
		2.1 (7)	4,540 (10,000)	1,424 (1,050)
		3.7 (12)	5,670 (12,500)	1,830 (1,350)
		4.6 (15)	6,800 (15,000)	2,169 (1,600)

Note: The construction of the type S-2A bit includes five 15.9-mm
(20/32-in.) diameter nozzles.

* Rate of penetration.

Table 4-2

Type S-2B Stratapax™ Bit, Bit No. SPX-016, Drilling
Carthage Marble at Atmospheric Pressure, with Water

Nozzle Diameter		Fluid Flow		rpm	ROP		Bit Weight		Torque	
mm	(in.)	m ³ /s	(gal/min)		m/h	(ft/h)	kg	(lb)	N•M	(lb•ft)
7.9	(10/32)	0.025	(400)	50	{ 8.5	(28)	2,270	(5,000)	1,627	(1,200)
					{ 13.1	(43)	3,400	(7,500)	2,305	(1,700)
					{ 17.1	(56)	4,540	(10,000)	3,376	(2,490)
7.9	(10/32)	0.025	(400)	100	{ 14.0	(46)	2,270	(5,000)	1,491	(1,100)
					{ 19.8	(65)	3,400	(7,500)	2,346	(1,730)
					{ 27.7	(91)	4,540	(10,000)	3,240	(2,390)
15.9	(20/32)	0.025	(400)	100	{ 13.1	(43)	2,270	(5,000)	1,464	(1,080)
					{ 17.8	(58)	3,400	(7,500)	2,078	(1,525)
					{ 18.9	(62)	3,400	(7,500)	2,240	(1,652)
					{ 25.0	(82)	4,540	(10,000)	3,084	(2,275)
					{ 36.6	(120)	5,670	(12,500)	3,796	(2,800)

Note: Each type S-2B bit has five nozzles.

• Field Test Summary

The type S-2B Stratapax™ bit was tested in well number L.F. 30. At the time of this test, the well was already producing steam, and drilling was being conducted, with air only, at a rate of 1.09 to 1.13 m³/s (2,300 to 2,400 ft³/min). The formation was graywacke, which is very abrasive, and the bottomhole temperature was approximately 249°C (480°F). The bit used prior to the Stratapax™ bit was a Hughes HH55, which drilled 39 meters (128 feet) in 5 hours. This bit came out of the hole 7.9 mm (5/16 in.) under gage due to the abrasive drilling conditions. A new Smith Tool 7GA bit was utilized to ream the hole before the Stratapax™ bit test, and the 7GA bit came out of the hole approximately 3.2 mm (1/8 in.) under gage.

The Stratapax™ S-2B bit, Smith Tool No. SPX-015, went into the hole at 11:30 p.m., 18 October 1980. It was necessary to connect the kelly and ream the last 9.1 meters (30 feet) to bottom. The reaming was done at 65 rpm with air, and no excessive torque was observed. The total reaming time was about 10 minutes. The bit reached the bottom, and the drilling experiment commenced at 3:56 a.m., 19 October 1980. The bottomhole depth was 2,042 meters (6,701 feet), and the hole deviation from the vertical was approximately 24°.

The initial rotary speed of the S-2B bit SPX-015 was 55 rpm. The bit weight was gradually increased in 2,268-kg increments from 2,268 kg to 11,340 kg (in 5,000-lb increments from 5,000 lb to 25,000 lb), but there was no measurable penetration. After 1/2 hour, the air pressure had increased from 2.62 MPa (380 psi) to 3.45 MPa (500 psi). When the bit was picked off the bottom, the pressure dropped to the original value, indicating that the bit might be wearing in a way that restricted the return flow of air out of the hole annulus. The rotary speed was increased to 78 rpm and the experiment repeated at 2,268, 4,536, and 6,804 kg (5,000, 10,000 and 15,000 lb) weight on bit. Again no measurable penetration was obtained, and the air pressure increased significantly with the bit rotating on bottom. At 4:49 a.m., drilling was terminated, and the trip out was begun. It should be noted that the torque remained relatively low and uniform throughout the drilling test and did not change appreciably with changes in rotary speed or weight on bit.

• Bit Wear

A preliminary examination of the bit after testing revealed that the 15 outermost cutter/stud assemblies, as measured by radial distance from the center of the bit, had worn excessively. The cemented carbide support studs for the nine outermost cutters were worn flush with the bit body, and the remaining six studs had no cutters and were worn away progressively less and less, starting with about 2/3 stud wear and ending with about 1/4 stud wear. The 10 remaining -25°-rake cutters were intact with little evidence of wear.

The central section of the bit contained 14 of the older style -20°-rake stud cutters. One of these studs had fractured, causing some minor damage to nearby -20° cutters. However, this damage was not sufficient to prevent effective drilling performance by this portion of the cutting structure.

• Possible Failure Mechanisms

Until a thorough examination and analysis is completed, it is not possible to say what the primary reason was for the rapid wear of the bit tested at The Geysers. Several possibilities can be suggested, including the following:

1. The extreme abrasive conditions, high bottomhole temperature, and very poor cooling achieved by air drilling resulted in frictional heat generation sufficient to rapidly thermally degrade the PDC cutters. However, the hot air drilling experiment performed at the Terra Tek Drilling Laboratory earlier this year on a parallel Sandia Laboratories contract, using a Stratapax™ bit, did not produce any thermal damage to the diamond compacts under very abrasive drilling conditions. Sintered diamond compact thermal degradation is not a strong failure mechanism candidate in the case of the S-2B bit SPX-015.
2. The hard, fractured formation in The Geysers initiated brittle fracture failure of the outermost cutter studs, which created a favorable condition for an avalanche of successive stud failures. The prior experience with stud fractures during field tests indicates that this was probably not the primary failure mode. Whenever massive carbide fracture has occurred, the carbide debris will remain in the cutting zone long enough to cut and machine deep grooves in the steel bit body, as well as to severely chip adjacent diamond compact cutters and support studs. There was no evidence that this process occurred on the bit run in The Geysers.
3. The drilling conditions in The Geysers are too severe for the braze attaching the Stratapax™ drill blanks to the cemented tungsten carbide studs. The hot air drilling tests at Terra Tek, mentioned previously, did demonstrate that, if sufficiently large wear flats were developed and if very high bit weights, for example 15,900 to 18,100 kg (35,000 to 40,000 lb) were used to drill hard rock, i.e., granite, the temperatures generated by rubbing could result in a loss of cutters through braze failure. However, the drilling performance at The Geysers suggests that, if Stratapax™ drill blank detachment was a major failure mechanism, it occurred at a relatively low bit weight with cutters that were not significantly worn.
4. The quality of the braze attachment of the Stratapax™ drill blanks to the special -25°-rake cemented carbide studs was poor. The shear strength/temperature relationship for the General Electric Co. "LS" bond has been determined, and quality control methods are utilized to assure that adequate bond strength is provided for standard products. The -25°-rake cutters used in the type S-2A and S-2B bits are not standard products; so it is possible that the attachment and/or quality control techniques need to be further modified to assure satisfactory bond strength.

Failure Analysis and Future Action -- A meeting was held on 10 November 1980 at Sandia Laboratories with the Drilling Technology Division--4741, at which a program was worked out to identify the principal failure mode for the bit tested at The Geysers.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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													

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

4.3 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 30 April 1981
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 polycrystalline diamond compacts (PDCs) in drill bits designed 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

The coordination of the project activities with related work and participating organizations was completed. The preparation of the test facilities and equipment was completed. Thirty-four single-cutter experiments have been completed on Nugget sandstone and Tennessee marble. Ten of these experiments were performed on Tennessee marble, using Stratapax™ cutters that contained thermocouples to measure the temperature in various areas of the cutter.

Quarterly Progress

Single-Cutter Experiments -- A total of 34 single-cutter experiments has been carried out using the newly installed 54-inch vertical turret lathe (VTL) that was modified for rock cutting. Eight rock cutting tests were unsuccessful; seven of these failures were due to malfunctions of the piezoelectric dynamometer charge amplifiers that apparently were caused by excessive humidity during a period of very hot weather; one test was terminated because the rock shifted, resulting in a varying depth of cut. The conditions of the 26 tests that have been carried out successfully are shown in Table 4-3.

• Rock Specimens, Cutting Pattern, and Speed

The rock specimens used are blocks approximately 0.9 by 0.9 by 0.46 meter (3 by 3 by 1.5 feet). All tests to date have been spiral cuts across the 0.9 by 0.9 meter (3 by 3 foot) face of the rock, starting from the outside and feeding the cutter toward the center of rotation. The feed is set so the cutting path does not overlap itself. Experiments

Table 4-3

Single-Cutter Experiments Using the 54-Inch Vertical Turret Lathe

Test No.	Rock			Fluid			Stratapax™ Cutter			Depth of Cut						Thermocouple Locations (Drawing No.)
	Type	Diameter		Type	Flow Rate		No.	Geometry	Edge Condition	rpm		Nominal		Cross Feed		
		cm	(in.)		m ³ /min	(gal/min)				Nominal	Actual	mm	(in.)	mm/rev	(in./rev)	
1	Nugget sandstone	45.7	(18)	H ₂ O ^a	0.024	(6.4)	1	Full round	Sharp	13	12.6	1.270	(0.050)	12.7	(0.500)	None
2	Nugget sandstone	45.7	(18)	H ₂ O	0.024	(6.4)	1	Full round	Sharp	13	12.6	0.635	(0.025)	12.7	(0.500)	None
3	Nugget sandstone	45.7	(18)	H ₂ O	0.024	(6.4)	1	Full round	Sharp	13	12.6	2.540	(0.100)	12.7	(0.500)	None
4	Nugget sandstone	45.7	(18)	H ₂ O	0.024	(6.4)	1 ^b	Full round	Sharp	13	12.6	0.3175	(0.0125)	6.2	(0.245)	None
10	Nugget sandstone	45.7	(18)	Air	---	---	3	Full round	Sharp	13	12.6	1.270	(0.050)	12.7	(0.500)	None
11	Nugget sandstone	45.7	(18)	Air	---	---	3 ^b	Full round	Sharp	13	12.6	2.540	(0.100)	12.7	(0.500)	None
12	Nugget sandstone	45.7	(18)	Air	---	---	4	Full round	Sharp	13	12.6	0.3175	(0.0125)	12.7	(0.500)	None
13	Nugget sandstone	45.7	(18)	Air	---	---	4 ^b	Full round	Sharp	13	12.6	0.635	(0.025)	12.7	(0.500)	None
14	Tennessee marble	45.7	(18)	Air	---	---	5	Full round	Sharp	13	12.6	0.3175	(0.0125)	12.7	(0.500)	None
15	Tennessee marble	45.7	(18)	Air	---	---	5	Full round	Sharp	13	12.6	0.635	(0.025)	12.7	(0.500)	None
17	Tennessee marble	45.1	(17.75)	Air	---	---	5 ^b	Full round	Sharp	13	12.6	1.270	(0.50)	12.7	(0.500)	None
18	Tennessee marble	45.7	(18)	Air	---	---	51	Full round	Sharp	13	12.6	2.540	(0.100)	12.7	(0.500)	None
20	Tennessee marble	45.7	(18)	H ₂ O	0.024	(6.4)	51 ^c	Full round	Sharp	13	12.6	0.3175	(0.0125)	12.7	(0.500)	None
21	Tennessee marble	45.7	(18)	H ₂ O	0.024	(6.4)	52	Full round	Sharp	13	12.6	0.635	(0.025)	12.7	(0.500)	None

^aOil solution, 1 part oil with 40 parts H₂O^bCutter removed for examination^cCutter went past center and fractured

Table 4-3 (Continued)

Single-Cutter Experiments Using the 54-Inch Vertical Turret Lathe

Test No.	Rock Type	Rock Diameter		Fluid Type	Fluid Flow Rate		Stratapax [™] Cutter			rpm		Depth of Cut		Cross Feed		Thermocouple Locations (Drawing No.)
		cm	(in.)		m ³ /min	(gal/min)	No.	Geometry	Edge Condition	Nominal	Actual	mm	(in.)	mm/rev	(in./rev)	
22	Tennessee marble	45.7	(18)	H ₂ O	0.024	(6.4)	52	Full round	Sharp	13	12.6	1.270	(0.050)	12.7	(0.500)	None
23	Tennessee marble	45.7	(18)	H ₂ O	0.024	(6.4)	52	Full round	Sharp	13	12.6	2.540	(0.100)	12.7	(0.500)	None
24	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	13	12.6	0.635	(0.025)	12.7	(0.500)	T-1
25	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	13	12.6	12.70	(0.500)	12.7	(0.500)	T-1
26	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	13	12.6	12.70	(0.500)	12.7	(0.500)	T-1
27	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	13	12.6	6.223	(0.245)	6.2	(0.245)	T-1
28	Tennessee marble	45.1	(17.75)	H ₂ O	0.024	(6.4)	6	Full round	Sharp	31	30.15	12.70	(0.500)	12.7	(0.500)	T-1
29	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	31	30.15	12.70	(0.500) ^f	12.7	(0.500)	T-1
30	Tennessee marble	45.7	(18)	Air	---	---	6	Full round	Sharp	31	30.15	12.70	(0.500)	12.7	(0.500)	T-1
31	Tennessee marble	45.6	(17.98)	Air	---	---	6	Full round	Sharp	31	30.15	12.70	(0.500)	12.7	(0.500)	T-1
33	Tennessee marble	45.7	(18)	Air	---	---	8 ^d	Flat on flank edge,	Sharp	13	12.6	12.70	(0.500)	12.7	(0.500)	T-2
34	Tennessee marble	45.7	(18)	Air	---	---	8 ^e	ground back 1.2 mm (0.047 in.)	Sharp	13	12.6	12.70	(0.500) ^g	12.7	(0.500)	T-2

^dNo end clearance, flat rubs on rock^eCutter attachment failed during test^fActual depth of cut questionable^gActual depth of cut = 0.48 mm (0.019 in.)

performed at 12.6 rpm have a maximum cutting speed of 36.0 m/min (118 ft/min), and those done at 30.15 rpm have a maximum cutting speed of 86.6 m/min (284 ft/min). The rpms are sufficient to exceed the speed of the gage cutters on a 22.2-cm (8.75-in.) diameter bit operating at 100 rpm. Without a change of the wiring on the VTL motor, the machine has a nominal maximum rotary speed of 56 rpm, which can produce a maximum cutting speed of 161 m/min (527 ft/min) if higher speeds are necessary.

• Cutter Fabrication and Geometry

The PDC cutters used are General Electric Stratapax™ blanks, Product No. 2550, attached to Carboloy grade 55B cemented tungsten carbide studs, as shown in Figure 4-2. The back rake for this stud/cutter configuration is -20° . Note that, for this work, the usual 5° end clearance has been increased to at least 20° in all cases. Additional grinding of the studs may be necessary in some test cases to assure that minimal contact exists between stud and rock. Because it is easier to grind the end clearance on the studs before attaching the diamond compacts, hand-brazing of the Stratapax™ blanks with Easy Flo-45 has been used up to this point in the program. However, in cases where very high cutter temperatures are generated, a higher strength attachment such as the "LS" bond may be necessary. (Note in Table 4-3 that in Test No. 34 the attachment failed.)

Some diamond compact cutters will be artificially "worn" by grinding in order to generate known areas of flat regions on the tool flanks; the flat regions will rub against the rock. These cutters will be used in conjunction with thermocouples that are inserted at specific places within the diamond compact cutters and the studs to obtain quantitative temperature information to support the cutter temperature modeling studies of A. Ortega at Sandia Laboratories. Several sharp and several artificially worn cutters have already been prepared, as shown in Figures 4-3 and 4-4. The holes to admit the thermocouples are 1.0 mm (0.040 in.) in diameter and were made by electrical discharge machining. (Note Tests Nos. 23 and 34 in Table 4-3).

• Data Acquisition and Data Reduction

The experimental arrangement has been set up to collect all cutting force and temperature data on magnetic tape. The collection of these data is accomplished by means of a Fluke data logger, which sequentially reads the piezoelectric dynamometer voltages and the thermocouple voltages and converts the data to digital form. The digital data are transmitted, along with a time signal for each data sampling cycle, to a Texas Instruments Silent 700 Terminal, where the information is recorded on tape.

After being recorded, the raw experimental data from the data logger can be read into the main Honeywell computer at CRD, but the data must be extensively reformatted in order to be analyzed. The reformatting is accomplished using software developed by D. Priest of CRD, which he has modified specifically for this application. In addition, software has been developed to (1) remove unwanted, spurious signals originating in the raw data recording system, (2) convert the dynamometer voltage output to forces, including corrections for charge amplifier drift that can become large at times, (3) print the experimental results in suitable form for

MATERIAL: CARBOLOY GRADE 55B

Figure 4-2. Cutter/Stud Specification; -20° Back Rake, 5° End Clearance

Figure 4-3. Thermocouple Locations in a Sharp Stratapax™-Cutter/Stud

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

either visual examination or further computer utilization, and (4) manipulate the data file for the purpose of plotting through the use of existing computer graphics hardware.

An example of part of a raw data file that has been reformatted for further computer use is shown in Figure 4-5. These same data are shown in Figure 4-6, after the actual cutting forces, the cutting speed, and the cutting path diameter have been calculated, in the format suitable for visual examination or further computer use. A computer-generated plot of cutting forces for this same experiment is shown in Figure 4-7.

Preliminary Observations of Single-Cutter Experimental Results -- the first 23 cutting tests were performed, using sharp, full round cutters without thermocouples, to check out the machine operation and experimental technique. Seven of these tests failed due to electronic data collection malfunctions. The signal drift characteristics of the charge amplifiers were recognized during this period, and methods to correct for drift were developed.

In spite of early experimental problems, 16 successful tests were completed, comprising four sets of four tests; in each test, wet and dry samples of Nugget sandstone and Tennessee marble were cut. (See Table 4-3, Tests Nos. 1 through 4, 10 through 15, 17 and 18, and 20 through 23.) The data from this series of tests have been reduced only to the extent necessary to indicate that the results are consistent and that the cutting forces observed will serve as useful baseline information with which to compare information obtained from future experiments concerning worn tools and different fluid environments.

Preliminary examination of the diamond compact cutters used for these baseline tests indicates that the wear rate occurring during the cutting of Tennessee marble will be very slow. There is an indication that the Nugget sandstone will prove somewhat more abrasive. However, the deliberate developing of worn cutting edges while instrumented rock cutting experiments are being carried out is probably not feasible, and additional techniques will have to be worked out if the effect of cutter wear on performance is to be evaluated using tools that have actually been worn by the cutting of rock. The alternative is to artificially "wear" the cutters by grinding. This approach is necessary to provide cutters for tests to validate the Ortega temperature model but is not desirable if the single-cutter experiments are expected to simulate the conditions existing in real drilling operations.

• Preliminary Cutting Temperature Measurements

Ten experiments have been performed cutting Tennessee marble with Stratapax™ cutters containing thermocouples. (See Table 4-3, Tests Nos. 24 through 34.) Eight of these tests have been performed using a sharp tool, and two were performed with a cutter that had a wear flat generated by grinding. (See Figures 4-3 and 4-4 for the thermocouple locations in these cutters.) One of the sharp cutter tests was done using a water coolant, and the remainder of the experiments were run in air.

These 10 rock cutting tests do not make up a complete set of experiments. The tests were performed to (1) check out the reliability of the

TEST 26 8/28/80 TENN MARB ROCK RADIUS 17-3/4" DRY CUT (5) TC									
3RD TEST W/SX.6 13RPM .100" DEPTH .500" FEED CUTTER SHARP									
FORCE	CAL	X= 20LBS/V	Y&Z= 100LBS/V	CHART		.2"/SEC		1V=1/2"	
10,	0.076,	0.003,	0.012,	23.00,	23.00,	23.10,	23.10,	23.30	
12,	0.075,	0.003,	0.011,	23.00,	23.00,	23.10,	23.20,	23.20	
14,	0.075,	0.003,	0.012,	23.10,	23.10,	23.20,	23.20,	23.40	
16,	0.075,	0.002,	0.012,	23.10,	23.10,	23.20,	23.30,	23.30	
17,	0.073,	0.003,	0.009,	23.00,	23.10,	23.20,	23.20,	23.40	
19,	-0.225,	0.171,	0.303,	23.20,	23.20,	23.30,	23.20,	23.80	
21,	-1.965,	1.409,	1.638,	43.60,	40.90,	36.00,	23.80,	30.30	
23,	-1.756,	3.067,	3.366,	97.90,	80.90,	61.50,	27.00,	44.60	
24,	-0.029,	3.765,	3.768,	99.60,	98.90,	93.50,	33.00,	63.80	
26,	-0.320,	3.484,	3.828,	100.50,	100.00,	99.60,	40.30,	80.20	
28,	-0.577,	3.743,	3.780,	100.50,	100.40,	99.40,	47.30,	92.30	
30,	-0.824,	3.120,	3.153,	100.10,	99.90,	98.90,	53.20,	98.40	
31,	-0.433,	3.419,	3.687,	100.60,	100.20,	99.20,	58.10,	99.10	
33,	-0.470,	3.768,	3.838,	101.20,	100.60,	99.60,	62.50,	98.80	
35,	-0.752,	3.491,	3.663,	101.10,	100.80,	100.20,	66.50,	99.50	
37,	-0.417,	3.531,	3.822,	101.60,	101.50,	100.70,	70.00,	100.10	
38,	-0.630,	3.549,	3.851,	101.30,	101.00,	100.50,	72.90,	99.80	
40,	-0.404,	3.350,	3.453,	101.50,	101.20,	100.50,	75.80,	100.60	
42,	-0.646,	3.472,	3.483,	102.00,	101.60,	100.80,	78.30,	100.00	
44,	-0.544,	3.545,	3.459,	102.10,	101.70,	100.60,	80.60,	100.30	
46,	-0.649,	2.932,	3.001,	101.50,	101.50,	100.30,	82.70,	100.60	
47,	-0.636,	3.598,	3.845,	102.70,	102.40,	101.50,	84.60,	100.00	
49,	-0.255,	3.595,	3.508,	101.50,	101.40,	100.60,	86.00,	98.50	
51,	-0.447,	3.502,	3.568,	100.40,	100.30,	99.40,	87.70,	99.10	
53,	-0.714,	3.933,	3.811,	100.80,	100.10,	99.70,	89.40,	99.60	
54,	-0.523,	3.059,	3.055,	100.30,	100.30,	99.60,	90.90,	99.20	
56,	-0.468,	3.124,	3.494,	100.90,	100.60,	100.20,	92.20,	99.20	
58,	-0.380,	3.427,	3.336,	100.30,	99.90,	99.00,	93.30,	99.30	
60,	-0.611,	3.632,	3.863,	100.90,	100.60,	99.90,	94.50,	99.60	
61,	-0.622,	3.382,	3.459,	101.20,	101.10,	100.50,	95.60,	99.30	
63,	-0.771,	3.471,	3.891,	100.60,	100.20,	99.30,	96.30,	98.80	
65,	-0.675,	3.200,	3.412,	100.60,	100.70,	100.10,	96.80,	99.40	
67,	-0.584,	3.076,	3.218,	100.30,	100.40,	99.80,	97.50,	98.80	
69,	-0.657,	3.531,	3.363,	100.10,	100.00,	99.50,	97.80,	99.50	
70,	-0.421,	3.675,	3.707,	100.20,	100.10,	99.40,	98.30,	98.50	
72,	-0.584,	3.878,	3.971,	99.70,	99.60,	99.00,	97.90,	98.60	
74,	-0.571,	3.487,	3.492,	100.60,	100.40,	100.00,	99.00,	99.70	
76,	-0.169,	3.545,	3.448,	101.30,	101.20,	100.60,	99.70,	99.60	
77,	-0.731,	3.500,	3.831,	101.10,	101.00,	100.30,	99.60,	100.10	
79,	-0.559,	3.498,	3.875,	101.50,	101.50,	101.10,	100.20,	99.90	
81,	-0.579,	3.644,	3.587,	101.20,	101.10,	100.40,	99.50,	99.50	
83,	-0.297,	3.735,	4.498,	100.60,	100.60,	100.00,	99.20,	98.70	
84,	-0.547,	3.808,	4.134,	100.50,	100.50,	99.50,	98.50,	98.60	
86,	-0.688,	3.460,	3.619,	99.80,	99.70,	99.00,	98.00,	98.10	
88,	-0.465,	4.123,	3.781,	99.00,	98.80,	98.10,	97.40,	97.60	
90,	-0.428,	3.439,	3.755,	98.80,	98.80,	97.90,	97.50,	97.50	
92,	-0.577,	2.964,	2.855,	98.50,	98.40,	98.00,	97.40,	97.50	
93,	-0.824,	2.872,	3.686,	99.20,	99.10,	98.60,	97.80,	98.20	
95,	-0.912,	2.890,	3.302,	99.20,	99.30,	98.90,	98.30,	98.70	
97,	-0.766,	3.729,	3.849,	99.30,	99.40,	99.00,	97.90,	98.20	
99,	-0.224,	3.535,	3.633,	99.30,	99.20,	98.90,	98.40,	98.40	
100,	-1.297,	3.126,	3.633,	99.80,	99.80,	99.20,	98.10,	97.50	
102,	-1.018,	3.229,	3.345,	99.00,	99.10,	98.50,	97.50,	97.50	

Figure 4-5. Example of a Reformatted Partial Raw Data File for Test 26. The first column is time, the next three are output voltages, and the last five are temperatures.

TIME	SIDE THRUST	VERTICAL THRUST	CUTTING FORCE	SPEED	(A)	(B)	(C)	(D)	(E)	DIAMETER
.0	-6.1	17.9	21.7	118.8	23.	23.	23.	24.	23.	36.0
2.0	-40.9	141.3	154.4	117.4	44.	41.	36.	30.	24.	35.6
4.0	-36.8	307.7	326.4	116.0	98.	81.	62.	45.	27.	35.2
5.0	-2.2	377.6	366.2	115.3	100.	99.	94.	64.	33.	34.9
7.0	-8.1	349.6	371.4	113.9	101.	100.	100.	80.	40.	34.5
9.0	-13.2	375.6	365.8	112.5	101.	100.	99.	92.	47.	34.1
11.0	-18.2	313.4	302.3	111.1	100.	100.	99.	98.	53.	33.7
12.0	-10.4	343.4	355.3	110.4	101.	100.	99.	99.	58.	33.5
14.0	-11.1	378.4	369.7	109.1	101.	101.	100.	99.	63.	33.1
16.0	-16.8	350.8	351.4	107.7	101.	101.	100.	100.	67.	32.6
18.0	-10.1	354.9	366.5	106.3	102.	102.	101.	100.	70.	32.2
19.0	-14.3	356.8	369.0	105.6	101.	101.	101.	100.	73.	32.0
21.0	-9.8	337.0	328.4	104.2	102.	101.	101.	101.	76.	31.6
23.0	-14.7	349.3	330.6	102.8	102.	102.	101.	100.	78.	31.2
25.0	-12.7	356.8	327.5	101.4	102.	102.	101.	100.	81.	30.8
27.0	-14.8	295.6	280.9	100.0	102.	102.	100.	101.	83.	30.3
28.0	-14.5	362.2	364.9	99.4	103.	102.	102.	100.	85.	30.1
30.0	-6.9	362.0	330.4	98.0	102.	101.	101.	99.	86.	29.7
32.0	-10.8	352.9	335.6	96.6	100.	100.	99.	99.	88.	29.3
34.0	-16.1	396.1	352.1	95.2	101.	100.	100.	100.	89.	28.9
35.0	-12.3	308.7	283.1	94.5	100.	100.	100.	99.	91.	28.6
37.0	-11.2	315.4	326.3	93.1	101.	101.	100.	99.	92.	28.2
39.0	-9.5	345.8	309.7	91.7	100.	100.	99.	99.	93.	27.8
41.0	-14.1	366.4	361.6	90.4	101.	101.	100.	100.	95.	27.4
42.0	-14.3	341.4	320.8	89.7	101.	101.	101.	99.	96.	27.2
44.0	-17.3	350.5	363.2	88.3	101.	100.	99.	99.	96.	26.8
46.0	-15.4	323.5	314.5	85.9	101.	101.	100.	99.	97.	26.3
48.0	-13.6	311.2	294.3	85.5	100.	100.	100.	99.	98.	25.9
50.0	-15.1	356.8	308.1	84.1	100.	100.	100.	100.	98.	25.5
51.0	-10.3	371.3	342.1	83.4	100.	100.	99.	99.	98.	25.3
53.0	-13.6	391.7	367.7	82.0	100.	100.	99.	99.	98.	24.9
55.0	-13.4	352.7	319.0	80.7	101.	100.	100.	100.	99.	24.5
57.0	-5.3	358.6	313.8	79.3	101.	101.	101.	100.	100.	24.0
58.0	-16.6	354.2	351.7	78.6	101.	101.	100.	100.	100.	23.8
60.0	-13.2	354.1	355.3	77.2	102.	102.	101.	100.	100.	23.4
62.0	-13.6	368.8	325.8	75.8	101.	101.	100.	100.	100.	23.0
64.0	-7.9	378.0	416.1	74.4	101.	101.	100.	99.	99.	22.6
65.0	-12.9	335.4	379.3	73.7	101.	101.	100.	99.	99.	22.4
67.0	-15.8	350.7	327.0	72.3	100.	100.	99.	98.	98.	21.9
69.0	-11.3	417.1	342.4	71.0	99.	99.	98.	98.	97.	21.5
71.0	-10.6	348.8	339.0	69.6	99.	99.	98.	98.	98.	21.1
73.0	-13.5	301.4	248.2	68.2	99.	98.	98.	98.	97.	20.7
74.0	-18.5	292.3	330.9	67.5	99.	99.	99.	98.	98.	20.5
76.0	-20.3	294.2	291.8	66.1	99.	99.	99.	99.	98.	20.0
78.0	-17.4	378.2	345.7	64.7	99.	99.	99.	98.	98.	19.6
80.0	-6.6	358.9	323.3	63.3	99.	99.	99.	98.	98.	19.2
81.0	-28.0	318.1	322.9	62.6	100.	100.	99.	98.	98.	19.0
83.0	-22.5	328.5	293.3	61.3	99.	99.	99.	98.	98.	18.6
85.0	-10.1	404.9	356.2	59.9	99.	99.	98.	98.	97.	18.2
87.0	-4.7	338.4	339.3	58.5	99.	99.	98.	98.	98.	17.7
88.0	-14.2	246.3	245.2	57.8	99.	99.	98.	98.	98.	17.5
90.0	-9.4	335.5	318.0	56.4	98.	98.	98.	98.	97.	17.1
92.0	-8.2	319.6	281.4	55.0	99.	99.	99.	98.	98.	16.7
94.0	-19.0	315.9	330.5	53.6	99.	99.	99.	98.	98.	16.3
96.0	-3.6	359.5	353.3	52.3	99.	99.	99.	99.	98.	15.8

Figure 4-6. Example of a Partial Data File for Test 26, with Calculated Forces, Cutting Speed, Diameter of Cutting Path, and Temperatures

Figure 4-7. Test 26: Cutting and Side Thrust Forces versus Time

thermocouple approach to cutter temperature measurement, (2) provide experimental data with which to test the computer plotting scheme, and (3) obtain a preliminary estimate of the differences in cutting forces and temperatures that might be expected between sharp and artificially worn diamond compact tools. All of these objectives were met successfully. A brief discussion of several specific examples follows.

1. No problems were encountered in installing the thermocouples in the cutters, and neither the vibrations generated during cutting nor the wet environment (Test No. 28) affected performance. No thermocouple failures were experienced. In addition, the introduction of the thermocouple holes in the Stratapax™ blank substrates did not weaken the cutter sufficiently to cause premature failure or increased wear. Even the cutter that became detached by a braze failure (See Table 4-3, Test No. 34) was still intact and essentially undamaged after the failure.

One minor effect of the hole drilling carried out by electrical discharge machining (EDM) was noted on cutter No. 8. The holes drilled for thermocouples A and B penetrate very close to the surface of the wear flat that was generated by grinding. When cutter No. 8 was run, the cemented carbide wear flat surface became hot enough to expand sufficiently to cause a tensile failure in the thin wall of material between the bottoms of the thermocouple holes and the outer surface. The cracks were short and probably will not propagate sufficiently far to damage the tool. However, additional tests with this cutter will demonstrate whether or not damage occurs.

2. The effect of wear flats on the vertical thrust force is shown quite dramatically by the comparison of plots for two tests, Nos. 26 and 34. (See Figures 4-8 and 4-9.) Thrust forces in excess of 4,000 newtons (900 pounds) were observed acting on the artificially worn tool at a 0.48-mm (0.019-in.) depth of cut. The thrust force necessary to remove rock to a depth of 2.54 mm (0.100 in.) with a sharp cutter was less than one-half of this value. Also, note that the point at which the cutter attachment failed is obvious in Figure 4-8. (Figures 4-10 and 4-11 are included for purposes of speed calibration.) The cutting speed had little effect on the vertical thrust force in either test, although this result may not be true for all cases.

It should be noted that the variation in force versus time shown in Figures 4-8 and 4-9 does not represent the true frequency caused by the continuously alternating crushing--fracture--crushing--fracture--... failure mechanism of the rock. The cyclical force variations shown represent the data logger sampling time intervals. In addition, the peaks and valleys do not represent the actual high and low force excursions because the dynamometer charge amplifier voltage signals are passed through an electronic filter before reaching the data logger. Averaging the recorded force values should provide a reasonably accurate value for the mean force. The averaging procedure can be accomplished easily during the computer data reduction process.

Figure 4-8. Test 26: Vertical Thrust Force versus Time

Figure 4-9. Test 34: Vertical Thrust Force versus Time

Figure 4-10. Test 26: Cutting Speed versus Time

Figure 4-11. Test 34: Cutting Speed versus Time

In order to obtain a true dynamic picture of the variations in forces during rock cutting, the data acquisition scheme will have to be changed. The data sampling rate must be increased several orders of magnitude by transmitting the data logger output directly into a computer memory bank. The sampling rate is presently limited by the speed at which the tape recording system will operate. If the dynamometer signal output is not filtered and the data sampling rate is greatly increased, a more accurate measure of maximum and minimum force excursions can be obtained, although obtaining absolute maximum and minimum values will still be left to chance unless the sampling rate is increased tremendously. To meet the objectives of this program, the present data acquisition technique should suffice, but an increased sampling rate capability would be a powerful tool for understanding the nature of the forces acting on the PDCs because it is the dynamic nature of these forces that ultimately cause the wear and failure of the cutters.

3. The temperatures recorded for three tests, Nos. 26, 34, and 28, are shown graphically in Figures 4-12 through 4-18. The maximum temperature recorded during cutting with a sharp tool, a process that produces very little rubbing action, was approximately 100°C (212°F), as shown in Figures 4-12 and 4-13, whereas a cut with a lighter weight on the bit and with high rubbing forces against a wear flat rapidly produced a significantly greater maximum temperature, close to 400°C (752°F), as shown in Figures 4-14 and 4-15. It should also be noted that cutting in still air provided very little cooling and that, for both tests, the center of the cutter and the center of the cemented tungsten carbide stud reached temperatures almost as high as points in the cutter that were very near the cutting edge. Because there was no means to remove heat other than by convection or by conduction through the cutter mount, true equilibrium heat flow conditions were not established. Therefore, the effect of cutting speed upon heat generation was essentially masked. On the other hand, Test No. 28 (Figures 4-16 through 4-18), which was run with a coolant, shows this speed/heat effect clearly. Equilibrium was established quickly, and the temperatures within the cutter dropped as the cutting speed was reduced. The thermocouple in location E at the end of the stud never changed from the ambient, i.e., water, temperature.

• Diamond Compact Wear

A brief comment on PDC wear and its relationship to cutter edge preparation should be made. When cutter No. 8 became detached during Test No. 34, the failure of the brazed joint was very rapid, subjecting the cutter to a severe shock. This cutter was subsequently examined by scanning electron microscopy for damage. No damage and no evidence of measurable wear was seen. What was very evident, however, was the contrast between the cutting edge prepared when the wear flat was ground on the cutter and the as-received edge for the remainder of the Stratapax™ drill blank. The edge that resulted from grinding the flat was almost perfect

Figure 4-12. Test 26: Temperatures in Stratapax™ Cutter versus Time

Figure 4-13. Test 26: Temperatures in Stratapax™ Cutter and Stud versus Time

Figure 4-14. Test 34: Temperatures in Stratapax[™] Cutter versus Time

Figure 4-15. Test 34: Temperatures in Stratapax™ Cutter and Stud versus Time

Figure 4-16. Test 28: Cutting Speed versus Time

Figure 4-17. Test 28: Temperatures in Stratapax™ Cutter versus Time

Figure 4-18. Test 28: Temperatures in Stratapax™ Cutter and Stud versus Time

with essentially no chipping, whereas the as-received edge was comparatively rough with many microscopic chips lost. It is likely that good cutting edge preparation that minimizes chipping also reduces the tendency for wear that initiates with macro-chipping, and, thus, good cutting edge preparation produces a tool that is more durable under severe rock cutting conditions. This result has been observed before--in an experiment using PDCs cutting granite in a pressurized, heated vessel to simulate geothermal drilling conditions. Cutters with carefully prepared edges showed much less tendency to fail by a macro-chipping mechanism.

Future Work -- Experiments in cutting during the use of drilling muds will be started soon. In addition, further baseline cutting data are necessary for the cutting temperature tests needed to provide information to test Sandia's cutting tool temperature model. Special straight edge cutters with a 20° end clearance are being prepared for this work.

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 ▼ COMPLETED

4.4 Wellbore Inertial Navigation System (WINS)

Sandia National Laboratories

Technical Consultant: A. McFall (505) 844-6782

Project Objective

The objective of this project is to provide a system that is capable of making an accurate positional survey of a geothermal wellbore.

Project Status

This project was initiated early in this quarter. The initial effort is being directed at developing a slim-hole tool 10.2 cm (4.0 in.) in diameter that, using available components, can verify the principles of this method of inertial surveying. This working device will then provide the foundation for the long-range development necessary to provide a tool with a geothermal capability. The first field test of WINS is planned for July 1981 at the Nevada Test Site (NTS).

Quarterly Progress

In recent years, uncertainties in determining the true position of a wellbore have become a cause for concern. This concern is the result of more demanding drilling requirements brought about by the need to

1. Drill more wells with closer interspacing from single platforms,
2. Drill deeper, more highly deviated wells,
3. Intersect smaller target formations, and
4. Rapidly drill relief wells for well control.

A proposed technique to alleviate these uncertainties involves the application of inertial navigation technology to wellbore surveying.

WINS is being developed at Sandia to provide a system that is capable of making an accurate positional survey of a wellbore. Technology developed as part of Sandia's efforts in fielding inertial navigation systems for flight vehicles is being used in this program. A conceptual sketch of WINS is shown in Figure 4-19. The system is 0.1 meter (0.33 foot) in diameter and approximately 6.1 meters (20 feet) long.

A hybrid navigation system has been designed for WINS that consists of a single-gimbal configuration with two strapdown axes. Successive

Figure 4-19. Wellbore Inertial Surveying System

integrations of the outputs from three accelerometers provide the velocity and position of WINS. Improved accuracy will be obtained by the use of a Kalman filtering formulation for estimating the inertial navigation system errors and updating the navigator.

It is anticipated that the first field test of WINS will be conducted at NTS in July 1981. Several candidate test holes have been selected, and their availability and condition are being determined at this time.

The fabrication of the system's components is proceeding on schedule. The pressure barrels, i.e., the sections of case, that house the system components have been delivered by Scientific Drilling Controls.

The layout of the printed circuit boards for the repackaging of the rate integrated measuring system (RIMS) to WINS is also proceeding on schedule. A RIMS unit has been delivered to Sandia, where the interface between the RIMS unit and the minicomputer that performs the navigation algorithm has been checked out. Some difficulties with the RIMS components were encountered during this checkout. Changes to correct these problems are presently being implemented.

During September and October 1980, briefings on WINS were presented to Eastman Whipstock, Shell, Mobil, Gearhart Industries, Conoco, Emco, Oil-Well Drilling Control, and Wilson Downhole Services. Industry is interested in following the progress of this program.

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 is 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, and of identifying and developing foam drilling fluids capable of operating in temperature environments to 310°C (590°F) and having chemical and foaming stability and anticorrosive and antioxidant properties. The demonstration of a technique of nitrogen generation from diesel engine exhaust using a catalyst and the field testing of a high-temperature drilling mud, HTM-1, were successfully completed in FY80.

During the first quarter of FY81, drill pipe corrosion field tests were run with air and nitrogen alternately used as the principal component of the drilling fluid. A significant reduction in drill pipe corrosion was observed when nitrogen was used.

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5.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories

Technical Consultants: P. Rand (505) 844-7953
A. Kraynik (505) 844-0780
L. Monday (505) 844-0780
A. Ortega (505) 846-0741
B. Blackwell (505) 844-6375

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 an overall project plan. 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 also has been conducted at 310°C (590°F) and is continuing.

During the first quarter of FY81, a rheology literature study was completed, a simple heat transfer model was developed, and tensiometer coalescence studies were initiated.

The high-temperature stability tests are scheduled to begin in January 1981.

Quarterly Progress

High-Temperature Stability Tests -- The autoclave for the high-temperature, high-pressure stability tests has been received and is awaiting safety approval. The tests are scheduled to begin in January 1981.

Rheology Literature Survey -- In order to assess the heat transfer to aqueous foam fluids that may be used in geothermal drilling, information about the rheological properties of this foam is needed. The results of a literature search in this area have defined the experimental work needed. The basic conclusions reached through a review of the literature are as follows:

1. The viscosity of foam is a strong function of the liquid volume fraction and shear rate, foam being most frequently modeled as Bingham plastic or pseudoplastic.

2. The most useful model to date for geothermal applications is that by Beyer, Millhone, and Foote of Chevron Oil Field Research Co.
3. The slippage of the foam along a thin liquid layer at the wall may be important.
4. The structure of the foam and the distribution of bubbles by size may be important.
5. Little is known as to how pressure and temperature affect the rheology of foam.
6. Little is known as to how the type and concentration of the surfactant affect the rheology of foam.

It is also concluded that a series of carefully controlled pipe flow experiments could be carried out in an attempt to verify Beyer's model and to provide information about the effects of wall slip, foam morphology, temperature, pressure, and various surfactants.

Heat Transfer Modeling -- A simple model has been developed for predicting the wellbore temperature distribution for the drilling of a geothermal well with drilling foam. The model is based on an analytical solution of the constant property form of the energy equation. The heat transfer by conduction from the hot formation to the foam in the annulus is based on earlier work done for steam/hot water injection into petroleum-producing formations. The convective heat transfer between the foam and the pipe walls is determined from analytical solutions for the thermally developing pipe flow of a large-Prandtl-number fluid with a uniform velocity profile. This simple code compares favorably with the more sophisticated GEOTEMP code. Preliminary analysis indicates that the tool joints could enhance the foam heat transfer coefficients by as much as a factor of 15 due to fluid mixing. Parameter studies have indicated that the maximum foam temperature is considerably lower than the bottomhole, undisturbed formation temperature. For example, for a representative geothermal formation in which the undisturbed bottomhole temperature is 232°C (450°F) at 1,829 meters (6,000 feet), the maximum foam temperature of approximately 127°C (260°F) occurs at a depth of 1,372 meters (4,500 feet). Consequently, it may not be necessary to investigate the thermal stability characteristics of foam at temperatures corresponding to maximum bottomhole temperatures.

The foam convective heat transfer coefficient is not known with any degree of certainty because there are no reported studies of the heat transfer behavior of foam. If the effect of the tool joints on the heat transfer coefficient is completely ignored, the predicted maximum foam temperature is considerably reduced. For example, a maximum foam temperature of 52°C (125°F) occurs at a depth of 457 meters (1,500 feet). Contrast this result with that mentioned previously, where the assumed enhancement of the heat transfer coefficient produced a maximum foam temperature of 127°C (260°F). If the tool joints do not appreciably enhance the foam heat transfer coefficients, then it appears that the foam may not be subjected to temperatures high enough for thermal stability to be a major problem.

The only way to quantify the effect of the tool joints on the heat transfer behavior of foam is to perform some experiments. At the present time, a simple counterflow heat exchanger-type experiment is being considered. The foam would be circulated through a center pipe while hot water would be circulated in the annulus between the center pipe and an outer pipe. Inlet and outlet foam and hot water temperatures would be measured along with their mass flow rates. Tests would be performed with two different center pipes: (1) a pipe with simulated tool joints and (2) a pipe with the same diameter but with no tool joints. These experiments should quantify the average behavior of pipe flow with and without tool joints; however, detailed measurements of the local heat transfer rate and fluid temperatures will not be attempted.

Tensiometer Coalescence Studies -- The stability of aqueous foams at temperatures above 100°C (212°F) must be determined in order to assess the suitability of the foams as drilling fluids for geothermal wells. The goal of the tensiometer coalescence studies is to examine bubble coalescence in three aqueous surfactant solutions at temperatures to 150°C (302°F). A surfactant system in which coalescence readily occurs would not be expected to produce a stable foam. The coalescence studies are being performed on a Site-P Spinning Drop Interfacial Tensiometer under the direction of Prof. R. Flumerfelt of the University of Houston, Houston, Texas.

Equipment difficulties have limited experiments to atmospheric pressure, thus far. However, extensive tests on an anionic surfactant, Lakeway 301-10, have been concluded at temperatures up to 98°C (208.4°F). Coalescence was not observed in 0.5% solutions in this temperature range. However, coalescence was observed in 0.05% solutions, especially at higher temperatures. Relatively large scatter in the observed coalescence times has lead Flumerfelt to speculate that the surfactant distribution in the interfacial region is not uniform at the lower concentrations. It is anticipated that the pressure capabilities of the Site-P instrument will soon be restored.

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>NITROGEN/DRILL PIPE CORROSION TEST</u>													
PRETEST DRILL PIPE INSPECTION													
INSTRUMENTATION CHECKOUT													
BACA 20 WELL													
BACA 21 WELL													
FIELD TEST AT BACA 22 WELL													
POST-TEST DRILL PIPE INSPECTION													
FINAL REPORT													

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5.2 Nitrogen/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, nitrogen, 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

The corrosion test was conducted from 6 November through 16 November 1980 during the drilling of the Baca Well No. 22. Data reduction has been completed. Data analyses and evaluations are under way.

Quarterly Progress

The test was completed on 16 November 1980. Three test phases were conducted and are defined in Figure 5-1. Figure 5-1 also shows the rig activities during each test phase and the well depth as a function of time.

The most significant test results are shown in Figures 5-2 and 5-3. Figure 5-2 shows results from corrosion rings that were installed at tool joints inside the drill pipe. Corrosion was higher near the bottom of the drill string during all test phases. Corrosion rates were at least an order of magnitude lower when nitrogen was used. Figure 5-3 shows a comparison between rings installed near the bottom of the drill string for comparable times. One was exposed to treated aerated water and the other to nitrogen and air.

The post-test inspection of the new drill pipe used during this test is scheduled for early January.

Papers summarizing the early test results have been prepared and will be presented to

1. The International Conference on Geothermal Drilling and Completion Technology, Albuquerque, New Mexico, 22 January 1981 and
2. The International Corrosion Forum, Toronto, Canada, 10 April 1981.

A final report will be published late in the second quarter.

Figure 5-1. Rig Activities Relative to Time Compared with the Plot of Well Depth versus Time

Figure 5-2. Corrosion Ring Data. Only rings that exhibited a weight loss corresponding to a uniform surface corrosion of more than $0.58 \mu\text{m}$ ($23 \mu\text{in.}$) are plotted.

RING NO. 6299

RING NO. 7868

Figure 5-3. Corrosion Ring Comparison. The ring on the left was exposed during phase 1 to treated aerated water for 66.8 hours; its measured corrosion rate is 4.1 mm/y (160 mils/y). The ring on the right was used during phase 2 (nitrogen and water) for 74.8 hours; its corrosion rate is 0.11 mm/y (4.4 mils/y). Both rings were installed just above the frill collars about 150 meters (500 feet) above the drill bit.

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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: C. Carson (505) 844-6477

Project Objective

This project will result in the fabrication of a drilling-mud testing instrument capable of measuring fluid properties under downhole conditions of up to 371°C (700°F) and 138 MPa (20,000 psi).

Project Status

State-of-the-art studies have been reviewed. Three fabrication bids for the pressure vessel were received, and a design was chosen. 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 has been selected. A contract extension is under consideration, and the schedule has been revised.

Quarterly Progress

Parts of the filter, rheometer, dispersator, and bucket lift system were assembled on the water-cooled mounting plate. The operation of these components was tested using computer software. A few minor difficulties were noted with some mechanical clearances, but, for the most part, the assembly operated well. It was taken apart again for minor machining and adjustments.

The success of the ceramic coatings in electrically insulating the corrosion probes now appears doubtful, and a new insulating method is being investigated. Corrosion coupons could be held in place by a spring-loaded, electrically conductive needle. Details are being worked out.

A single resistance thermometer device (RTD) was successfully tested up to 138 MPa (20,000 psi) at room temperature in NL Baroid's small pressure vessel. The remaining four RTDs were subsequently ordered and have been received. A solid-state contactor for the vessel heater control was also ordered and received. The RTDs and the contactor will be used in further tests of proportional-integral-derivative software temperature control laws. The uninterruptible power supply was received and functions satisfactorily. Packaging of all the electronics systems is nearly complete.

The manufacturing of the filter belt is awaiting a final bid proposal. A partial delivery of high-pressure valves and fittings has been made.

The filter collection system electropneumatic ON-OFF proportioning valves were received and checked out. Although slightly longer than expected closure times were experienced, they will probably be acceptable.

The filtration software control task was completed by Systran Corp., Dayton, Ohio. During computer memory-saving operations, it was discovered that 15 of the 60 object files had previously been destroyed by a malfunctioning computer component. All but one are available on backup files.

The computer software for several of Systran's tasks has been satisfactorily checked out using a fabricated sensor simulator together with a recorder and an oscilloscope. The problem of losing real time was solved by using a programmable interval timer on an SBC* 534 board and modifying the system software slightly. It is expected that Systran will complete its subcontract work early next quarter.

The software for the bucket lift control task has been coded, debugged, and interfaced with existing software by NL Baroid. The interfacing with hardware awaits the reassembling of machined parts.

Systran will write the software maintenance manual for the microcomputer system, and Baroid will be responsible for the system operation manual. Both manuals should be completed next quarter.

An NL Baroid appropriation request to cover the construction of the geothermal drilling fluid test system (GDFTS) building will now require approval from the NL Baroid board of directors. Construction drawings were received from the architect and reviewed for the final time. The current plans call for moving the building site about 6 meters (20 feet) to the west to avoid having to relocate the reserve pit serving the test wells. The original construction time was estimated to be 5 months, assuming that no weather or other delays occurred. The amount of time could possibly be reduced to 3 months provided that testing in the building can proceed temporarily with plywood doors, no cabinets or workbenches, and a rental hoist. A more accurate time estimate awaits a decision by another NL division on where to locate their reactor building.

The GDFTS water-cooled mounting plate was shipped to National Forge Co., Irvine, Pennsylvania, for an external hydrostatic pressure test at 138 MPa (20,000 psi). No damage to the cooling plate was apparent following the test. The plate will be checked inside for liquid leakage when it is returned to Baroid in Houston, Texas. Once it is checked out, the hardware that it supports can be remounted.

The 207-MPa (30,000-psi) Hydropac pressure intensifier and 41-MPa (6,000-psi) inert gas storage cylinder were received. Tubing was bent to make the interior GDFTS condenser coil. A quotation of roughly \$4,000 was

* single-board computer

received from Ebtec Corporation, Agawam, Massachusetts, to manufacture 10 filter belts at \$195 each plus tooling setup charges. The flame-sprayed corrosion probes failed to insulate electrically in salt water, and a new approach is needed. The Petrolite corrosion rate electronics were received.

When the GDFTS building construction schedule has been more accurately estimated, an application will be made to DOE for an additional time extension of the contract.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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>													SEP 81
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 30 September 1981
Contract Number: 13-5104 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

Project Objective

This project will result in a fundamental understanding of clay particle morphology under the influence of both 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.

Quarterly Progress

Sandstone Cores from East Mesa, Imperial Valley -- Cores from Republic Geothermal, Inc., Well No. 70-30rd, East Mesa, Imperial Valley, were studied using several analysis techniques. These cores were previously tested by Terra Tek, Inc., Salt Lake City, Utah, in order to assess the possible formation damages caused by drilling fluids. HTM-1, a sepiolite/bentonite-based fluid, was among the fluids evaluated. Geothermal wells are naturally susceptible to formation damage from drilling fluids because the high temperature and complex chemistry of the formation fluids affect drilling fluids. The problem is a significant one that has been studied at the Terra Tek laboratories.

A virgin core of East Mesa sandstone was designated as core 1-64, and cores 2-64 and 2-76 were those subjected to tests HTM-212-4 and HTM-148-3, respectively, as described in Table 3, page 24, in Terra Tek's November 1979 report by D. Ennis et al.¹ The final to initial permeability ratios were reported to be 0.24 for core 2-76 and 0.94 for core 2-64. Thus, core 2-76 lost a great deal of permeability after being subjected to the HTM-1 drilling fluid for 12 hours on stagnation time at 100°C (212°F), whereas the same test for core 2-64 at 200°C (392°F) for 12 hours did not cause significant permeability impairment. These results led D. Ennis et al.¹ to the conclusion that HTM-1 drilling mud was responsible for the damage to core 2-76.

In the current work, three cores were examined by X-ray diffraction, scanning electron microscopy, and energy dispersive X-ray analysis. Each 10.16-cm (4-in.) long core was divided into four parts, each part being 2.54 cm (1 in.) long. These sections were designated "A," "B," "C," and "D," where "A" was the section of the core next to the filter cake end and "D" was the opposite end of the core. The four sections of each core were separately examined, and the following observations were made.

The original, virgin core 1-64, consists of about 50% quartz, 30% feldspar, 10% calcite, and 10% clay minerals. These clay minerals are illite/smectite mixed layers and chlorites. The relative amounts of these components show a small variation among the four sections, 1-64A, 1-64B, 1-64C, and 1-64D. The scanning electron micrographs in Figures 5-4 through 5-7 show the typical composition of the section 1-64A at magnifications from 100X to 10,000X. In Figure 5-4, individual sand grains of quartz and of feldspar are observed. Most of these grains are coated with a fine material that is better characterized at higher magnifications. Figure 5-5 shows a grain boundary between two grains that are coated with a fine material. In Figure 5-6, a section of Figure 5-5 is magnified and shows that the fine material coating the grains has the typical morphology of illite/smectite mixed layers with illite laths protruding from them. A closer look at the illite laths and flaky illite/smectite mixed layer is given in Figure 5-7. Chlorites in all sections of core 1-64 occur as rosettes, as shown in Figure 5-8 at a magnification of 300X and in Figure 5-9 at a magnification of 5,000X. The latter figure shows also the hairy illite and flaky illite/smectite mixed layer.

The illite laths and illite/smectite mixed layer and chlorites are well-known for their water sensitivity; that is, they migrate easily in the pores of the reservoir rock and plug the pore throats. In fact, core 2-76, with large formation damage, displayed exactly the same clay minerals around the sand grains and in the pores. Similar observations were made on core 2-64. The conclusion reached from the analysis was that no clays from the HTM-1 mud were observed to have invaded cores 2-64 and 2-76.

Installation and Calibration of the Autoclave and the Fann 50C Viscometer -- The autoclave was assembled and put into operation. Geothermal drilling fluids I and II were then heated to 316°, 317°, and 427°C (600°, 700°, and 800°F) for later testing. Similarly, sepiolite- and attapulgite-based pure fluids, i.e., 5% suspensions of sepiolite and attapulgite, were heated to 371° and 427°C (700° and 800°F).

New bearings were furnished by Fann Corporation, Houston, Texas, and the Fann 50C high-temperature viscometer was installed. However, it was recognized after the recorder was installed that the viscometer responded unsatisfactorily to temperature. Consequently, the recorder was hand-carried to Houston for repair and adjustments. Finally, the Fann 50C was calibrated, and rheology measurements were successfully made on the previously autoclaved fluids.

Sepiolite Testing in the Magcobar Flow Loop -- The Magcobar loop² consists of series of capillaries that can be heated to 204°±14°C (400°±25°F) while a fluid is circulated through shear valves. The system is designed to pump about 0.0014 to 0.0076 m³ (0.38 to 2.0 gal) of fluid

Figure 5-4. A Low-Magnification (300X) STEM Image of the Virgin Core of East Mesa Sandstone Showing the Sand Grains with a Clay Coating

Figure 5-5. A Grain Boundary with Clay Coating, Magnified from Figure 5-4 to 500X

Figure 5-6. An Image from Figure 5-5 Magnified to 5,000X that Shows the Clays at the Grain Boundary

Figure 5-7. Illite laths and the Flaky Illite/Smectite Mixed Layer from Figure 5-6 Magnified to 10,000X

Figure 5-8. Another Low-Magnification Image (500X) of the Cross Section of the Virgin Core (I-64C) with Clay Coating the Grains. Note that secondary quartz grains not coated with clays also are present.

Figure 5-9. Typical Images of Chlorite Rosettes, Illite Laths, and the Flaky Illite/Smectite Mixed Layer in the Pores of the Virgin Core I-64 before Testing with Mud

from an atmospheric pressure reservoir through a cycle of heating, intensive high-temperature shearing, cooling, low-temperature shearing, and final return to the reservoir. Typically, for a 0.0076-m³ (2.0-gal) system, the entire mud volume passes through 6 to 12 cycles each hour, during which time the individual mud particle goes through each active heating cycle, shearing cycle, and cooling cycle in about 30 seconds. Intensive shearing occurs at both high and low temperatures when the mud is forced through spring-loaded back-pressure valves. The usual mud tests can be made on samples taken at the reservoir under atmospheric conditions.

• Results of Flow Loop Tests

A mixture of 0.0076 m³ (2.0 gal) of 5% sepiolite fluid was circulated through the flow loop for an average of six circulations per hour. Each sample of fluid was subjected to the maximum temperature for about 30 seconds for each hour of circulation. Table 5-1 gives the rheological measurements on these samples, which are designated as samples Nos. 2, 6, 11, 14, 15, and 18, and on the original sepiolite fluid before treatment, sample No. 1. Circulation times and temperatures during circulation are listed in columns 2 and 3 of the table. The data in this table indicate that the viscosity is first increased by the initial shearing at room temperature. Then the viscosity begins to decrease with circulation time, with increasing temperature, and with shearing. In fact, the viscosity drops from 0.012 to 0.0035 Pa·s (29 to 8.5 lb/ft·h). At the same time, the fluid loss increases from 54 cm³ (3.3 in.³) to more than 96 cm³ (5.9 in.³).

The X-ray diffraction analysis of these samples indicates that sepiolite-to-smectite conversion starts to take place after 12 hours of circulation (sample No. 11), although in very small quantities. The presence of smectite is distinctly indicated by its characteristic, glycolation-induced, 17.5-Å reflection after 18.25 hours of circulation (sample No. 18). Original sepiolite slurry after being sheared at room temperature consists of well-dispersed sepiolite fibers. As indicated in Table 5-1, these fibers seem to slightly increase the viscosity and the fluid loss. In Figure 5-10, the rheogram for the original sepiolite fluid, No. 1, shows a maximum at about 149°C (300°F). The sepiolite sample No. 2, which was sheared for 2 hours in the flow loop, has a similar rheogram as the original sample. X-ray diffraction and electron microscopic examinations do not show any conversion of sepiolite to smectite. However, during low shearing in the Fann 50C viscometer, the sepiolite fibers develop coagulations into large spherical flocks.

Sample No. 6 was taken from the flow loop after 7.5 hours of circulation and heated to a temperature of 188°C (370°F). No conversion of sepiolite to smectite was observed as a result of this circulation. Sepiolite particles occurred in smaller aggregates, and the individual fibers seemed to disappear. This fluid had a somewhat lower viscosity, as shown in Table 5-1, and, with the Fann 50C measurements, gave a different rheogram (see curve No. 6 in Figure 5-10). The viscosity was then observed to be maximum at about 204°C (400°F). After the sample was subjected to 260°C (500°F) in the Fann 50C viscometer, the conversion of sepiolite to smectite occurred. The conversion was indicated by the X-ray diffraction data. The particles in the fluid again aggregated to large floccules during the testing with the Fann 50C viscometer. These floccules seemed to consist of sepiolite

Table 5-1

Circulation Times, Temperatures, and Rheology of the Samples Run in the Magcobar Flow Loop

Sample Number	Hours Circulated	Average Temperature During Circulation, °C (°F)		Rheology Data*										API Fluid Loss cm ³ (in. ³)	
				Viscosity Data						Yield Point (lb/ft ²)					
				Average		at 600 rpm		at 300 rpm				Plastic			
				Pa·s	(lb/ft·h)	Pa·s	(lb/ft·h)	Pa·s	(lb/ft·h)			Pa·s	(lb/ft·h)		
1	0	not applicable		0.0105	(25.4)	0.021	(50.8)	0.018	(43.5)	0.003	(7.3)	71,800	(1,500)	54	(3.3)
2	2	22	(72)	0.0120	(29.0)	0.024	(58.1)	0.022	(53.2)	0.002	(4.8)	95,800	(2,000)	55	(3.4)
6	7.5	188	(370)	0.0100	(24.2)	0.020	(48.4)	0.017	(41.1)	0.003	(7.3)	67,000	(1,400)	96	(5.9)
11	12	193	(380)	0.0075	(18.1)	0.015	(36.3)	0.012	(29.0)	0.003	(7.3)	43,100	(900)	96	(5.9)
14	15.5	218	(425)	0.0065	(15.7)	0.013	(31.4)	0.009	(21.8)	0.004	(9.7)	23,900	(500)	no data	
15	16	218	(425)	0.0060	(14.5)	0.012	(29.0)	0.008	(19.4)	0.004	(9.7)	19,200	(400)	no data	
18	18.5	224	(435)	0.0035	(8.5)	0.007	(16.9)	0.006	(14.5)	0.003	(7.3)	14,400	(300)	96	(5.9)

*Obtained from measurements with the FANN 35A Visiometer.

Figure 5-10. Rheograms of the Sepiolite Samples Taken from Magcobar's Flow Loop. The sample numbers correspond to those in Table 5-1.

fibers with the thin smectite films acting like a gelating agent between the fibers. The conversion of sepiolite to smectite occurred in small amounts in the flow loop circulations above 204°C (400°F), and the smectite content slightly increased with time, i.e., from sample No. 14 through sample No. 15 to sample No. 18 in Table 5-1. The fine sepiolite fibers disappeared, and bundles of sepiolite fibers dominated. More smectites formed as thin films around the sepiolite fibers during testing at 260°C (500°F) in the Fann 50C. These thin films seemed to coagulate with sepiolite fibers into large flocks. The pretreatment of the fluid in the flow loop seems to promote the sepiolite-to-smectite conversion in the Fann 50C viscometer at 260°C (500°F). This conversion is probably responsible for the shifting of viscosity maxima to higher temperatures in the rheograms for the fluids No. 14, No. 15, and No. 18 in Figure 5-10.

References

1. D. O. Ennis, I. L. Bergosh, S. W. Butlers, and A. H. Jones, "Drilling Fluid/Formation Interaction at Simulated In Situ Geothermal Conditions," report submitted to Sandia Laboratories in November 1979.
2. Reece Wyant, "A Unique System for Preparation and Evaluation of High-Temperature Drilling Fluids," Society of Petroleum Engineers of AIME Paper No. 5515, Dallas, Texas, September 1975.

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) investigating drilling fluid/formation interactions, (3) defining current problems with completion equipment and recommending potential solutions, and (4) developing a model that will evaluate the cost of current completion technology, the areas needing development, and the cost benefit of new technology. 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 the 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.

The necessary development was determined, and the requirements were defined for downhole primary cementing tools and for monitoring tools to detect the critical failure modes of a geothermal well completion.

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 was completed this quarter. During a field demonstration, a cavitation descaler tool successfully removed scale at a cleaning rate of $0.957 \text{ m}^2/\text{min}$ ($10.3 \text{ ft}^2/\text{min}$) with an operating pressure of 34 MPa (5,000 psi). A more detailed account of this demonstration can be found in Section 6.3.

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.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>HIGH-TEMPERATURE PERFORATOR</u>													
STUDY OF OFF-THE-SHELF PERFORATORS	▼												
STUDY OF MDS IGNITION SYSTEMS	●												
STUDY OF HIGH- TEMPERATURE DETONATORS	●												

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 the perforators were heated, the explosive charges were 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 would function as designed. Perforators containing the explosive HNS were 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).

Mild detonating fuse (MDF) is presently being manufactured for use as an initiating train for high-temperature perforators. Studies are in progress that attempt to demonstrate the feasibility of using a detonator to initiate the MDF train by an electrical signal.

Quarterly Progress

The MDF containing the explosive HNS-II and having an aluminum jacket is currently being manufactured. The MDF will be of two types, one type being round in cross section and the other type being rectangular in cross section. The MDF will be used to successively initiate a string of perforators.

A detonator capable of functioning at and after exposure to elevated temperatures will be needed to initiate the MDF train. A study has begun in order to select candidate explosive materials. Explosive powders confined in a steel housing are being heated at different temperatures to determine the maximum temperature at which they can survive for 2 hours.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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

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

○ 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. Reports on the cementing and monitoring tools were completed and published separately.

FY80 Progress

A report titled "Primary Cementing Equipment and Critical Development Needs" was completed this quarter. The objective of the study was to identify limitations in downhole primary cementing equipment that may be preventing cost effective geothermal development in the United States.

Data were obtained for this report through published technical papers and meetings with cementing companies and geothermal operators including Union Oil of California, Aminoil, U.S.A., Republic Geothermal, Shell Oil Company, and Magma Energy Company.

An effective evaluation of the reliability of primary cementing equipment was not possible using cementing company records and published

technical papers for the following reasons. First, with industry drilling only 70 to 80 wells per year, it is difficult to establish conclusive statistical confirmation of either past or present equipment reliability. Second, failures that occurred some time ago may not represent current equipment performance because (1) equipment modifications may have been made by the service company, (2) procedures may have been revised to eliminate the need for the item, or (3) operating conditions may have changed. Third, specialized site-specific cementing techniques that are successful may represent a competitive advantage for the experienced service company. Fourth, suppliers are understandably reluctant to divulge tool limitations. It was necessary, therefore, to base the results of this study on equipment performance as provided by geothermal operators, even though such reports are quite subjective, often outdated, and rarely documented.

The consensus of CTC's operator contacts is that the limitations of primary cementing equipment are not currently restricting geothermal development in the United States. In geothermal areas presently being developed, common failures are being minimized or eliminated through the use of improved, site-specific cementing techniques and of equipment that is reasonably reliable at moderate temperatures and pressures. It was determined, therefore, that the development of new or modified primary cementing tools is not critical to the geothermal industry at this time. However, immediate and long-term benefits could be derived from a series of independent surface and/or downhole equipment tests designed to verify reliability and establish limits of more sophisticated cementing techniques that are required for more severe operating conditions. Examples of such severe conditions are those that will be encountered in production and injection wells deep in the Salton Sea, Brawley, and Heber areas of the Imperial Valley. Existing cementing problems in deep, very hot wells in Cerro Prieto, Mexico, are evidence of the need for advanced tools and technologies.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

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: J. Kelsey (505) 844-6968

Project Objective

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

The 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 for the demonstration system were identified based on data from a test conducted on 29 and 30 March 1979 at the East Mesa, California, geothermal test facility. The water-powered hydraulic cleaning head motor to be used in the demonstration system was fabricated based on this design, and a field demonstration was performed in November 1980. During the demonstration, the cavitation descaler tool successfully removed scale with an operating pressure of 34 MPa (5,000 psi) at a cleaning rate of 0.957 m²/min (10.3 ft²/min).

Quarterly Progress

The test well was Imperial Magma's Woolsey No. 1 located at their Niland, California, test site. The Dia-Log Company was contracted to perform a minimum-i.d. caliper measurement of the test well. Three hundred and five meters (1,000 feet) of the 21.9-cm (8-5/8-inch), 248-kPa (36-lb) casing was logged. The nominal thickness of the lead sulfide scale in the well was 9.5 mm (3/8 in.). Water was standing in the casing at a depth of approximately 18 meters (60 feet).

The descaling operation began on 25 November 1980. When the descaling tool was placed on the first section of drill pipe and pressurized, the joints in the drill string leaked badly. It was apparent that this leakage would result in an inability of the pumping system to maintain sufficient operating pressure.

The drill pipe that was available for this test would accommodate an internal pressure of 83 MPa (12,000 psi) before yielding. In order to maintain a margin of safety, the maximum pressure that was utilized at the start of the test was 62 MPa (9,000 psi). Initially, the tool was to be lowered into the well as slowly as possible. If the tool was able to remove the scale, the rate of injection of the tool would be increased to the planned 1.5-m/min (5-ft/min) rate.

The tool was guided past the gate valve on the well, and the stripper on top of the blowout preventer was sealed. The tool was then pressurized and lowered into the hole. At the end of the first 9.1-meter (30-foot) section of pipe, the injection rate was calculated to be 1.5 m/min (5 ft/min). The tool was allowed to continue into the hole under these conditions until the end of the first stand was reached at the 18-meter (60-foot) level. It was decided to remove the first stand at this time and attempt to make a visual inspection of the first few meters of the well. The stand was removed from the well, and a flashlight was lowered to just below the gate valve. The visual inspection made just before the start of the test had shown a uniform scale layer. After the cleaning operation, no scale was visible.

One goal of the test was to determine the minimum pressure at which the tool would remove the scale. Due to the leakage problem, it was important to obtain this information as quickly as possible. Therefore, it was decided to operate in the next 9.1 meters (30 feet) at 52 MPa (7,500 psi) at 1.5 m/min (5 ft/min) and, in the following 9.1 meters (30 feet), at 34 MPa (5,000 psi).

The descaling tool was again inserted into the well. Starting at the 18-meter (60-foot) level, the pressure was set at 52 MPa (7,500 psi). The tool was run in until the 24-meter (80-foot) level was reached, at which point the tool would not proceed.

Cleaning head rotation is indicated by a distinctive vibration of the drill pipe. At the point at which the tool would no longer advance, there was no indication of this rotation, and so the tool was pulled for inspection. When the tool was above the surface, an attempt was made to rotate it by hand. It could not be rotated and behaved as if the motor were locked. The tool, which did not have a filter incorporated into it to prevent foreign material from getting into the motor, was torn down for inspection. It was seen that the motor was prevented from rotating by grit that had built up between the rotor and its outer casing. The cleaning nozzles were removed from the tool for inspection, and flakes of dark-colored material that were easily picked up with a magnet were found to be clogging them. The material that had locked the motor was also magnetic. These observations led to the conclusion that, although the interior of the drill string had been water blasted to remove dirt and rust, large areas of rust remained on the inside of the drill pipe, flaking off as the pipe flexed and depositing in the motor and nozzle assemblies.

The hydraulic motor and cleaning head were disassembled and cleaned. The tool was then reassembled for further testing.

On 26 November 1980, the testing resumed at the 24-meter (80-foot) level. The pressure was set at 52 MPa (7,500 psi), and the string was lowered at 1.5 m/min (5 ft/min). When the 30-meter (100-foot) level was reached, the pressure was lowered to 34 MPa (5,000 psi). The injection rate was slowed to approximately 0.9 m/min (3 ft/min). It was noticed that the above-surface tool joints appeared to be leaking more severely than they had the previous day. The pump operator raised the rpm of the pump to compensate for the additional leakage and to maintain the specified pressure. When the tool reached the 34-meter (110-foot) level, the pump began to produce severe pressure pulsations. It was thought initially that one of the output valves of the triplex pump had broken, but later this was determined not to be the case. To compensate for the leaking joints, the rpm of the pump was continually increased until a level was reached at which the output valves of the pump would not fully close before the next pressure stroke began. In essence, the valves experienced high-rpm "float." In light of this condition, continuing became impossible, and the test was terminated.

The following conclusions were reached as a result of the field test.

1. The lead sulfide scale could be removed successfully from the casing walls using the tested technique.
2. The minimum operating pressure utilized during this test to remove the scale was 34 MPa (5,000 psi).
3. Even at the 34-MPa (5,000-psi) operating pressure, an injection rate of 1.5 m/min (5 ft/min) could be maintained. This injection rate corresponds to a cleaning rate of 0.957 m²/min (10.3 ft²/min).

These tests were conducted in the upper portion of the well, where the hydrostatic pressure due to the wellbore fluid was quite low. Laboratory tests indicate that jet performance is degraded as the exhaust pressure is increased. Thus, it cannot be concluded that the performance parameters displayed in this test are applicable to scale removal at increased depths.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DRILLING FLUID/ FORMATION INTERACTIONS: TERRA TEK</u> FILTRATE CHEMISTRY EFFECTS PARTICLE SIZE EFFECTS FRACTURED FORMATION SIMULATION EAST MESA FORMATION DAMAGE INVESTIGATION FINAL REPORT													

LEGEND: ——— ACTIVITY PERIOD ○ PLANNED START ▽ PLANNED COMPLETION
 - - - - - RESCHEDULED ● STARTED ▼ 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: J. Kelsey (505) 844-6968

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 known geologic resource area (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 and is continuing.

The East Mesa formation damage investigation was completed this quarter. It was concluded that pore fluid effects in a matrix-permeability resource can significantly impact formation productivity.

Quarterly Progress

East Mesa Formation -- Four long-term permeability tests were performed on East Mesa core samples. The purpose of this testing was to address the phenomena observed in permeability comparison tests for Republic Geothermal, Inc., Santa Fe Springs, California. As reported previously, tests run on the core sample from 1,694 meters (5,557 feet) showed significant permeability degradation with increasing time and flow volumes.

To isolate the suspected mechanisms, which were test duration and flow volume, a test program was conducted to examine each factor separately. The exposure rate, which was hypothesized as a possible contributing factor to permeability degradation, also was examined. The results of this testing indicated that the behavior observed in the sample from 1,694 meters (5,557 feet) also was evident in the samples used in the long-term tests. Permeability degradation did increase with duration and flow volume but ceased in all cases and, in some, was reversible.

The results of the permeability comparison testing on East Mesa sandstone were evaluated in October 1980. This task was targeted at determining permeabilities in specified footages of core for comparison with existing values. Sample permeabilities to liquid and nitrogen were determined. The analysis indicated a strong correlation between the test data and existing values. The correlation coefficient was 0.9134.

An analysis of the four long-term permeability tests performed on core samples from East Mesa KGRA was completed. The preliminary results indicated that a significant permeability degradation occurred when core samples were flowed with simulated pore fluid and that the degradation increased with time (see Figure 6-1).

An additional long-term permeability test on East Mesa sandstone was completed. This test assessed the effects of the simulated pore fluid on core permeability. Previous long-duration testing had revealed a significant impairment of permeability, and, in this latest test, the order of flowing fluids was reversed. Shown in Figure 6-2 is the core behavior when a 3% KCl brine is initially flowed, followed by the simulated pore fluid. Note that the introduction of the simulated pore fluid resulted in a severe impairment over the course of 10 hours before stabilization occurred at a value 70% below the stable KCl permeability. It can be concluded that pore fluid effects in a matrix-permeability resource can impact formation productivity quite significantly, as indicated by the test results.

Particle Size Effects -- Testing involving the use of particles 5, 20, and 50 microns (0.2, 0.8, and 2.0 mil) in size to evaluate the most effective pore-bridging size was begun. The Statement of Work specifies that the three different sizes plus combinations of these will be tested at temperatures of 23°, 175°, and 250°C (73.4°, 347°, and 482°F) while in situ conditions are simulated. Initial testing indicated that particle abrasion was causing excessive wear on critical seals and pumps in the flow circulation system. System modifications are being examined in an effort to alleviate particulate effects.

Figure 6-1. Permeability Test Results on East Mesa Sandstone Using a Simulated East Mesa Brine

Figure 6-2. Core Behavior when 3% KCl Brine is Initially Flowed, Followed by East Mesa Brine, a Simulated Pore Fluid

Fractured Formation Simulation -- Following an extensive literature review, efforts to simulate naturally occurring fractures in the laboratory proceeded with the preparation of several samples. Because United States geothermal resources exist in such a diverse range of rock types, two materials, representing the igneous and sedimentary classifications, were chosen for evaluation. Fracture simulation, because of the complexity involved, is highly controversial. Therefore, to include a wide range of characteristics, the initial efforts focused on bracketing the nature of fracturing. Core samples of granite and sandstone were prepared in three ways:

1. Saw cutting along the length and matching the faces together,
2. Saw cutting along the length and roughing the faces by sand blasting, and
3. Tensile fracturing by the "Brazil Method."*

Future efforts will address (1) the procedures needed to measure effective fracture width at simulated in situ conditions and (2) design modifications needed to accommodate the higher flow rates associated with fractures.

*The "Brazil Method" is a rock mechanics test frequently used to measure the tensile properties of rock. For these fracturing tests, the "Brazil Method" was modified by the prenotching of the core samples in order to create a planar tensile fracture in each sample.

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6.5 Completion Equipment Study

Contractor: Foster-Miller Associates, Inc. (FMA)
Principal Investigator: B. Doherty (617) 890-3200
Contract Period: 1 August 1980 to 1 June 1981
Contract Number: 49-8367 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

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. Organizational meetings were held on 28 August 1980 and 11-13 November 1980 to coordinate the work done by FMA and their subcontractor, Completion Technology Company (CTC), with Sandia's overall completion technology program. The pertinent data on completion equipment have been compiled, and the defining of the related problems is continuing. An engineering analysis of the equipment was initiated this quarter.

Quarterly Progress

A problem reference system was established for use throughout the contract period. This system assigns to each problem a number based on the task and the technical question that introduced the problem, thus helping to focus the research efforts on discrete, manageable problems and providing a mechanism for cross-referencing.

CTC prepared a written discussion of each problem that was identified through the use of the reference system. The discussions include a re-statement of the technical question, a detailed statement of the implied

problem, a technical discussion, and a definition of solutions or technical needs. The definition section establishes the direction for the Phase II and Phase III efforts.*

The technical questions were reviewed, and an independent listing of implied problems and information requirements was developed. A listing of the equipment used in each task area was also developed. In this listing, the aspects of the equipment that could represent problem areas and hence could be addressed in the technical evaluation of the equipment were identified.

Phase I Review Meeting -- On 11-13 November 1980, FMA met with CTC, Houston, Texas, to review the Phase I work and to organize the Phase II tasks in order to minimize duplication of effort, define responsibility for the tasks, and define the goals and deliverables.

In order to help in the organizing of the technical investigations, the flowchart shown in Figure 6-3 was prepared. Phase I, encompassing the "Problem Definition" stage and the "Problem Summary," was completed. Phases II and III cover the remaining stages. Many of the problems covered in the "Problem Summary" have not yet been quantitatively identified as problems experienced in the field. Examples include the need for sand control, improved wellhead design, and remedial cementing. An attempt will be made to verify these hypothesized problems, and priorities will be adjusted depending on whether or not verification is found. Some of these problems will probably not be verified because of the lack of industry experience. An example is the need for sand control, which has not yet surfaced as a significant problem but which is a problem in formations such as those located in the Imperial Valley. Problems like this will be addressed but will be given a lower priority than known problems.

Organization of Phase II Efforts -- The technical discussions prepared in Phase I were reviewed to define those problems that have common characteristics. The review resulted in the grouping of problems into three categories, as shown in Table 6-1. These categories are

1. Tubular design, installation, and repair,
2. Startup and productivity maintenance, and
3. Wellbore and formation evaluation.

The emphasis in the investigation of these categories will be on the equipment problems. These priorities are shown in listings in Table 6-1.

As can be observed, the problems from any one task may be distributed throughout these categories. Task 5 can be examined as a case in point. Problems 5.1.1 and 5.2.1 center on defining the need for repair tools and

* Phase I efforts included all activity from September 1980 to 15 November 1980. Phase II activities began on 15 November 1980 and will conclude on 15 January 1981. Phase III activities include all efforts from 15 January 1981 to May 1981.

Figure 6-3. Steps to Complete for Each Task

Table 6-1

Problem Grouping and Priorities

Group 1: Tubular Design, Installation, and Repair		
Priority	Problem No.	Problem Title
1	1.1.1	Well Design
	1.2.1	Liner Materials and Couplings
	1.3.1	Liner Hangers and Packers
2	7.1.1	Scale Removal Techniques
	7.2.1	Alternative Scale Control Concepts
3	5.1.1	Definition of Tubular Repair Needs
	5.2.1	Evaluation of Repair Tools
4	6.1.1	Definition of Remedial Cementing Needs
	6.2.1	Remedial Cementing Equipment Limitations
5	4.1.1	Well Control Requirements
	4.2.1	Wellhead Design
Group 2: Startup Productivity Maintenance		
Priority	Problem No.	Problem Title
1	1.4.1	Slotted Liner and Washing Tool Design
	1.5.1	Slotted Liner Feasibility
2	3.1.1	Adequacy of Perforating Tools
3	2.1.1	Need for Sand Control
	2.2.1	Technical Needs for Effective Sand Control
4	8.2.1	Cold Water Entry Sealing Techniques
	8.3.1	Slotted Liner Design for Cold Water Entry
5	9.2.1	Startup Techniques--Formation Damage
	9.3.1	Startup Techniques--Completion System Damage
	9.4.1	Startup Test Procedures
Group 3: Wellbore and Formation Evaluation		
Priority	Problem No.	Problem Title
1	3.1.2	Efficiency and Perforating Operations
	3.2.1	Adequacy of Auxiliary Perforating Equipment
2	5.2.1	Evaluation of Repair Tools (instruments needed to define damaged zones)
3	8.1.1	Cold Water Zone Identification
4	9.1.1	Startup Data Requirements

the adequacy of these tools. In the evaluation of these tools, the material systems, the mechanical design, and the mechanisms and procedures used to activate them will be examined. These considerations are common to those components studied in Category 1.

The repair of casing also requires that the problem area be identified with caliper logs or the like. These evaluation tools will be investigated in Category 3 along with other tools used to gather information about the wellbore or formation. Such tools include temperature and pressure logs (8.1.1), fracture permeability logs (8.1.1), collar locators (3.2.1), and core sample tools (9.1.1).

Investigations in Category 2 will concentrate on examining the functional design of equipment and on procedures used to start up a well or to maintain productivity. Included in these investigations will be gravel-packing equipment (2.1.1, 2.2.1), slotted liners (1.4.1, 1.5.1), perforating guns and explosives (3.1.1), cold water entry prevention procedures and equipment (8.2.1, 8.3.1), and startup procedures and tests (9.2.1, 9.3.1, 9.4.1). The emphasis in these efforts will be on the functional design considerations such as slot sizing, washing tool cup spacing, shaped charge spacing, etc. Material and elastomer selection will be studied in Category 1.

The need to define a minimum set of typical downhole conditions was also realized. The conditions defined will provide the basis for evaluation in all three categories and will include such items as fluid and formation descriptions, wellbores, flow rates, etc. Much of this information has already been acquired and simply needs to be compiled into a useful format.

Division of Labor -- A natural division of labor evolved from the categorizing of problems. FMA will have the responsibility for investigating Categories 1 and 3, while CTC will be responsible for Category 2. CTC will also compile the typical downhole conditions.

Goals and Deliverables -- The goal of completing a writeup of the top two priority problems in each category and of compiling typical downhole conditions by 15 January 1981 has been established. The objective is to include in these writeups the following:

- Background discussion
- Definition of equipment limitations
- Projection of laboratory tests to be conducted
- Proposed alternative solutions intended for investigation

The "Solution/Technical Needs" section in each writeup will provide the direction for these investigations. The "Problem Discussion" provides the background information that will appear in the final report. Any additional information obtained will be used to expand these background discussions.

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6.6 Completion Technology Life Cycle Cost Model

Contractor: The BDM Corporation
Principal Investigator: A. Mansure (505) 848-5302
Contract Period: 10 November 1980 to 31 October 1981
Contract Number: 46-8777 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

Project Objective

The objective of this project is to provide a model that will evaluate (1) the cost of current completion technology, (2) the areas needing development, and (3) the cost benefit of new technology.

Project Status

The project was initiated late in this quarter. Work has begun on parameter identification and characterization.

Quarterly Progress

The project was divided into five tasks:

1. Parameter identification and characterization,
2. Model development,
3. Model implementation,
4. Model sensitivity and limitation analysis, and
5. Additional data identification.

The identification of the parameters that affect the life cycle cost of completing geothermal production and injection wells and the characterization of the response of the life cycle cost to the parameters were initiated and are continuing.

Model Overview -- BDM proposed a life cycle cost model that will make possible the representation of a wide spectrum of geothermal completion technologies, well types, and applications. This model is composed of three separate modules that include

1. The geothermal completion configuration definition,
2. The engineering cost and performance models, and
3. The life cycle cost algorithm.

The architecture of the overall model and the relationship between the modules is provided in Figure 6-4.

The first module of the geothermal completion configuration definition will include the procedural documentation and data worksheets required to process raw data into specified input for the program. A broad data base made available through the program will also be utilized by the user for the development of the completion configuration definition.

Once the basic data describing the geothermal completion configuration and application have been defined by the user, the data processing will be initiated within the computer model. A large portion of this processing will take place in the second module, which is composed of engineering and cost estimate models.

Four separate models are included in the cost and performance estimating module. These include the well drill cost model, the well completion cost model, the recurring operations and support cost model, and the well performance model. In each of these models, cost or performance estimating relationships will be provided to transfer the basic input data, provided by the configuration definition, into specific life cycle cost data.

The life cycle cost data processed by the engineering cost and performance estimate module will be automatically forwarded to the life cycle cost algorithm within the third module. If desired by the user, the processed life cycle cost data can be output to hard copy or to other storage media for future use.

The life cycle cost algorithm will compute the present value as well as the equivalent uniform annual cost of the geothermal well and will provide levelized energy cost and benefit cost ratios. The algorithm will be configured to allow the user to scan various economic parameters such as fuel escalation rates, inflation, or rate of return and will provide the results of the analysis in the form of computer output.

The computer code has been designed so that it may be available to Sandia personnel in a timely manner to assist with the program evaluation and decision-making processes. The balance between the user data processing and the automated calculations will allow a reliable, functional code to be developed, verified, and utilized within a 12-month period.

KEY

USER DATA PREPARATION

USER ENTERED DATA

BDM PROVIDED
COMPUTER CODE

• KNOWN DATA

• ENGINEERING CALCULATIONS

• DATA PROVIDED BY EXISTING COMPUTER CODES

Figure 6-4. Structure of the Geothermal Completion Technology Life Cycle Cost Model

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 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 and (2) 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.

The assessment of the state of the art of mapping lost circulation zones in geothermal wells was completed this quarter. The major summaries and conclusions that resulted from this project are reported in Section 7.1.

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PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>LOST CIRCULATION</u> <u>MAPPING TOOLS:</u> <u>MAURER ENGINEERING</u> COMPILE TOOL LIST INDUSTRY SURVEY EVALUATION OF TOOLS AND TECHNIQUES FINAL REPORT													

COMPLETED

COMPLETED

COMPLETED

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

7.1 Lost Circulation Mapping Tools and Techniques

Contractor: Maurer Engineering, Inc.
Principal Investigator: W. McDonald (713) 683-8227
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 was finished and included in the final report, which was subsequently completed and published separately.

Quarterly Progress

The final report was completed this quarter. The conclusions and results from the final report follow.

The results of the evaluation of the lost circulation mapping tools and techniques are shown in Tables 7-1 and 7-2. Table 7-1 is a master collation summarizing the tool evaluation data. Table 7-2 gives the rank ordering of tools based on an overall score, performance, and risk. The fact that a tool is not available lowers its overall rank, but such tools were not disqualified because some of the tools not available are worthy of further study.

In this study, the geothermal capabilities have been judged on a relative basis. For example, low-temperature tools have been ranked lower than high-temperature tools. This rank does not imply that these tools

Table 7-1
Tool Evaluation Scores

Tool	Type	Performance (50%)*							Risk (20)*					Cost (10%)*	Availabil-ity (20%)*	Weighted Final Score	Overall Rank
		Locate Zones	Quantify Size	Geothermal Operations	Accuracy	Reliability	Weighted Sum	Performance Rank	Development Stage	Design Approach	Testing	Weighted Sum	Risk Rank				
Borehole Sound-Temperature Survey	C	74	60	84	86	80	77	1	86	80	90	85	2	80	100	84	1
Borehole Televiewer	A	42	59	72	63	60	58	13	86	45	70	67	9	60	100	68	8
Compensated Sonic Logs	A	20	23	77	46	70	44	23	76	25	50	50	19	70	100	59	18
Conventional Resistivity Logs	E	34	23	80	63	70	52	19	86	30	30	48	21	80	100	64	14
Downhole Camera	O	26	63	23	50	80	44	23	29	30	60	40	24	70	60	49	20
Downhole Television	O	82	63	30	66	50	59	12	38	60	40	47	23	10	20	44	24
Dual Induction-Laterolog	E	34	23	83	68	70	54	15	90	30	50	57	12	70	100	65	12
Fluid Velocity Indicator	E	58	40	67	78	70	62	11	55	70	30	51	15	0	0	41	25
Focused Electrode Logs	E	42	26	77	65	70	54	15	76	35	40	51	15	80	100	65	12
Formation Density Log	R	18	26	91	43	70	47	22	91	30	30	50	19	70	100	61	17
Fracture Identification Log	E	42	26	77	71	70	55	14	90	45	50	62	11	70	100	67	9
Hot Film Anemometer	E	66	60	87	83	70	75	2	73	80	20	57	12	0	0	49	20
Hot Wire Survey	E	66	53	70	83	50	67	7	60	80	90	77	5	0	0	49	20
Impression Packers	M	26	63	91	66	90	64	9	91	40	90	74	7	90	100	76	7
Induction Logs	E	34	23	83	63	70	53	17	90	30	40	54	14	80	100	66	11
Lost Circulation Detector	E	74	56	67	78	70	70	4	65	75	50	63	10	0	0	48	23
Microresistivity Logs	E	36	26	70	58	70	50	21	76	35	40	51	15	80	100	63	15
Neutron-Log	R	10	16	91	45	70	43	25	91	15	10	38	25	70	100	57	19
Neutron-Sonic Porosity Log	C	34	26	77	58	70	51	20	76	35	40	51	15	60	100	62	16
Radioactive Tracer Log	R	58	53	77	73	70	65	8	70	80	80	76	6	90	100	77	5
Spinner Survey	M	58	60	77	78	60	68	6	91	80	80	83	3	90	100	80	3
Spinner-Temperature Survey	C	66	60	77	86	70	72	3	91	80	90	87	1	80	100	81	2
Spontaneous Potential Logs	E	34	30	80	55	80	53	17	91	25	30	48	21	100	100	67	9
Straddle Packer	M	58	53	74	78	90	69	5	64	70	80	71	8	90	100	78	21
Temperature Log	E	58	33	91	73	80	64	9	91	65	80	78	4	90	100	77	5

Legend

A = Acoustic
E = Electrical

M = Mechanical
O = Optical

R = Radioactive
C = Combination

* Indicates the weight that was given to the score of each of the four categories in the preparation of the weighted final scores.

Table 7-2
Ranking Comparisons*

<u>Tool</u>	<u>Overall Ranking</u>	<u>Performance Ranking</u>	<u>Risk Ranking</u>
Borehole Sound-Temperature Survey	1	1	1
Spinner-Temperature Survey	2	3	1
Spinner Survey	3	6	3
Straddle Packer	4	5	8
Radioactive Tracer Log	5	8	6
Temperature Log	5	9	4
Impression Packers	7	9	7
Borehole Televiewer	8	13	9
Fracture Identification Log	9	14	11
Spontaneous Potential Logs	10	17	21
Induction Logs	11	17	14
Dual Induction-Laterolog	12	15	12
Focused Electrode Logs	12	15	15
Conventional Resistivity Logs	14	19	21
Microresistivity Logs	15	21	15
Neutron-Sonic Porosity Log	16	20	15
Formation Density Log	17	12	19
Compensated Sonic Logs	18	23	19
Neutron-Log	19	25	25
Downhole Camera	20	23	24
Hot Film Anemometer	20	2	12
Hot Wire Survey	20	7	5
Lost Circulation Detector	23	4	10
Downhole Television	24	12	23
Fluid Velocity Indicator	25	11	15

* Duplicate rankings indicate identical score.

cannot be used in geothermal wells. Many such tools can be used at shallow depths and also in deeper investigation applications in wells that have been adequately cooled.

Overall Results — A scatter plot of the overall scores is presented in Figure 7-1, from which several facts are apparent. First, there are no low scores. This bias occurs because no tools were evaluated that are not used presently or that have not been used in the past in attempts at lost circulation detection and mapping. Next, there are no perfect or near-perfect scores. This bias occurs because each tool has limitations. Finally, the data fall into clusters. The seven tools in the top group are obviously better candidates and should be considered first in selecting a system that is used in an attempt to quantify lost circulation zones. These seven are listed separately in Table 7-3.

The sound-temperature survey received the top ranking because it offers excellent performance characteristics and reliability and has the capability to provide data in a wide range of harsh geothermal environments. This tool 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.

Good results can be obtained in the mapping of lost circulation zones with the spinner-temperature survey and the independent spinner survey, the second- and third-ranked tools, respectively, 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 hot wire survey.

The straddle packer and 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 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. 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.

The temperature log and the impression packer complement each other in function. Impression packers are best used after the lost circulation zones have been located because, like the temperature log, they are limited in their capability to map lost circulation zones in the complete sense. The use of impression packers after the use of the temperature log allows the zone to be completely quantified and the type of zone causing lost circulation to be determined.

Figure 7-1. Scatter Plot of Overall Scores

Table 7-3

Overall Best Tools

Tool	Type	Performance		Overall	
		Score	Ranking	Score	Ranking
Borehole Sound-Temperature Survey	C	77	1	84	1
Spinner-Temperature Survey	C	72	3	81	2
Spinner Survey	M	68	6	80	3
Straddle Packer	M	69	5	78	4
Temperature Log	E	64	9	77	5
Radioactive Tracer Log	R	65	8	77	5
Impression Packers	M	64	9	76	7

Performance Evaluation -- Performance is the key criterion for tool selection and represents 50% of the total evaluation score. It consists of the following elements, which are weighted as shown.

Capability to locate zones	22.5%
Capability to quantify size	22.5%
Capability to operate in geothermal well	22.5%
Accuracy	22.5%
Reliability	10.0%
Total	100.0%

The performance scores for the tools range from 43 to 77, and, as shown by the scatter plot in Figure 7-2, these scores are more or less uniformly distributed. However, the rank ordering of tools is different from that for the overall evaluation (see Table 7-2).

Figure 7-2. Scatter Plot of Performance Scores

The main reason for the difference is the lack of availability of the hot film anemometer, the lost circulation detector, and the hot wire survey, which lowered their overall score and ranking. The availability of reliable, higher temperature tools, particularly in the case of the hot wire survey, would increase capabilities to map lost circulation zones. Like the sound-temperature survey, the hot film anemometer is not influenced by mud type or weight and has high-temperature and high-pressure capabilities. However, the anemometer is less accurate than the sound-temperature survey. Unfortunately, there appear to be no plans for reintroducing these three tools into service.

For special applications, the use of impression packers, the downhole camera, downhole television, and borehole televiewer can be effective, particularly if the locations of the lost circulation zones are known. The borehole televiewer's ability to make a film record of the fluid flow into

the lost circulation zone and provide information on the orientation of the zone is the most realistic survey available. An added benefit is that the type of lost circulation zone, i.e., fractured or vugular, is discovered. But, because the borehole televiwer is restricted to being used in low-solids fluids and at low temperatures and pressures, 93°C and 41.4 MPa (200°F and 6,000 psi), its applicability is sharply curtailed. This limitation is shown in its geothermal ranking of eighth.

The downhole camera is available as a substitute for the downhole television, which, although accurate for mapping lost circulation zones, is limited in its 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.

The borehole televiwer provides no flow information but can help with the visualization of the borehole in most geothermal drilling fluids. Significant progress is being made by Sandia toward developing a high-temperature televiwer. The good performance scored by the impression packers can be misleading because some vendors may supply impression packers that have a poor high-temperature capability and that therefore should be used in a more limited temperature range.

The use of a particular survey in geothermal wells is strongly dictated by the temperatures and pressures encountered and the type and weight of drilling fluid used. Therefore, the system that combines good performance with the ability to function under a wide range of conditions is a better choice than one, such as the downhole television, that offers somewhat better results but is limited to a narrow range of effective operation.

The best performing tool for locating circulation zones in geothermal wells is the sound-temperature survey. While the survey cannot provide information on the orientation of the zone like the downhole television can, the survey can locate the depth of the zone, the most important aspect of location, with comparable accuracy. Furthermore, its high-temperature and high-pressure capabilities coupled with its insensitivity to the type or weight of mud used allow it to operate in a much wider range of conditions. These characteristics enable the system to provide successful results in almost all environments. A focused device may allow the lost circulation zone to be localized. However, no work is currently being done on such a device.

When the lost circulation detector and spinner-temperature survey are compared, the tradeoff of performance versus geothermal applicability is again noted. In this case, the difference in performance is slight, the lost circulation detector having the somewhat greater resolution in locating the depth of the zone. On the other hand, the temperature capabilities are quite different. Currently, there exist spinner-temperature logging tools rated to 260°C and 172 MPa (500°F and 25,000 psi). The original lost circulation detector was capable of operating up to 121°C (250°F). Both tools are affected by mud type and weight. The lost circulation detector requires conductive mud, while the spinner portion of the spinner-temperature log is subject to clogging when used in muds containing sealing

agents. A high-temperature lost circulation detector would be superior to the spinner-temperature log.

Several tools previously discussed and other tools that will be discussed have met with good success in locating lost circulation zones. The reasons for their assigned rankings are similar to those already discussed, namely,

1. The applicability of the method,
2. The accuracy with which the method can locate the zone, and
3. The geothermal capabilities of the method.

These tools can be classified into two main categories:

1. Tools that aid: These tools are used to locate fractures, vugs, and high-permeability zones that may be indicative of lost circulation. Such tools are unable to provide a characteristic response to lost circulation.
2. Limited application: This category represents those tools that can provide a characteristic response to lost circulation zones in certain limited instances.

The demarcation between the ability of these tools and the tools previously mentioned to locate lost circulation zones is quite sharp. These tools should only be used when (1) conditions are favorable for their use and (2) experience in the area has proved the worth of the method. Notable among these tools are the borehole televiewer, downhole camera, fracture identification log, and focusing electrode logs.

As noted, the borehole televiewer and the downhole television provide similar information. Both tools record features of the borehole wall such as intersecting fractures and vugs, the televiewer employing a near-field acoustic signal and the camera obtaining photographs. These two tools are much better suited to locating fracture and vugular zones than are the resistivity logs.

The fracture identification log (FIL) and the focusing electrode log are the best of the resistivity devices. The FIL logging sequence consists of a Dual Induction-Laterolog (DIL) and a microresistivity log. The DIL can provide a characteristic response to high-conductivity lost circulation zones, while the microresistivity device is useful in locating fractures that may be the cause of lost circulation.

The following tools are not recommended for locating lost circulation zones:

1. Impression Packers: The limited duration of investigation and the inability of the tool to provide a characteristic response to loss zones make its use impractical.
2. Neutron Logs: The tool's shallow depth of investigation, 5.1 to 15.2 cm (2 to 6 inches), and inability to provide a discernable response rule out its use.

3. **Formation Density Log:** The portion of the bulk density measurement subject to change is quite small. Furthermore, the tool is a shallow-investigation device that averages values over a fairly large volume. The cost versus benefit is too high to make this survey an acceptable method.

Risk, Cost, and Availability Evaluation -- The criteria of risk (20%), cost (10%), and availability (20%) constitute the other half of the evaluation weighting. The risk ranking is given in Table 7-2. Risk and availability of either 0 or 100% can significantly impact overall ranking. For example, the downhole television drops from a high performance potential to near the bottom of the list in overall potential because its use entails the risk of failure at high temperatures or in opaque muds. More important, however, is the fact that this survey is highly limited in availability. A high-temperature tool, if available, would place this tool above the spinner survey.

Three of the better tools for mapping lost circulation zones--the hot film anemometer, the hot wire survey, and the lost circulation detector--currently are unavailable, and no plans were found for reintroducing them into commercial use. A result is that these tools had to be judged on technical properties only, and the scores were therefore adjusted. Of these tools, the hot wire survey and the lost circulation detector were found to be highly successful in use, the testing of the latter being limited, however. The hot film anemometer had high-temperature capabilities, but it had not been tested as thoroughly as had the downhole television. The availability of high-temperature tools and the increased reliability of all tools, particularly of the hot wire survey, would increase the capability of mapping lost circulation zones.

Evaluation Conclusions -- The conclusions resulting from the assessment of the capability of equipment and methods to map and quantify lost circulation zones in geothermal wells follow.

1. Several methods are available to map lost circulation zones in geothermal wells at temperatures to 275°C (527°F) and 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. The future availability of high-temperature geothermal logging tools having a 260° to 288°C (500° to 550°F) and a 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., the 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.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>LOST CIRCULATION/ CEMENTING TEST FACILITY</u>													OCT 81 START OCT 81
EVALUATION OF EXISTING FACILITIES	COMPLETED												
CONCEPTUAL DESIGN	COMPLETED												
DETAILED DESIGN	<div></div>												
FABRICATION	<div></div>												
PRELIMINARY TESTING													

LEGEND: ACTIVITY PERIOD
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PLANNED START
STARTED

PLANNED COMPLETION
COMPLETED

7.2 Lost Circulation/Cementing Test Facility

Sandia National Laboratories

Technical Consultants: J. Kelsey (505) 844-6968
V. Behr (505) 846-0301

Project Objective

The first objective of this project is to construct a facility that will provide the capability to test lost circulation/cementing materials and techniques at simulated geothermal conditions. Following the construction of the facility, the evaluation of materials and techniques used for managing problems with cementing and with lost circulation in geothermal wells will begin. The final objective is to recommend the proposed solutions that stand the best chance for success in the field; thus, the facility will serve as a final screening facility before field testing.

Project Status

During the past quarter, the facility design approached the final stages, and hardware procurement and fabrication were started. The plans for the construction modifications necessary for the building of the facility were finalized. The computer necessary for system control and data acquisition was received.

Quarterly Progress

The facility is presently in the final design stages, and the fabrication and procurement of hardware have begun. Figure 7-3 is a schematic flow diagram of the facility. For a lost circulation test, the accumulators will serve to drive the fluid through the system because a lost circulation operation is primarily a constant pressure situation. The positive displacement mud pump will be used in a cementing test to pump mud and cement at the appropriate times through the test vessel. The test vessel, shown diagrammatically in Figure 7-4, is the actual test section of the facility. Inside the vessel will be a core formulated to simulate the formation and wellbore conditions that are found during a drilling or completion operation. Inside the simulated wellbore, which will be full-scale in diameter, will be a section of pipe to simulate either drill pipe or casing depending on the type of test. The core will also be surrounded by a fluid annulus that will allow any flow through the core to be drained off, thus simulating a permeable formation and/or a lost circulation zone.

Figure 7-3. Lost Circulation/Cementing Test Facility Flow Schematic

Figure 7-4. Lost Circulation/Cementing Test Facility Test Vessel

Following a test, the core will be removed and sectioned so that conclusions can be drawn from the test. The maximum and minimum design limits of the facility are shown in Table 7-4.

Table 7-4

Test Facility Characteristics

<u>Parameter</u>	<u>Limits</u>
Pressure	0.103 to 6.89 MPa (15 to 1,000 psi)
Temperature	21° to 204°C (70° to 400°F)
Flow Rate	No flow to 0.95 m ³ /min (250 gal/min)
Core Size	5- to 30.5-cm (2- to 12-in.) bore diameter

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND:

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○ PLANNED START

● **STARTED**

▽ PLANNED COMPLETION

▼ COMPLETED

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

Contractor: Maurer Engineering, Inc.
Principal Investigator: D. Dareing (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 permit 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

All background data for the evaluation of pressure balance drilling techniques are complete, and the final analysis and documentation of the results was initiated.

Quarterly Progress

The performance requirements for the pressure balance drilling methods have been established for both the Baca and The Geysers geothermal areas. Figures 7-5 and 7-6 show formation pressure magnitudes and distributions that represent the engineering baseline for evaluating various drilling techniques. Figures 7-5 and 7-6 also show the hydrostatic drilling mud pressure for a 1,000-kg/m³ (9-lb/gal) mud and illustrate the unbalanced pressure condition that can cause lost circulation.

Pressure profiles were developed for different air/mud ratios, and the various aerated systems are being studied to determine how they can best be applied. For example, Figure 7-7 compares pressure distributions for air/mud ratios of 10/1, 15/1, and 20/1 with the formation pressure for the

Figure 7-5. Pressure Distributions of the Formation Pressure and of a 1,000-kg/m³ (9-lb/gal) Drilling Mud for the Baca Area

Figure 7-6. Pressure Distributions of the Formation Pressure and of a 1,000-kg/m³ (9-lb/gal) Drilling Mud for The Geysers Area

Figure 7-7. Pressure Distributions for Air/Mud Ratios of 10/1, 15/1, and 20/1 Compared with the Formation Pressure of the Baca Area

Baca area. The 15/1 air/mud pressure nearly matches the formation pressure. It is usually desirable to have some production from the formation as opposed to losing drilling fluid to the formation, i.e., the formation pressure should be slightly greater than the drilling fluid hydrostatic pressure.

Figure 7-8 shows the pressure distribution of drilling mud when a parasite tube is used at 457 metres (1,500 feet) to produce a 15/1 air/mud ratio. The difference in the pressure gradient of the formation and mud columns is due to the temperature, which produces a lighter fluid. The average temperature of the drilling mud is less than formation temperature, and, therefore, the density of the drilling mud is greater than the density of the formation fluid.

The documentation of the description of each pressure balance system has begun. The parameter study of pressure profiles for each of the pressure balance systems was completed late in the quarter.

Figure 7-8. Pressure Distributions of Drilling Mud when a Parasite Tube Is Used at 457 meters (1,500 feet) To Produce 10/1, 15/1, and 20/1 Air/Mud Ratios for the Baca Area

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 (1) to expand capabilities to predict transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells, (2) to determine the optimal number, size, and placement of nozzles used for bit cooling and cleaning, (3) to optimize the design of polycrystalline diamond compact (PDC) geothermal bits by studying the stress buildup and chip formation processes of rock cutting tools utilizing PDC cutters, (4) to study the metallurgical composition of conventional drill stem and make compositional changes in the drill stem material to maximize its chemical resistance to geothermal H_2S environments without large sacrifices in its mechanical properties or cost, and (5) 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. The validation of the model involved the 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.

The 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 the use of the model.

A laboratory facility for use in optimizing drill bit hydraulics has been designed and fabricated at Sandia. Drilling Research Laboratory, Salt Lake City, Utah, has been modified to provide torque capabilities to 13,600 N·m (10,000 ft·lb) and rotary speeds to 500 rpm.

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 tetrafluoroethylene (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 drill 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 noncoated rings, and exhibited improved abrasion resistance.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE	
<u>BIT HYDRAULICS STUDIES</u>														
TEST FACILITY	COMPLETED													
DRILL PIPE MODIFICATION STUDIES	▼													
FLOW SIMILARITY	○—————													
FLOW VISUALIZATION	○—————													
CUTTER HEAT TRANSFER	○—————													
BOTTOMHOLE PRESSURE	○—————													
CHIP REMOVAL	○—————													
ANNULAR CHIP MOVEMENT	○—————													
SINGLE-CUTTER TESTS														

LEGEND: ——— ACTIVITY PERIOD

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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. The flow channel has been used to test the heat transfer coefficient measurement technique. A preliminary analysis of the results from this testing indicates that the measurement technique is accurate. The new drill pipe was installed in the bit hydraulics test stand, and the testing of the stand was initiated.

Quarterly Progress

The flow channel described in the previous progress report has been used to test the heat transfer coefficient measurement technique to be used in future bit hydraulics facility tests. Although the data have not been completely analyzed, a preliminary analysis indicates that the measurement technique produces accurate results and should provide valuable data for bit/cutter thermal analysis.

The new drill pipe has been installed in the bit hydraulics test stand. Testing to verify the operation of the test stand is currently under way. The initial results thus far reveal no problems. Actual bit hydraulics testing should begin early next quarter.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

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LEGEND:

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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 H_2S environment without large sacrifices to its mechanical properties or cost.

Project Status

An Internal R&D research report was issued. The test facility design and fabrication was completed. Compositional changes to the drill stem material were defined, and conventional drill stem material suitable for the corrosion fatigue study was identified. The dual-phase steel alloys have been made and the conventional drill stem material delivered. The processing of the dual-phase alloys has been completed, and the fabrication of specimens for the heat treatment experiments is proceeding. Fatigue tests have been completed in a variety of environments, using Grade E drill stem material to establish baseline data.

Quarterly Progress

In the previous progress report, the results of the fatigue tests conducted in several different environments were reported for the Grade E material manufactured by Wheeling-Pittsburgh. Fatigue tests on this material have now been completed in a brine solution saturated with H_2S gas. The results of these tests are shown in Figure 8-1, where the crack growth rate is plotted as a function of the stress intensity level. Note that the test data for the H_2S environment show more scatter than do the fatigue data taken in less severe environments, including dry air, NACE brine, and brine saturated with air and with nitrogen. The increase in scatter is common in fatigue tests when the environment, in this case, H_2S , strongly interacts with and corrodes the test sample.

A smooth curve drawn through the data in Figure 8-1 is shown in Figure 8-2. Superimposed on Figure 8-2 is the smooth curve drawn through the previously reported data taken in other environments. The effect of adding H_2S to the NACE brine solution thus is shown. The crack growth rate for this Grade E material in an H_2S environment is a factor of 2 to 10 times greater than the rate in environments that do not contain H_2S . Note that this result is valid only for the conditions of this test, which include a loading frequency of 5 Hz, ambient pressure, and a room temperature of approximately $25^\circ C$ ($77^\circ F$).

Figure 8-1. Fatigue for Grade E Alloy (Manufactured by Wheeling-Pittsburgh) in an H₂S-Brine Solution (5 Hz, $\Delta K = K_{\max.} - K_{\min.}$, $K_{\min.} = 0.1 K_{\max.}$)

Figure 8-2. Fatigue for Grade E Alloy (Manufactured by Wheeling-Pittsburgh) in Various Environments (5 Hz, $\Delta K = K_{\text{max.}} - K_{\text{min.}}$, $K_{\text{min.}} = 0.1 K_{\text{max.}}$)

Using the same frequency, pressure, and temperature, Figure 8-3 compares the crack growth rates in H_2S -saturated brine for the Wheeling-Pittsburgh Grade E material and a 4140 alloy. The 4140 alloy shows a significantly lower crack growth rate than is shown by the Grade E alloy.

Heat treating studies have been repeated on the steel alloy, Fe plus (by weight percent) 2.0Si-0.1V-0.1C, which has been hot forged and rolled into plate. The grain size was refined by the forging and rolling, and the presence of smaller grains will generally induce a different response to heat treating than that which is characteristic of the large-grained as-cast material. Figure 8-4 shows hardness as a function of annealing temperature for two different dual-phase heat treatments. The intermediate quench heat treatment is the conventional dual-phase heat treatment, while the step quench heat treatment was suggested by this study to produce a different microstructure and chemical partitioning. The hardness of the step quenched alloy is higher than that of the intermediate quenched material. The volume fraction of martensite as a function of annealing temperature is shown in Figure 8-5. At each annealing temperature, the volume fraction of martensite is higher for the step quenched alloy than for the intermediate quenched material.

At least some of the differences between the material heat treated by these two techniques are due to a difference in substitutional solute partitioning. The silicon and vanadium in this steel enter as substitutional solutes. Their behavior as a function of heat is shown in Figures 8-6 and 8-7. In Figure 8-6, the microprobe trace shows that the concentrations of silicon and vanadium increase in the ferrite compared with their concentrations in the martensite as a result of the intermediate quench, i.e., conventional, heat treatment. A significantly different situation is shown in Figure 8-7 as a result of the step quench heat treatment. The concentrations of silicon and vanadium do not vary from ferrite to martensite. This result indicates several possible responses of materials properties in addition to those shown in Figures 8-4 and 8-5. The lack of substitutional solute partitioning suggests that general corrosion rates may be improved. The uniform distribution of the substitutional solutes promotes hardenability in dual-phase steels and may also allow for further property improvements as a result of low-temperature tempering treatments.

Tensile tests have been performed on dual-phase steel alloys that have undergone the step quench heat treatment. Annealing temperatures ranged from 850° to 942°C (1,562° to 1,728°F), and, consequently, the volume fraction of martensite increased with increased annealing temperature. The martensite ranged from about 20% to about 40% by volume.

Samples were cut in two different orientations--longitudinal, i.e., parallel, to the rolling direction and transverse, i.e., perpendicular, to the rolling direction. Tensile specimens cut in circular cross section were used, and, thus, only one direction is used to specify the orientation.

The average results for strength and ductility are shown in Figures 8-8 and 8-9 as a function of annealing temperature for the step quench heat treatment. Figure 8-8 shows the results for the longitudinally oriented samples, while Figure 8-9 gives the results for the transversely oriented samples. The longitudinal samples show a relatively small variation in

Figure 8-3. Fatigue Behavior in H_2S -Saturated Brine for Grade E and 4140 Alloys (5 Hz, $\Delta K = K_{\text{max.}} - K_{\text{min.}}$, $K_{\text{min.}} = 0.1 K_{\text{max.}}$)

Figure 8-4. The Hardness of the Plate Material of Steel Alloy, Fe plus (by weight percent) 2.0Si-0.1V-0.1C, as a Function of Annealing Temperature for Two Dual-Phase Heat Treatments

Figure 8-5. The Volume Fraction of Martensite in Plate Material of Steel Alloy, Fe plus (by weight percent) 2.0Si-0.1V-0.1C, as a Function of Annealing Temperature for Two Dual-Phase Heat Treatments

Figure 8-6. Concentration Variations of Silicon and Vanadium in Ferrite and Martensite for Material Receiving an Intermediate Quench Heat Treatment

Figure 8-7. Concentration Variations of Silicon and Vanadium in Ferrite and Martensite for Material Receiving a Step Quench Heat Treatment

Figure 8-8. Tensile Test Results for Longitudinal Samples of Rolled Fe-2Si-0.1V-0.1C in the Step Quench Heat Treatment

Figure 8-9. Tensile Test Results for Transverse Samples of Rolled Fe-2Si-0.1V-0.1C in the Step Quench Heat Treatment

strength with annealing temperature. The transverse samples show an increase in strength with increasing annealing temperature. The ductility of the samples is measured by total elongation and by reduction in area. The longitudinal samples show a small variation in total elongation with annealing temperature. A greater variation is seen in the reduction of the cross-sectional area with annealing temperature. The variations in ductility reflect changes in strength; the higher strength samples have a lower ductility. In general, the ductility in the transverse specimens also shows a decrease with increasing strength.

Tensile data from the step quenched dual-phase alloys will be compared with data from the conventional, intermediate quenched, dual-phase alloys when the samples are returned from the machine shop. Corrosion fatigue tests will also be run on samples that receive one of the two types of heat treatments as the samples and machine time are available.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>ROCK MECHANICS</u>													
CALCULATIONS													
TOOL													
STRESSES													
FRICTIONAL FORCES													
HEAT INPUT	COMPLETED												
WEAR													
THERMAL ANALYSIS													
FLUID STUDIES													
EXPERIMENTS													
CHIP FORMATION													
FORCE DETERMINATION													
TEMPERATURE													
MEASUREMENTS	COMPLETED												
FRICTION MEASUREMENTS													
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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 polycrystalline diamond compact (PDC) cutters in order to optimize the design of bits using these cutters.

Project Status

A study of the procedures necessary for conducting chip formation testing was initiated. The 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.

Quarterly Progress

Analysis of Drag Bit Drilling -- Finite element models of the drag bit cutting process using PDC cutters are being developed with the ultimate objective of optimizing drill bit design. During this quarter, progress was made in three areas: constitutive modeling of rock, preparation of experiments to verify the rock model, and analysis of the experiments and of drag bit cutting.

A constitutive model that represents brittle materials, such as rock, concrete, and soil, that fail by cracking was developed and input into the HONDO II finite element code. Cracking can occur either due to maximum tensile stresses or to maximum shear stress, i.e., Coulomb's criterion. If cracking occurs, subsequent stresses are modified to reflect the presence and status of the crack, e.g., if the crack is open or closed.

A necessary part of the analysis effort is verification of the constitutive models. A contract has been placed with Atkinson, Noland & Associates to perform basic material tests on a Berea sandstone sample. This testing is in progress. More complicated prototypic tests that approximate the loading during drilling will be performed at Sandia on block specimens of the same material. These tests will be used for model verification using the material properties from the Atkinson tests. The preparation of the specimens and loading fixtures is in progress.

Preliminary analyses of the prototypic tests have been completed. Also, some exploratory analyses of the drag bit cutting process were made, including an analysis of the variations of the cutting tool parameters.

Calculations Including Downhole Pressure -- Recent calculations that describe a drag bit cutting rock have included the downhole hydrostatic pressure and indicate that the failure mechanism in the rock is a combination of shear and tensile fractures. Prior calculations that did not include the hydrostatic pressure displayed only tensile fractures. In all of the calculations, a vertical crack forms from the bottom of the bit, but the length of the vertical crack was much smaller in the runs with the hydrostatic pressure than in the runs without that pressure. A decrease of the length of the vertical crack may imply a decrease in the efficiency of rock removal.

The two calculations that included the hydrostatic pressure differed only in their postfracture treatment of the rock strength. In one calculation, there was no loss of strength after shear fracture, i.e., perfect plasticity. In the other, the cohesion of the Coulomb model was set to 1% of the cohesion of the competent rock after shear fracture, i.e., the rock behaved like sand after shear failure. The behavior of a real rock lies somewhere between these limiting cases. Similar vertical cracks formed from the bottom of the bit in both calculations. The formation of the crack ahead of the bit was very slow and steady in the perfect plasticity calculation. However, in the other calculation, a sudden catastrophic failure occurred in front of the bit at about 160 μ s.

These calculations indicate that (1) the downhole fracturing process may be different from the fracturing process observed in the laboratory unless the hydrostatic pressure is simulated in the laboratory, (2) the rock removal efficiency may decrease at high confining pressure, and (3) the postfailure strength of the rock strongly influences the chip formation process.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	★												END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>TEST CAPABILITIES</u> <u>EXTENSION: DRL</u>													
ROCK SPECIFICATION AND ACQUISITION													
BIT DYNAMICS													
HIGH-SPEED/TORQUE DRILL BIT TESTS													
HIGH-PRESSURE CAPABILITIES													

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

8.4 Modification and Extension of Testing Capabilities

Contractor: Drilling Research Laboratory, Inc. (DRL)
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

Rock specification data were 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. The testing on a pulsation dampener supplied by Hydrodyne Industries, Inc., 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.

Quarterly Progress

Rock Selection and Acquisition — The selection and acquisition of rock was completed in the last quarter of FY80. The information acquired from the performing of this task included (1) a report, "Representative Geothermal Rocks - Rock Specifications and Material Properties," which is reproduced in Appendix B, (2) a list of key rock properties affecting drillability, (3) a summary of factors affecting the rate of penetration, (4) an estimated comparison of rock drillability between selected representative rocks for geothermal areas and standard rocks, (5) cost data on representative rocks for geothermal areas, and (6) cost data for rocks for full-scale drilling tests.

High-Speed/High-Torque Capabilities — The new control panel for the two 93.2-kW (125-hp) drive motors was designed, and the parts were ordered and received. The idler arm on the main drive belt was redesigned, fabricated, and installed. Work on the 500- to 1,000-rpm drive system has been initiated.

Provisions are being made to temporarily hook up a controller for the second 125-hp drive motor for upcoming Sandia Stratapax™ bit tests in January. Due to the long delivery time for a few parts, the new and pertinent control panel will be completed in about 2 months.

High-Pressure Capabilities — Tests were conducted on a pulsation dampener supplied by Hydrodyne Industries, Inc., and the DRL Continental Emsco pulsation dampener. The purpose of the testing was to supply Hydrodyne with pulsation data that could be used to design a high-pressure, 103.4-MPa (15,000-psi) dampener for this program. The DRL standard 1,140-kg/m³ (9.5-lb/gal) drilling mud was pumped with the DRL 1,190-kW (1,600-hp) Continental Emsco FA 1600 triplex pump. All tests were conducted at 36,000 kg/m³ (300 gal/min) and at pressures of 13.8, 20.7, and 27.6 MPa (2,000, 3,000 and 4,000 psi). The gas pressures in the pulsation dampeners were varied, and the dynamic pressure fluctuations were recorded through the dynamic data acquisition computer program developed in this program.

The analysis of the pressure pulsation dampener test data was completed. The test conditions are summarized as follows:

Pulsation dampeners tested: Hydrodyne Industries, Inc., Model AX-50-5, 0.057-m³/min (15-gal/min) flow rate, 34.5-MPa (5,000-psi) service pressure
Continental Emsco Model PD55, 0.076-m³/min (20-gal/min) flow rate, 34.5-MPa (5,000-psi) service pressure

Pump: Continental Emsco FA 1600, 13.97-cm (5.5-in.) diameter liners by 30:48-cm (12-in.) stroke

Fluid: 1,140-kg/m³ (9.5-lb/gal) water-base mud

Flow Rate: 1.14 m³/min (300 gal/min)

Nominal Pressures: 13.7, 20.7, and 27.6 MPa (2,000, 3,000, and 4,000 psi)

Charge Pressures: Hydrodyne--2.07, 3.80, 5.17, and 6.76 MPa (300, 550, 750, and 980 psi)
Continental Emsco--0.34 (baseline), 2.07, and 3.80 MPa (50, 300, and 550 psi)

Data Acquisition: The strain-gage pressure transducer output was recorded on a PDP 11/34 computer; the data rate was 4,000 data points over a 5-second interval; the computer plot program calculates the average nominal pressure and the standard deviation of the plus or minus pressure fluctuation above or below the average.

The results are summarized in Figures 8-10 and 8-11. Figure 8-10 shows the percent of pressure pulsation from nominal pressure for both pulsation dampeners at different charge pressures. Figure 8-11 shows the percent of pulsation reduction from baseline conditions versus charge pressure at the three nominal pressures. The following conclusions can be drawn from the test data:

1. An increased charge pressure reduces the pressure pulsations,
2. The pressure pulsations increase slightly at higher nominal pressures,

Figure 8-10. Percent Pressure Pulsation from Nominal Pressure for Each Pulsation Dampener at Different Charge Pressures

Figure 8-11. Percent Pulsation Reduction from Baseline Conditions versus Charge Pressure at Three Nominal Pressures

3. The dampening effect that results from increasing charge pressures is greater at the lower nominal pressures, and the maximum pressure pulsation reduction approaches 35% to 45% at the higher charge pressures, and
4. The Hydrodyne pulsation dampener gave slightly better dampening than the Continental Emsco; however, this difference may be due to the fact that the Continental Emsco dampener was in-line with a 345-kPa (50-psi) charge during the Hydrodyne test but the Hydrodyne unit was not in-line during the Continental Emsco test.

In conjunction with the high-pressure pulsation dampener, Hydrodyne, Inc., has agreed to design and provide the internal components for a 103.5-MPa (15,000-psi) experimental pulsation dampener. Drawings for the unit will be prepared in December. DRL will then fabricate the external pressure chamber according to the Hydrodyne design.

In addition, A. Black and G. Tibbitts of DRL met with B. Humpy of Hydril in Houston, Texas, to discuss high-pressure pulsation dampening. Hydril now has a dampener with a working pressure of 41.4 MPa (6,000 psi) and a test pressure of 165 MPa (24,000 psi). The company is experimenting with a unit having a working pressure of 68.9 MPa (10,000 psi). The possibility of Hydril's providing a 41.4-MPa (6,000-psi) unit for the program in exchange for test data was discussed. The 68.9-MPa (10,000-psi) unit will not be available. Hydril is also developing several proprietary dampening media that may be made available for evaluation. Further details will be worked out with Hydril during the next reporting period.

Interaction with Hitco, Inc., was continued regarding the possible use of a new low-velocity pressure-reducing method. Hitco has completed a series of computer calculations and indicated their method will work for DRL's application. Cost estimates have been obtained from Hitco, and drawings of the DRL high-pressure pipe connections were delivered to Hitco. DRL is still waiting to receive some additional information from Hitco on the proposed low-velocity pressure-reducing system before a decision can be made to proceed.

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>ADVANCED WELLBORE</u> <u>THERMAL CODE:</u> <u>ENERTECH</u> EXISTING CODE MODIFICATION ADVANCED CODE DEVELOPMENT SINGLE-PHASE COMPRESSIBLE FLOW TWO-COMPONENT COMPRESSIBLE FLOW USERS' MANUAL FINAL REPORT													
	COMPLETE												
	COMPLETE

LEGEND: ACTIVITY PERIOD
 RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

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. The 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. The provision for a deviated wellbore and
2. Advanced code development providing for
 - a. The formulation of single-component, compressible flow in a wellbore,
 - b. The formulation of multicomponent, compressible flow in a wellbore, and
 - c. The 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 Part I report, covering the modified single-phase wellbore model and the compressible single-phase wellbore model, was completed and submitted to Sandia. The compressible single-phase wellbore model was thoroughly tested, and several minor errors were corrected. Work on the cuttings transport model is continuing.

Quarterly Progress

Cuttings Transport Model — The following equations were developed for a continuum mixture theory model for cuttings transport:

$$\Delta \left(\bar{\rho}_s v_s^2 \right) = F_{sg} + F_{sf} + \hat{P}, \quad (1)$$

$$\Delta \left(P + \bar{\rho}_g v_g^2 \right) = F_{gg} + F_{gf} - \hat{P}, \quad (2)$$

and

$$\bar{\rho}_s V_s \Delta \left(e_s + 1/2 v_s^2 \right) + \bar{\rho}_g V_g \Delta \left(h_g + 1/2 v_g^2 \right) = \dot{Q}, \quad (3)$$

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, and

$\dot{Q}$ = rate of heat input to mixture.

Part of the work done in September consisted of selecting correlations for the force terms listed above. The gravity force terms are

$$F_{sg} = \int_{Z_1}^{Z_2} \bar{\rho}_s g \cos \theta \, dZ \quad (4)$$

and

$$F_{gg} = \int_{Z_1}^{Z_2} \bar{\rho}_g g \cos \theta \, dZ. \quad (5)$$

The "bar" above the ρ in each equation denotes the in-mixture density, which is the volume average density of the mixture components and not the actual microscopic density of each component.

The friction force terms are assumed to have the same general form as that used in single-component compressible flow:

$$F_{sf} = 1/2 \int_{Z_1}^{Z_2} \bar{\rho}_s V_s^2 \frac{f^1}{D} (N_{Rs}) \, dZ \quad (6)$$

and

$$F_{sg} = 1/2 \int_{Z_1}^{Z_2} \bar{\rho}_g v_g^2 \frac{f^1}{D} (N_{Rg}) dZ . \quad (7)$$

The friction factor, f^1 , in Equations (6) and (7) is assumed to be the conventional friction factor correlation. The effect of the mixture is incorporated into the equations through the Reynold's number for the solids, N_{Rs} , and the Reynold's number for the gas, N_{Rg} . The gas Reynold's number can be evaluated from the in-mixture properties in the conventional way. To evaluate the solids' Reynold's number, a numerical value for the viscosity is needed for the solids. The value for the viscosity can be estimated through the application of the principles of the kinetic theory of gases. In kinetic theory, the viscosity, μ , is given by

$$\mu = 1/2 \rho \lambda \bar{c} , \quad (8)$$

where ρ is the density, λ is the mean free path, and $\bar{c}$ is the mean velocity. The mean free path for a Maxwellian velocity distribution is given by

$$\lambda^{-1} = \sqrt{2} \pi N d^2 ,$$

where N is the number of solid particles per volume and d is the average particle diameter. The effective viscosity of the solids can now be evaluated:

$$\mu_s = \frac{\rho_s d}{12\sqrt{2}} \cdot v_g . \quad (9)$$

The drag forces between the gas and the solids can be expressed

$$\hat{P} = \int_{Z_1}^{Z_2} 1/2 c_D \bar{\rho}_g \phi \left(v_g - v_s \right)^2 \frac{A_p}{v_p} dZ , \quad (10)$$

where

c_D is the drag coefficient of the solids,

A_p is the average cross-sectional area of a solid particle, and

V_p is the average volume of a solid particle.

The drag coefficient can be evaluated from terminal settling velocity data.¹

The numerical implementation of Equations (1) through (3) will be done by the method used to solve the compressible flow equations, except that there are now three equations to solve simultaneously rather than two:

$$A_1 \Delta V_s + B_1 \Delta V_g + C_1 \Delta T = D_1, \quad (11)$$

$$A_2 \Delta V_s + B_2 \Delta V_g + C_2 \Delta T = D_2, \quad (12)$$

and

$$A_3 \Delta V_s + B_3 \Delta V_g + C_3 \Delta T = \dot{Q}. \quad (13)$$

The independent variables are the velocities V_s , V_g , and the temperature T , and Equations (11) through (13) compute the change in these variables from the entrance to the exit of a duct ΔZ in length. The length ΔZ is chosen small enough so that Equations (1) through (3) can be linearized as Equations (11) through (13). The coefficients in Equations (11) through (13) have been derived,

where

$$A_1 = G_s + 1/4 \frac{f^1}{D} G_s \Delta Z + \hat{P}_1,$$

$$A_2 = -P\phi/V_s - \hat{P}_1,$$

$$A_3 = G_g V_g,$$

$$B_1 = -\hat{P}_1,$$

$$B_2 = -P/V_g + G_g + 1/4 \frac{f^1}{D} G_g \Delta Z + \hat{P}_1 ,$$

$$B_3 = G_s V_s ,$$

$$C_1 = 0 ,$$

$$C_2 = P_1/T ,$$

$$C_3 = G_s C_s + G_g C_p ,$$

$$D_1 = -\frac{G_s}{V_s} g \cos \theta \Delta Z - 1/2 \frac{f^1}{D} G_s V_s \Delta Z + \hat{P}_0 ,$$

$$D_2 = -\frac{G_g}{V_g} g \cos \theta \Delta Z - 1/2 \frac{f^1}{D} G_g V_g \Delta Z - \hat{P}_0 ,$$

$$\hat{P}_0 = 1/2 C_D \frac{A_p}{V_p} \frac{G_g G_s}{\rho_s} \frac{(V_s - V_g)^2}{V_s V_g} \Delta Z , \text{ and}$$

$$\hat{P}_1 = 1/4 C_D \frac{A_p}{V_p} \frac{G_g G_s}{\rho_s} \frac{(V_s^3 - V_g^3)}{V_s^2 V_g^2} \Delta Z .$$

Other variables have previously been defined.

These equations have been programmed, and the transport model is currently being tested.

Compressible Flow Model — The compressible flow model discussed in previous reports has been incorporated into GEOTEMP and successfully tested. Minimum changes have been made to the GEOTEMP input format. A copy of the revised input format is contained in Appendix C.

The compressible flow calculations have been programmed in a very general form so that different flow correlations and equations of state can be employed. In the current test program, ideal gas correlations and conventional darcy friction factors are used. The original GEOTEMP thermal simulator was retained, but, in the present version, the momentum equations are

solved simultaneously with the energy equations. Kinetic energy terms that were neglected in the original GEOTEMP have been added to the energy equations and cannot be neglected for compressible flow analysis. Test cases have shown that the momentum and energy equations must be solved simultaneously and that the sequential calculations scheme originally proposed introduces unacceptable errors.

Figure 8-12 shows the revised input data for compressible flow. The only changes from the previous input are

1. Flowing option 5 is added--forward circulation with compressible flow,
2. Fluid type numbers are interpreted--
1 = air
2 = nitrogen, and
3. The flow rate is given as SCF/MIN.*

The program output has been changed to reflect these input changes, and there will be no question about the input variables used. Figure 8-13 shows the standard GEOTEMP input summary with no changes. Figures 8-14, 8-15, 8-16, and 8-17 show the output to the problem given in Figure 8-12. Figure 8-14 gives the standard GEOTEMP distribution summary with two changes: (1) under flowing options, "air" is given as the fluid injected and (2) the flow rate is given as SCF/MIN. Figure 8-15 is completely new and summarizes the pressures, densities, temperatures, and velocities of the flowing stream for the tubing and the annulus. The pressures are determined to be the minimum pressures consistent with the specified flow rate. The possibility of choked flow is considered in this calculation, and the pressures are determined in order to prevent choking. Figures 8-16 and 8-17 repeat Figures 8-14 and 8-15 for a lower flow rate. These results are interesting because gravity has a greater impact on pressures than the flow has at this low flow rate.

Recently, the compressible flow code was extensively tested, and the following modifications have been completed:

1. A coefficient has been omitted from the kinetic energy term in the wellbore formulation.
2. A "free-format" input format has been adapted to GEOTEMP.
3. The GEOTEMP "change card" format has been modified to reflect input needs for gas drilling.
4. The time increment calculation routine has been modified to improve convergence.
5. An error in the calculation of depth during drilling has been corrected.
6. The code has been modified to allow wells deeper than 5,970 meters (19,600 feet). The new depth limit is 9,020 meters (29,600 feet).
7. A new heat transfer film coefficient is used for free convection during shut-in.
8. Choked flow in the drill bit is now detected, and annulus back pressure is adjusted to admit the specified flow rate.

* SCF/MIN = cubic feet per minute of gas flow at specified standard conditions of temperature and pressure.

GEOTEMP2 TEST DATA : COMPRESSIBLE FLOW						
CONTROL CARD	1	4	2			
TUBING CARD	1	3.9580	4.500	5000.0	2000.0	
CASING CARD	1	8.6810	9.625	5000.0	2200.0	
CASING CARD	2	12.3470	13.370	3000.0	2200.0	
CASING CARD	3	19.1240	20.000	1000.0	1000.0	
CASING CARD	4	29.0000	30.000	100.0	100.0	
GEOMETRY CARD		5000.	5000.	4500.	2000.	40.00
INITIAL TEMPERATURE		70.0	145.00	70.	20.	
FLUID CARD	1	10.	15.	5.	PRIMARY	
FLUID CARD	2	10.	15.	5.	ANNULAR	
INITIAL FLUID	1	1	2	145.0	0.0	
CHANGE CARD	5 0 1	70.	2000.	10.		
CHANGE CARD	5 0 2	70.	100.	20.		

Figure 8-12. GEOTEMP2 Revised Input Test Data: Compressible Flow

TUBING CONFIGURATION					
TUBING	ID, IN.	OD, IN.	TOP, FT.	BASE, FT.	CEMENT, FT.
1	3.958	4.500	0.	5000.	2000.0

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/100FT ²
FLUID TYPE NO.	2 ANNULAR
DENSITY=	10.0 LBM/GAL
PLASTIC VISCOSITY=	15. CENTIPOISE
YIELD POINT=	5. LBF/100FT ²

WELLBORE INITIAL STATE	
FLUID # 1	IN TUBING & TUBING ANNULUS
FLUID # 2	IN CASING - CASING ANNULI

Figure 8-13. GEOTEMP2 Standard Input Test Data: Compressible Flow

SET VARIABLES AT TIME = 0.000 DAYS

FLOWING OPTION = FORWARD CIRCULATION

AIR INJECTED INTO TUBING

INLET TEMPERATURE= 70. F

FLOW RATE = 2000. SCF/MIN

TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	0.1	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	70.0	73.0	73.0	73.0	73.0
400.	70.0	70.0	76.4	76.4	76.4	76.4
600.	70.0	70.0	79.7	79.7	79.7	79.7
800.	70.0	70.0	83.1	83.1	83.1	83.1
1000.	70.0	70.0	86.4	86.4	86.4	86.4
1200.	70.0	70.0	89.8	89.8	89.8	89.8
1400.	70.0	70.0	93.1	93.1	93.1	93.1
1600.	70.0	70.0	96.5	96.5	96.5	96.5
1800.	70.0	70.0	99.8	99.8	99.8	99.8
2000.	70.0	70.0	103.1	103.1	103.1	103.1
2200.	70.0	70.0	105.9	105.9	105.9	105.9
2400.	70.0	70.0	108.7	108.7	108.7	108.7
2600.	70.0	70.0	111.5	111.5	111.5	111.5
2800.	70.0	70.1	104.0	109.1	112.2	114.3
3000.	70.0	70.2	102.0	109.5	114.0	117.1
3200.	70.0	70.5	102.3	111.0	116.3	119.9
3400.	70.0	70.7	104.1	113.3	118.9	122.7
3600.	70.0	70.9	106.0	115.6	121.5	125.5
3800.	70.1	71.2	107.9	118.0	124.1	128.3
4000.	70.1	71.4	109.8	120.3	126.7	131.0
4200.	70.1	71.7	111.7	122.6	129.3	133.8
4400.	70.2	72.0	113.6	125.0	131.9	136.6
4600.	70.2	72.2	115.5	127.3	134.5	139.4
4800.	70.2	72.5	117.4	129.6	137.2	142.2
5000.	70.3	72.8	123.0	133.9	140.6	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 8-14. Temperature Distribution Output Resulting from the Compressible Flow Problem Given in Figure 8-12

FLOWING STREAM PROPERTIES

TUBING					ANNULUS			
DEPTH FT	PRESSURE PSIA	DENSITY LBM/CF	TEMP F	VELOCITY FT/SEC	PRESSURE PSIA	DENSITY LBM/CF	TEMP F	VELOCITY FT/SEC
0.	120.5	0.614	70.0	48.5	14.7	0.075	70.0	113.
200.	118.9	0.602	70.0	49.4	16.3	0.082	70.0	102.
400.	117.3	0.590	70.0	50.4	17.7	0.089	70.0	94.
600.	115.6	0.578	70.0	51.5	19.1	0.096	70.0	88.
800.	113.8	0.566	70.0	52.6	20.4	0.101	70.0	83.
1000.	111.9	0.553	70.0	53.8	21.6	0.107	70.0	79.
1200.	110.0	0.540	70.0	55.1	22.8	0.112	70.0	75.
1400.	107.9	0.527	70.0	56.5	24.0	0.117	70.0	72.
1600.	105.8	0.514	70.0	58.0	25.1	0.122	70.0	69.
1800.	103.6	0.500	70.0	59.6	26.2	0.126	70.0	66.
2000.	101.2	0.485	70.0	61.4	27.3	0.131	70.0	64.
2200.	98.7	0.471	70.0	63.3	28.3	0.135	70.0	62.
2400.	96.0	0.456	70.0	65.3	29.3	0.139	70.0	60.
2600.	93.2	0.441	70.0	67.6	30.3	0.143	70.0	59.
2800.	90.3	0.425	70.0	70.1	31.3	0.147	70.1	57.
3000.	87.3	0.408	70.0	72.9	32.2	0.151	70.2	56.
3200.	84.0	0.391	70.0	76.1	33.1	0.154	70.5	54.
3400.	80.6	0.374	70.0	79.7	34.0	0.158	70.7	53.
3600.	77.0	0.355	70.0	83.9	34.9	0.161	70.9	52.
3800.	73.1	0.336	70.1	88.8	35.8	0.165	71.2	51.
4000.	68.9	0.315	70.1	94.6	36.7	0.168	71.4	50.
4200.	64.4	0.293	70.1	101.7	37.6	0.171	71.7	49.
4400.	59.4	0.269	70.2	110.7	38.5	0.174	72.0	48.
4600.	53.9	0.243	70.2	122.6	39.3	0.177	72.2	47.
4800.	47.6	0.214	70.2	139.4	40.2	0.180	72.5	47.
5000.	40.2	0.180	70.3	165.8	41.0	0.183	72.8	46.

Figure 8-15. Flowing Stream Properties Output Resulting from the Compressible Flow Problem Given in Figure 8-12

SET VARIABLES AT TIME = 10.000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION

NITROGEN INJECTED INTO TUBING

INLET TEMPERATURE = 70. F

FLOW RATE = 100. SCF/MIN

TIME TO CHANGE DATA = 20.000 DAYS

TIME = 20.000 DAYS

ITERATIONS = 1

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	0.1	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	70.1	72.5	72.8	72.9	73.0
400.	70.0	70.3	75.3	75.8	76.1	76.4
600.	70.0	70.7	78.1	78.9	79.4	79.7
800.	70.1	71.2	80.9	82.0	82.6	83.1
1000.	70.1	71.7	83.9	85.2	85.9	86.4
1200.	70.2	72.5	86.6	88.2	89.1	89.8
1400.	70.3	73.3	89.5	91.3	92.4	93.1
1600.	70.4	74.2	92.4	94.4	95.6	96.5
1800.	70.6	75.3	95.3	97.6	98.9	99.8
2000.	70.8	76.4	98.3	100.7	102.2	103.1
2200.	71.0	77.5	100.8	103.3	104.9	105.9
2400.	71.3	78.8	103.3	106.0	107.6	108.7
2600.	71.6	80.0	105.8	108.6	110.4	111.5
2800.	72.0	81.3	106.8	109.6	111.6	114.3
3000.	72.3	82.5	108.5	111.4	113.6	117.1
3200.	72.7	83.7	110.2	113.4	115.9	119.9
3400.	73.2	85.0	112.6	115.9	118.5	122.7
3600.	73.7	86.4	114.9	118.4	121.1	125.5
3800.	74.2	87.8	117.3	120.9	123.7	128.3
4000.	74.7	89.2	119.7	123.4	126.3	131.0
4200.	75.3	90.7	122.1	125.9	128.9	133.8
4400.	75.9	92.1	124.5	128.4	131.5	136.6
4600.	76.6	93.6	126.9	130.9	134.1	139.4
4800.	77.3	95.2	129.3	133.4	136.7	142.2
5000.	77.7	96.4	136.4	138.6	140.7	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 8-16. Temperature Distribution Output Resulting from the Compressible Flow Problem Given in Figure 8-12 for a Low Rate of Flow

FLOWING STREAM PROPERTIES

TUBING					ANNULUS			
DEPTH FT	PRESSURE PSIA	DENSITY LBM/CF	TEMP F	VELOCITY FT/SEC	PRESSURE PSIA	DENSITY LBM/CF	TEMP F	VELOCIT FT/SEC
0.	16.1	0.079	70.0	18.1	14.7	0.072	70.0	5.7
200.	16.1	0.080	70.0	18.1	14.8	0.073	70.1	5.6
400.	16.2	0.080	70.0	18.0	14.9	0.074	70.3	5.6
600.	16.3	0.080	70.0	17.9	15.0	0.074	70.7	5.5
800.	16.3	0.081	70.1	17.9	15.1	0.075	71.2	5.5
1000.	16.4	0.081	70.1	17.8	15.2	0.075	71.7	5.4
1200.	16.4	0.081	70.2	17.7	15.4	0.076	72.5	5.4
1400.	16.5	0.082	70.3	17.7	15.5	0.076	73.3	5.4
1600.	16.6	0.082	70.4	17.6	15.6	0.077	74.2	5.3
1800.	16.6	0.082	70.6	17.5	15.7	0.078	75.3	5.3
2000.	16.7	0.082	70.8	17.5	15.8	0.078	76.4	5.2
2200.	16.7	0.083	71.0	17.4	15.9	0.079	77.5	5.2
2400.	16.8	0.083	71.3	17.4	16.0	0.079	78.8	5.2
2600.	16.8	0.083	71.6	17.3	16.2	0.080	80.0	5.1
2800.	16.9	0.083	72.0	17.3	16.3	0.080	81.3	5.1
3000.	16.9	0.084	72.3	17.2	16.4	0.081	82.5	5.1
3200.	17.0	0.084	72.7	17.2	16.5	0.081	83.7	5.0
3400.	17.0	0.084	73.2	17.1	16.6	0.082	85.0	5.0
3600.	17.1	0.084	73.7	17.1	16.7	0.082	86.4	5.0
3800.	17.1	0.085	74.2	17.0	16.8	0.083	87.8	4.9
4000.	17.2	0.085	74.7	17.0	16.9	0.083	89.2	4.9
4200.	17.2	0.085	75.3	16.9	17.0	0.084	90.7	4.9
4400.	17.3	0.085	75.9	16.9	17.1	0.084	92.1	4.9
4600.	17.3	0.086	76.6	16.8	17.2	0.085	93.6	4.8
4800.	17.4	0.086	77.3	16.8	17.3	0.085	95.2	4.8
5000.	17.4	0.086	77.7	16.8	17.5	0.086	96.4	4.8

Figure 8-17. Flowing Stream Properties Output Resulting from the Compressible Flow Problem Given in Figure 8-12 for a Low Rate of Flow

9. The viscosity routine has been modified to supply viscosities up to 816°C (1,500°F).

A tape of the corrected version of the code was sent to Sandia. To document the changes listed above, the modified code has been directly compared to the version of GEOTEMP supplied to Sandia at the 28 May 1980 meeting.

A report was completed on the compressible single-phase wellbore model. This report was incorporated into the Part I report, which was completed and presented to Sandia. A meeting was held with Sandia on 13 October 1980, at which the compressible flow model was discussed and the current status and goals of the project were reviewed.

Reference

1. G. W. Govier and K. Aziz, The Flow of Complex Mixtures in Pipes (Huntington, NY: Krieger Publishing Co., 1977).

9. ADVANCED DRILLING SYSTEMS

Advanced and innovative drilling systems will be required in order to meet the long-term 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) optimize the design of cavitating-jet nozzles for use with rock cutting bits, (4) develop high-pressure fluid delivery systems compatible with fluid-jet drill bits and downhole motors, and (5) 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 the on-going 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.

The 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 were used to correlate rock response to cavitation/water-jet action.

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 the 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 (5,000 psi). The design parameters include a differential pressure across the bearing/seal package of 0 to 13.8 MPa (0 to 2,000 psi), a flow rate of 0.006 to 0.013 m³/s (100 to 200 gal/min), a rotational speed of 100 to 1,000 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.

The performance potential and economics of erosion drilling systems were assessed and characterized. These activities involved the collection, analysis, and presentation of the available data. The conclusions reached as a result of the study are reported in Section 9.1.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>STUDY OF HIGH-PRESSURE JET DRILLING TECHNOLOGY: FOSTER-MILLER</u> STATE-OF-THE-ART ASSESSMENT ESTABLISH SYSTEMS DEFINITION AND COSTS ESTABLISH SYSTEMS OPERATING CHARACTERISTICS AND REQUIREMENTS EVALUATE OPERATIONAL IMPACTS RECOMMEND NEEDED DEVELOPMENT FINAL REPORT													

COMPLETED

COMPLETED

COMPLETED

COMPLETED

EXTENSION

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

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.

The final economic analysis was completed. Typical East Mesa geothermal well costs were received. The final report is nearing completion. A no-cost time extension to 28 February 1981 has been requested.

Quarterly Progress

The final report has been submitted to Sandia in draft form. The major conclusions from this report follow.

1. Jet drilling systems are capable of significant penetration rate increases over conventional drilling systems,
2. Fluid jet drilling costs appear to be comparable to conventional drilling costs,
3. There are serious technical problems associated with both clear jet and abrasive jet drilling systems, and
4. Clear jet drilling systems designed to maximize mechanical/hydraulic cutting interaction would offer the greatest potential for drilling cost reduction.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>DOWNHOLE MOTOR SEALS AND BEARINGS; TERRA TEK</u>													
SEAL TESTING	<div></div>												
BEARING/SEAL PACKAGE TESTING	<div></div>												

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 May 1981
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 (5,000 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 laboratory tested in the Bearing/Seal Package Test Facility.

Both the seal tester and the Bearing/Seal Package Test Facility are being overhauled in preparation for the next series of tests. Seal and bearing testing and evaluation will continue next quarter.

Quarterly Progress

Seal Testing and Evaluation — Five seal tests were completed during this reporting period. (See Table 9-1.) Following is a description of each test.

DMT-049 tested the mesh matrix-copper wire seals with SAE 660 bronze backup rings. The seal would not hold a static differential pressure, and the test was terminated. Apparently, the seal was too stiff and would not flex under a differential pressure to form a seal.

DMT-050 tested the mesh matrix-glass fiber seals with SAE 660 bronze backup rings. The test seal ran for 1.97 hours before failing. Apparently, this type of seal was too stiff to form an effective seal.

DMT-051 tested the canted high-temperature, corrosion-resistant (HTCR) seal. The seal ran for approximately 5 minutes before failing. An inspection of the seals after the test indicated that the seal lips had been damaged by the installation process, which was the same problem that had been experienced previously with the 1.27-cm (1/2-in.) cross section canted

Table 9-1

Seal Test Conditions

Test No.	Seal Type	No. of Pressure Rings	Backup Rings	Duration h	Chrome Shaft Coating Finish (rms) μm ($\mu\text{in.}$)	Diametral Clearance: Shaft to Backup Rings mm (in.)
049	Mesh matrix-copper wire	3	SAE 660 bronze	0	0.1 to 0.2 (4 to 8)	0.406 (0.016)
050	Mesh matrix-glass fiber	3	SAE 600 bronze	1.97	0.1 to 0.2 (4 to 8)	0.406 (0.016)
051	Canted HTCR	2	SAE 660 bronze	0	0.2 to 0.3 (8 to 12)	0.203 (0.008)
052	Grafoil®-phosphor bronze	3	Backup III w/4 ea 0.397 mm (1/64-in.) thick leaves	3.73	0.1 to 0.2 (4 to 8)	Flexing leaves: 0.025 (0.001) Backup ring: 4.318 (0.170)
053	Variseal® (double spring)	1	SAE 660 bronze	0.93	0.2 to 0.3 (8 to 12)	0.127 (0.005)

Note: All tests were run at 412 rpm and at a ΔP of 10.3 MPa (1,500 psi).

seal. Additional testing of the canted seal will occur with the 1.905-cm (3/4-in.) cross section seal.

DMT-052 tested the Grafoil®-horizontal laminates with the zero clearance backup system III, which uses four 0.397-mm (1/64-in.) thick leaves. The seal ran for 3.73 hours before failing. An inspection of the seals after the test showed that a large amount of material was lost from the seal ring closest to the flexing leaves.

DMT-053 tested the Variseal®-double spring seal. The seal ran for approximately 1 hour before failing. An inspection of the seals after the test showed the same cracking of material that was observed in DMT-047. The seals from DMT-053 and DMT-047 were sent to American Variseal Corporation, Denver, Colorado, for inspection and analysis.

After the completion of DMT-053, the seal tester was disassembled for a complete overhaul. The slip rings were rewired, new bearings were installed on the shaft, and the 1.905-cm (3/4-in.) cross section main vessel seal carrier was installed. New 1.905-cm (3/4-in.) cross section spacers are being manufactured, and the design is being completed for the mud injection system.

The matrix is being established for the next series of tests in the seal tester. The following seals will be tested with abrasives:

1. Canted seal, 1.905-cm (3/4-in.) cross section: The seals have been ordered from Utex Industries.
2. HTRC Chevron Packing: The seals have been ordered from Utex. The two new test sleeves manufactured out of 9310 steel for the HTRC seals have been completed.
3. Face Seals: The seals have been ordered by Sandia.
4. Variseal®: The failure analysis report on the Variseal® will be received and reviewed by Terra Tek before additional tests are scheduled.

The design of the mud injection system was completed. The system will consist of a cylinder with mud on one side of the piston and hydraulic fluid on the other side. The hydraulic fluid will be pressurized by the existing Haskel pump. The mud will be injected into the seal tester low-pressure port and will pass through a valve downstream of the seal tester and into a mud reservoir. The valve will be used to create a backpressure on the mud. At each 4-hour shutdown, the cylinder will be recharged with mud.

At the present time, the high-pressure port is in the middle of the two test seals, with the low-pressure ports on each end of the shaft next to the vessel seals. Therefore, the vessel seals experience a differential pressure of 6.89 MPa (1,000 psi). In the mud injection system, the high- and low-pressure ports will be reversed. Thus, the vessel seal packs will experience a higher differential pressure than they do at present. An endurance test of the vessel seals with a differential pressure of 17.2 MPa (2,500 psi) was performed late in this quarter. The data from this test will be used to plan the test conditions for the seal tests in the next phase of the program.

A new torque cell has been strain gaged and calibrated.

The lubricant has been changed from Texaco EP 85-90 to Pacer PLX-014 in the seal tester.

Bearing/Seal Package Testing and Evaluation — The Bearing/Seal Package Test Facility is being overhauled in preparation for the next series of tests. The hydraulic lines to the dynamic actuator and the hydraulic drive motor are being changed so that the 746-kW (100-hp) power supply will drive the motor and the 29.8-kW (40-hp) power supply will drive the dynamic actuator. These modifications are being made to increase the rpm capacity of the drive motor. New load and torque cells have been installed, and the system has been completely rewired for greater reliability. This work has been performed in anticipation of the heavy testing schedule for the bearing/seal package.

Phase IV Final Report — The rough draft of the Phase IV Final Report was completed and distributed late in this quarter. The conclusions from this report will be presented in the next quarterly.

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GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

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													NOV 81

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.

Quarterly Progress

The modifications in the seal retaining system on the Ryton floating piston are complete. The piston will be shipped to Terra Tek.

Recommendations will be made in the final report for modifications applicable to the basic Variseal® design. These recommendations will be based on recent runs in the seal test machine and on recent experience from the Los Alamos National Laboratory hot dry rock program.

The evaluation of the face seal proposal is continuing, and this work will be summarized in the final report.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	FISCAL YEAR 81												END DATE
	O	N	D	J	F	M	A	M	J	J	A	S	
<u>PERCUSSION DRILLING HAMMERS AND BITS</u>													
CONVENTIONAL PERCUSSION SYSTEMS TESTS (DRL)													
DESIGN OF IMPROVED PERCUSSION SYSTEMS													
IMPROVED PERCUSSION SYSTEMS TESTS (DRL)													
DATA COLLECTION													
BIT GAGE WEAR (CSM)													
HOT ROCK DRILLING (CSM)													
INDUSTRIAL DATA (RTI)													

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

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.4 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 and the designing and testing of improved percussion systems were completed. The collecting of data on bit gage wear and on hot rock drilling is continuing, as is the collecting of data from industry.

Quarterly Progress

Percussion Drilling Tests — Tests of percussion drilling equipment were performed at the Drilling Research Lab, Salt Lake City, Utah, during the week of 20-25 October 1980. The tests had three major objectives:

1. To evaluate the performance of a liquid-powered hammer designed and built by Amoco Research,
2. To assess the performance of commercially available air hammers operated with stable foam as the driving fluid, and
3. To measure the life of a modified commercial air hammer operated at high temperature, up to 260°C (500°F).

All of these objectives were met, and a summary of the test results is given below:

1. The Amoco hammer was operated over a range of flow rates, pressure drops, and bit weights; the rates of penetration with a 20.0-cm (7-7/8-in.) roller bit in Sierra white granite varied from 2.4 to 6.4 m/h (8 to 21 ft/h). (See Figure 9-1.) Two attempts were made to operate the hammer with air as the driving fluid, but, in each case, the hammer's valve assembly broke because of insufficient damping. This was not unexpected because the valve dashpot was designed for mud, not air.
2. A Mission A63-15 hammer was successfully operated on stable foam having an exhaust liquid volume fraction (LVF), i.e., the ratio of liquid volume to total volume, in the range of 0.02 to 0.08, the same range that gives maximum lifting capacity for the foam. For

- = AMOCO HAMMER, WATER USED AS DRILLING FLUID
- = AMOCO HAMMER, AIR DRILLING, 1.90 MPa (275 psi), 38.2 m³/min (1350 scfm)
- ▲ = AMOCO HAMMER, AIR DRILLING, 0.86 MPa (125 psi), 22.1 m³/min (780 scfm)
- ◆ = ROLLER BIT, NO HAMMER, 40 rpm

Figure 9-1. Drilling Performance Using a Reed M-70, 20.0-cm (7-7/8-in.) Roller Bit

a given gas flow rate, the hammer's penetration rate was comparable with air or with foam. However, the higher viscosity of the foam required a higher pressure drop to maintain the given flow rate.

3. The Mission A63-15 hammer was fitted with high-temperature O-rings, a makeup ring, and a foot valve and was operated at temperatures up to 232°C (450°F). The hammer ran for 14.5 hours before failing, and the failure mode was apparently not related to the high temperature.

Each of the test activities is described in more detail below.

Amoco Hammer. This tool was developed by Amoco Research about 10 years ago but was not produced because of its limited life, which is approximately 25 hours with mud, and its lack of applicability to the shale encountered in much oil drilling. The hammer is fitted with a sliding valve assembly to vent the incompressible mud, but, in theory, it can operate on any fluid. If a single tool with a high rate of penetration could operate on air, mud, or foam, there would be great flexibility in drilling varying formations.

The hammer was fitted with a Reed M-70, 20.0-cm (7-7/8-in.) tungsten carbide insert bit used in previous tests, and the test rock was the same Sierra white granite used for all previous percussion penetration tests. The test plan was to run the hammer on water for baseline data at different flow rates and bit weights and then to try the operation with air and/or foam. The water-powered operation was done, and typical hammer operation was observed; that is, penetration rate was not a strong function of bit weight but was significantly affected by changes in fluid flow rate. These results are shown in Figure 9-1. Figure 9-1 also shows that the mud hammer performance is roughly comparable to a Mission oil field air hammer drilling the same rock with the same bit. The flow rates for the Amoco tool represent the fluid needed to operate the hammer mechanism plus flow through a 0.635-cm (1/4-in.) diameter bypass used to improve hole cleaning.

After the water tests were completed, the air compressor was connected, and air flow rates up to 0.708 m³/s (1,500 scfm), the compressor's limit, were fed to the hammer. Even with the high flows, the pressure differential (ΔP) across the hammer was only about 1.4 MPa (200 psi), and so the penetration rate was low, about 2.6 m/h (8.4 ft/h). In an attempt to develop higher pressures, the 0.635-cm (1/4-in.) bypass was plugged, and the hammer was restarted. After operating for about 20 seconds, the hammer stopped. It was disassembled, and the procedure revealed that a part in the sliding valve assembly had broken. Because this assembly had been used for other tests, there was some reason to believe that it had been weakened by the earlier use. This explanation of the failure was disproved when a spare valve assembly was installed and the hammer was run again. Failure occurred in less than 10 seconds of operation because the new part broke in the place in which the original part had broken in the first air test.

The hammer incorporates a cylindrical sliding section that serves as a dashpot to mitigate the stress in the valve stem when the valve assembly reaches the upper limit of its travel. It is reasonable to assume that the

damping is adequate when liquid is the driving fluid but is almost nonexistent with gas. The possibly inadequate damping by the air could have caused the breaking of the sliding valve assemblies in these tests. A different design could provide gas damping, but a scheme to accommodate all fluids would be much more difficult to achieve. A development of this tool for air is probably unnecessary because its performance on air would not be too different from that of existing oil field hammers.

Foam Tests. Stable foam with its great lifting capacity and low flow rate requirements compared to air offers definite advantages for drilling with low-density fluid. Foam is usually characterized by its LVF. The test plan was to attempt to operate a Mission A63-15 hammer with the LVF of the exhaust foam in the maximum lifting capacity range of 0.02 to 0.08. Because of the high pressure drop through the hammer, exhausting the foam to atmospheric pressure with the optimum LVFs would require a very high LVF of the intake foam. This problem was alleviated by restricting the foam exhaust to create a backpressure; this solution meant that the expansion ratio for a given pressure drop was much less than for atmospheric exhaust. The foam was generated by the injecting of air and surfactant into a cylindrical chamber partially filled with sheet metal mixing tubes. These tubes, approximately 1.27 cm (1/2 in.) in diameter by 2.54 cm (1 in.) in length, are stamped to create many vanes on the inside and thus to provide a larger surface area and a high turbulence in flow through them. After the air and the liquid enter the top of the chamber, they pass through the tube-filled section, to be whipped into foam that flows out the bottom of the chamber.

The hammer was operated in this test setup at air flow rates from 0.448 to 0.142 m³/s (950 to 300 scfm) and exhaust LVFs from 0.02 to 0.08. (See Table 9-2.) The data from the tests indicate that the hammer will operate on foam at a somewhat lower performance than on air, but it is not clear which variables are most important to the penetration rate. In particular, it seems odd that the pressures and blow frequencies remain almost constant over a wide range of flow rates. A possible explanation for this is that the total pressure drop across the hammer occurs in stages the relative magnitudes of which change with the flow rate. For example, the air passage through the bit might act as an orifice to increase the pressure on the downstream side of the piston as the flow rate increases, thus preventing the ROP and frequency from increasing with greater flow. Also, the penetration rate is not clearly correlated with the obvious parameters except that a tendency exists for ROP to increase with rotary speed.

Another variable that does not appear explicitly in Table 9-2 is gage wear on the bit. After test No. 9, several data points were observed at which the ROP fell very low—under 0.61 m/h (2 ft/h). The flow rates were raised to previous values, but the performance could not be repeated. An examination of the bit showed large flat spots on the gage carbides, which probably resulted from the reaming of 20.0-cm (7-7/8-in.) holes with the roller bit. The reamed holes were less than one foot in total depth, which shows the ease with which carbides can be worn as well as the extreme sensitivity of ROP to such wear. Between tests 9 and 10, the worn bit was replaced by one that had been used for tests in February 1980 but showed no flat spots. The replacement of the bit returned the performance to its original level.

Table 9-2

Mission Hammer Tests on Foam

Test Number	rpm	Blow Frequency Hz	Air Flow m ³ /s (scfm)	Liquid Flow		LVF	Pressure						ROP	
				m ³ /s x 10 ⁻³	(gal/min)		Intake MPa (psi)	Exhaust MPa (psi)	AP MPa (psi)				m/h	(ft/h)
Reference, with air only	15	13.0	0.354 (750)	0	(0)	0	1.45 (210)	0.21 (30)	1.24 (180)				12.19	(40.0)
1	15	—	0.448 (950)	1.26	(20)	0.016	2.28 (330)	0.48 (70)	1.79 (260)				10.97	(36.0)
2	15	15.5	0.354 (750)	0.95	(15)	0.019	2.14 (310)	0.62 (90)	1.52 (220)				6.49	(21.3)
3	25	15.5	0.354 (750)	0.95	(15)	0.019	2.21 (320)	0.62 (90)	1.59 (230)				8.29	(27.2)
4	15	16.2	0.354 (750)	1.58	(25)	0.029	2.34 (340)	0.55 (80)	1.79 (260)				9.97	(32.7)
5	25	16.0	0.354 (750)	1.58	(25)	0.029	2.28 (330)	0.52 (75)	1.76 (255)				9.75	(32.0)
6	15	16.0	0.236 (500)	0.63	(10)	0.022	2.34 (340)	0.72 (105)	1.62 (235)				6.31	(20.7)
7	25	15.2	0.236 (500)	0.63	(10)	0.021	2.21 (320)	0.66 (95)	1.55 (225)				6.86	(22.5)
8	15	16.2	0.236 (500)	1.58	(25)	0.048	2.34 (340)	0.62 (90)	1.72 (250)				7.50	(24.6)
9	25	16.0	0.236 (500)	1.58	(25)	0.048	2.34 (340)	0.62 (90)	1.72 (250)				8.99	(29.5)
(changed bit)														
10	15	15.3	0.354 (750)	0.95	(15)	0.016	2.00 (290)	0.52 (75)	1.48 (215)				7.32	(24.0)
11	15	16.6	0.354 (750)	2.02	(32)	0.045	2.48 (360)	0.69 (100)	1.79 (260)				7.62	(25.0)
12	15	14.5	0.236 (500)	0.76	(12)	0.019	1.79 (260)	0.48 (70)	1.31 (190)				7.01	(23.0)
13	15	16.2	0.236 (500)	1.77	(28)	0.056	2.31 (335)	0.66 (95)	1.65 (240)				5.94	(19.5)
14	15	16.2	0.236 (500)	2.52	(40)	0.084	2.59 (375)	0.69 (100)	1.90 (275)				7.47	(24.5)
15	15	11.3	0.142 (300)	0.57	(9)	0.022	1.31 (190)	0.45 (65)	0.86 (125)				1.86	(6.1)
16	15	13.2	0.142 (300)	1.10	(17.5)	0.050	1.62 (235)	0.55 (80)	1.07 (155)				1.52	(5.0)

Note: The bit weight used for all tests was 2,270 kg (5,000 lb). The size of the bits used was 20.32 cm (8 in.).

Further work will be done to analyze the performance of the foam-driven hammer and to assess the effect of foam operation on the well cost model.

High Temperature. The Mission hammer was fitted with silicone rubber O-rings, a silicone rubber makeup ring, and a foot valve made of DuPont's Vespel plastic. In the first high-temperature test of this tool, the factory foot valve, made of Delrin, failed in approximately 4 minutes. Vespel is a polyimide compound having a higher strength at 260°C (500°F) than Delrin has at room temperature. The primary disadvantage of Vespel is its brittleness compared to Delrin.

The modified hammer, surrounded by an insulated shroud, was set up to drill into a cast-iron target. Hot air passed through the hammer with the bit off bottom brought the temperature of the hammer up to 177°C (350°F) over a 1-hour period. After an hour, the hammer was lowered, and drilling began. It continued for about 4 hours with no apparent problems other than a higher than normal pressure drop for the flow rate. After 4 hours, the hammer stopped and was cooled and disassembled. When the hammer was removed from the insulated sub, several pieces of insulation and seven of the foam generator mixing tubes were found to be on top of the air distribution manifold. Further disassembly revealed that the piston was jammed in the case, which had stopped the hammer's operation. When the piston was forced out of the case, several metal fragments from the mixer tubes were found between the piston and the case wall. Apparently, the mixer tubes had been blown back up the supply line when the compressor bypass was opened with backpressure still on the hammer. The hammer was cleaned and inspected for gouges, the compressor lines were blown clean (a dozen other tubes having remained in line), and the test setup was reassembled. The temperature was brought up to 204°C (400°F), and drilling was resumed. After 9 more hours of operation, the cast-iron billet was drilled through, and the hammer was cooled to ambient temperature and a new billet installed. The temperature was brought up to 232°C (450°F), and drilling was resumed. After about 1-1/2 hours, the hammer stopped and was once again cooled and disassembled. When the bit was removed, the foot valve was found to be crushed, but it did not appear to have been distorted by the heat. When the retaining lip in the bit that holds the foot valve in place was measured, the lip was found to have worn to a diameter larger than the diameter of the retaining protrusion on the foot valve. (See Figure 9-2.) This wear allowed the valve to come out of the bit and be crushed by the piston. Measurements taken of the remains of the valve did not indicate significant wear on its surface. It is not clear if the Vespel material of which the foot valve is made is inherently abrasive or if particles of the air swivel insulation were trapped in the valve-bit interface before the first stoppage. An examination of the silicone rubber parts showed them to be in generally good condition, although there was some wear on one edge of the makeup ring.

Although the total run of 14-1/2 hours at high temperature is not in itself enough, it is encouraging that the failure mode was not directly attributable to high temperature. There seems to be good potential for further development of this system into a long-lived high-temperature tool.

Figure 9-2. Schematic of Foot Valve Failure

GEOTHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>IMPROVED CAVIJET®</u> <u>NOZZLES: HYDRONAUTICS</u>													OCT 81
INITIAL NOZZLE TEST (DRL)	COMPLETED												
MODIFY TEST FACILITY	COMPLETED												
FLUID-DYNAMIC STUDIES	COMPLETED												
ROCK CUTTING TESTS													
FINAL NOZZLE TESTS	▽												
NOZZLE CHARACTERIZATION TESTS	○→▽												
FLUID DYNAMIC STUDIES (UCSD)	→▽												
BIT TESTS (DRL)	▽												
FLOW STUDIES (HSC)	▽												

LEGEND:

ACTIVITY PERIOD

RESCHEDULED

PLANNED START

STARTED

PLANNED COMPLETION

COMPLETED

9.5 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 the Drilling Research Laboratory (DRL) and the modification of the Hydronautics test facilities were completed. Rock cutting tests and cavitation inception studies were initiated and are continuing. Bit tests at DRL and flow studies at the University of California at San Diego were completed at the end of this quarter.

Quarterly Progress

Cavitation Inception Studies — Testing under this task was continued during this quarter with work being carried out both in the air-flow facility and in the high-pressure chamber (HPC). These tests concentrated on the Pulser-Fed Cavijet® concept. A systematic variation of nozzle design parameters was performed in air to establish the most promising combination of nozzle orifices and resonating chamber configurations. The Pulser chamber geometry parameters were varied to obtain a design with an optimum performance at a Mach number around $M = 0.08$ to 0.11 ($\Delta P = 6.9$ to 13 MPa [1.0 to 1.9 ksi] in water). It was required that the design demonstrate vortex-ring cavitation with a passively modulated but otherwise "clean" jet. The parameters were restricted to values that were deemed appropriate for adaptation to roller bits.

The performance of each configuration was compared on the basis of the relative sound pressure transmitted by the nozzle in tests in air. The best geometry was duplicated in a more rugged version for subsequent testing in the HPC with water.

The Pulser-Fed Cavijet® was tested in the HPC for cavitation inception, which was detected by means of a pressure transducer placed in the wall of the HPC. This type of Cavijet® was found to have its peak pressure fluctuation intensity at a Mach number of 0.08 . At this condition, the cavitation number (σ_i) for inception was also maximized, with $\sigma_i = 1.09$. The same Cavijet® nozzle operating at identical conditions but without the

upstream Pulser section had cavitation inception at $\sigma_1 = 0.90$. The cavitation number here is the ratio of the HPC ambient pressure to the pressure drop across the exit CaviJet® nozzle. In practice, the pressure drop across the entire Pulser-Fed CaviJet® system was measured and corrected for the head lost in the upstream Pulser section. This head loss was determined from tests in air to be about 22% of the total pressure drop.

To begin the effort of recontouring the flow within the Pulser-Fed CaviJet® in order to reduce the internal head losses experienced with this concept, a diffuser profile has been designed. Following the successful approach that was established during the earlier phases of its development, this new design first will be tested in the Hydronautics air-flow facility. This diffuser section will be fabricated from a versatile casting material that seems to allow the rapid and economical iterations that are necessary in the type of design-test-evaluate-redesign cycle that is being pursued. This casting material is a two-part epoxy compound having very fine aluminum particles suspended in one of the components. It can easily be poured into complex shapes, sets up overnight, and can either be machined or added to if changes are found to be required after the initial casting has been completed.

Initial Rock Cutting Tests in the HPC — A number of alternative approaches to the actual cutting of rock have been examined in an effort to assess the relative performance of various nozzle types. Currently, attention is being directed toward the original concept of using Berea sandstone as the test material. Although this rock type is more homogeneous than many that have been tested, there are considerable variations among specimens and at different locations on the same 15-cm (6-in.) cube of rock. Thus, a "calibration" scheme is being developed to take into consideration these intrinsic variations in the erodibility of the specimens. A standard nozzle will be used at standard conditions of pressure and translation velocity to slot each face of a specimen that has been used in prior HPC nozzle performance evaluations. It is possible that this standardized approach will minimize the apparent scatter and permit meaningful comparisons among nozzle types.

The rock cutting technique, using only the tops and bottoms of the 15-cm (6-in.) cubes of Berea sandstone with the jet impinging perpendicularly to the bedding planes, has proven to be a viable way to obtain reasonably reproducible data. The test mode being used in these nozzle evaluations is slot cutting with 10 passes at 7.6 cm/s (3 in./s) as the standard exposure. This technique seems to minimize or smooth out the undulations created by using a single pass at a lower velocity of translation. Also, multiple passes are more replicative of the actual action of a drill bit.

Using a thin piece of metal plate in lieu of the shutter plate to cover one-half of the rock face, smaller standoffs can now be run, and, also, each half of that face can be used for direct comparisons of two nozzles and/or operating conditions.

A comparative test series is being run with a plain CaviJet® nozzle and a Pulser-Fed CaviJet® nozzle, both having the same exit-orifice nozzle diameter (d) of 4.98 mm (0.196 in.). (See Figure 9-3.) In standoff

Figure 9-3. Slot Cutting Comparison Tests in Berea Sandstone

distance tests run at 9.7, 15.7, and 22.4 mm (0.38, 0.62, and 0.88 in.), the deepest slots were created at the smallest distance, where $X = 9.7$ mm (0.38 in.). Note that this corresponds to an $X/d = 1.9$, which is below the X/d of 2 to 4 reported in an earlier, stationary mode, rock cutting study by Hydronautics.¹ The slot depths for both nozzles were more than two times deeper at $X = 9.7$ mm (0.38 in.) when compared to $X = 22.4$ mm (0.88 in.), where $X/d = 4.5$. Further consideration will be given to why such differences in optimum standoff seem to arise between the stationary and slot cutting modes of operation.

The results are now being analyzed both by comparing the results achieved by the two nozzles and the results achieved at several cavitation numbers. Preliminary analyses indicate that, when pressure drops at the internal chamber are accounted for so that a direct comparison at the same exit-orifice velocity can be made, then the Pulser-Fed Cavijet® nozzle creates a deeper slot than does the plain Cavijet® nozzle.

These analyses also indicate that the cause of the variability between tests must be only partially attributed to scatter in the intrinsic erodibility between rock specimens. Indeed, following the "calibrating" of several specimens at the same time in a large, atmospheric pressure test chamber, the standard deviation of the variation in calibration slot depth was found to be only about 5% of the mean depth. However, when the same test conditions were applied to different specimens in the HPC at different times, the resulting variability, or standard deviation of the mean depth, was about 10%. Thus, it is believed that about half of this variability must be attributed to other factors such as settings of pressures and translation speeds. Efforts to further minimize the overall test variability will be made.

Certain apparent inconsistencies in the results achieved during the use of Berea sandstone to compare a plain Cavijet® and a Pulser Cavijet® nozzle have led to the question of how this particular type of rock responds under impulsive loading and under high ambient pressures. Although these questions are only now beginning to be examined, an initial check of the literature revealed that similar rock cutting tests on Berea sandstone have produced comparable observations.

For instance, rock cutting tests performed by Nebecker^{2,3} with an interrupted jet in air showed improved rates of cutting as compared with those achieved by a conventional steady jet in a number of rock types including limestones and granite. With Berea sandstone, however, Nebecker reported essentially no difference in erosion between the two jets. In single-bit-tooth erosion tests conducted both statically and dynamically under elevated ambient pressures with water or with drilling mud as the pressurizing fluid, Maurer⁴ observed a number of effects on the erodibility of Berea sandstone and Indiana limestone. It is possible that Maurer's observations can be related to some of the apparent inconsistencies that have been seen both recently and during earlier phases of this program. The inconsistencies of rock responses will be explored further, and attempts will be made to reconcile the future results with those described previously and with other studies that can be identified.

Bit Test at DRL — Preliminary design drawings for these bits were made by NL/Hycalog and conveyed to Hydronautics for review and comment. Final designs were made. Three 3-bladed bits were made, each containing three nozzles. The bits are identical except that only Cavijet® nozzles were inserted into the first bit, only Pulser Cavijet® nozzles were inserted into the second bit, and only conventional oil field nozzles were inserted into the third bit at the time of fabrication.

The bit tests at DRL were completed in December 1980. The results are presently being analyzed and will be reported in the next quarterly report.

Flow Studies in the High-Speed Channel (HSC®) -- Flow studies in the HSC® were conducted late in this quarter. The results of these tests will be reported in the next quarterly report.

References

1. HYDRONAUTICS, Incorporated, Technical Report 7821-1, Evaluation of Cavijet® Cavitating Jets for Deep-Hole Rock Cutting, SAND07-7067 (Albuquerque: Sandia Laboratories, 1979).
2. E. B. Nebecker and S. E. Rodriguez, "Percussive Water Jets for Rapid Excavation," Scientific Associates Technical Reports, 1973.
3. E. B. Nebecker and S. E. Rodriguez, "Development of Percussive Water Jets," Scientific Associates Technical Reports, May 1979.
4. W. C. Maurer, "Bit-Tooth Penetration Under Simulated Borehole Conditions," Transactions, Volume 234, (AIME, 1965), pp I-1433 to I-1442.

GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	END DATE
<u>FLEXIBLE DRILLING PIPE:</u> <u>L'GARDE</u> HIGH-TEMPERATURE POLYMER COMPATIBILITY EXPERIMENTS	<div></div>												

LEGEND: ACTIVITY PERIOD
 RESCHEDULED

○ PLANNED START
 ● STARTED

▽ PLANNED COMPLETION
 ▼ COMPLETED

9.6 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 modify existing flexible drill pipe so that it can be used in geothermal drilling applications.

Project Status

The project was begun in the latter part of FY80. Several materials have been tested at 2.07 MPa (300 psi) and 250°C (482°F) and at 68.9 MPa (10,000 psi) and 125°C (257°F). These tests showed Teflon PFA, EPDM 267, and Aflas 291 to be the most extrusion-resistant of the materials tested. Additional testing of these materials is in progress.

An aging study that examines the chemical effect of drilling fluids on liner candidates was initiated and is continuing.

Quarterly Progress

Liner Material Criteria — At the present time, flexible drill pipe cannot be used in geothermal applications primarily because of the temperature and pressure limitations of the inner and outer liners. These liners are made from a thermoplastic called Polyamide 11, which cannot be used at temperatures above 100°C (212°F). Above 100°C (212°F), under pressure, Polyamide 11 extrudes into the gap of the steel, spiral "Z" section causing this section to prematurely fail by fatigue during flexing. The general function of the inner thermoplastic liner is to contain the drilling fluids and prevent abrasion and corrosion of the steel carcass. The function of the outer liner is to prevent abrasion and corrosion and to prevent ingress of fluids from the outside.

For geothermal applications, the ideal liner should not extrude into the gap of the spiral overlay under the following set of conditions:

1. At 68.9 MPa (10,000 psi) at 125°C (257°F) within 24 h or
2. At 2.1 MPa (300 psi) at 250°C (482°F) within 4 h.

In addition, the candidate liner materials should not react with the drilling fluids and well components and should be fairly flexible and be processible by standard extrusion methods. These characteristics qualitatively translate to the following set of property criteria:

- Low creep at elevated temperatures
- High heat-distortion temperature
- High melting point
- High thermal stability
- Medium elongation (>15%)
- High compressive yield strength
- High abrasion resistance
- Good stability toward drilling fluids, water, oxygen at low concentration, and brine

Extrusion Screening Tests — On the basis of these property criteria, the following materials were selected for extrusion screening tests to be carried out by L'Garde.

<u>Designation</u>	<u>Supplier</u>	<u>Type</u>
Polyamide 11	L'Garde	Thermoplastic
Tefzel 280	DuPont	Fluorocarbon
Teflon PFA	DuPont	Fluorocarbon
Noryl	General Electric	Polyether
UDEL 1700	Union Carbide	Polysulfone
Astrel 360	Carborundum	Polysulfone
Victrex	ICI	Polysulfone
PEEK	ICI	Polyketone
EPDM 267	L'Garde	Ethylene/propylene
Aflas 291	L'Garde	Fluoroelastomer

All of these materials extruded at 125°C (257°F) and 250°C (482°F) under the conditions indicated previously. (See Figures 9-4 to 9-14.) Teflon PFA was the most extrusion-resistant material, followed by EPDM and Aflas. Additional testing was initiated on Polyamide 11, Teflon PFA, EPDM, and Aflas and is continuing. Some preliminary results from these tests are shown in Tables 9-3 and 9-4. Both Polyamide 11 and Teflon PFA appear to be of marginal use at 125°C (257°F) when the pressure exceeds approximately 48.3 MPa (7,000 psi). However, prior testing has shown that the Teflon does not melt at 250°C (482°F).

Figure 9-4. Test Apparatus and Test Fixtures Used To Test the Flat-Polymer/Simulated-Z-Section Combination under High Temperature and Pressure

Figure 9-5. Polyamide 11 Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-6. Aflas 291 Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-7. Y267 EPDM Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-8. Teflon PFA 350 Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-9. Tefzel 280 Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-10. Noryl ENG 265 Sample Tested at 250°C (482°F) and 2.07 MPa (300 psi)

Figure 9-11. UDEL Sample Tested at 250°C (482°F)
and 2.07 MPa (300 psi)

Figure 9-12. Polyamide II Sample Tested at 125°C (257°F)
and 68.9 MPa (10,000 psi)

Figure 9-13. Aflas 291 Sample Tested at 125°C (257°F) and 68.9 MPa (10,000 psi)

Figure 9-14. Teflon PFA 350 Sample Tested at 125°C (257°F) and 68.9 MPa (10,000 psi)

Table 9-3

**Polyamide 11 Liner Penetration Distance into the
Coflexip Zeta Pipe Gap for a 1-Hour Test**

Temperature °C (°F)	Pressure MPa (psi)	Gap Width mm (in.)	Penetration mm (in.)
25° (77°)	34.5 (5,000)	1.02 (0.04)	0.25 (0.01)
		1.52 (0.06)	0.25 (0.01)
		2.03 (0.08)	0.76 (0.03)
	68.9 (10,000)	1.02 (0.04)	0.25 (0.01)
		1.52 (0.06)	0.25 (0.01)
		2.03 (0.08)	0.76 (0.03)
125° (257°)	17.2 (2,500)	1.02 (0.04)	0.51 (0.02)
		1.52 (0.06)	0.51 (0.02)
		2.03 (0.08)	1.02 (0.04)
	34.5 (5,000)	1.02 (0.04)	1.02 (0.04)
		1.52 (0.06)	1.52 (0.06)
		2.03 (0.08)	1.52 (0.06)
250° (482°)	51.7 (7,500)	1.02 (0.04)	1.52 (0.06)
		1.52 (0.06)	1.78 (0.07)
		2.03 (0.08)	2.29 (0.09)
	68.9 (10,000)	1.02 (0.04)	3.05 (0.12)
		1.52 (0.06)	4.06 (0.16)
		2.03 (0.08)	5.59 (0.22)
250° (482°)	Sample Melts		

Table 9-4

Teflon PFA Liner Penetration Distance into the Coflexip Zeta
Pipe Gap for a 1-Hour Test at 125°C (257°F)

<u>Pressure, MPa (psi)</u>	<u>Gap Width, mm (in.)</u>	<u>Penetration, mm (in.)</u>
17.2 (2,500)	1.02 (0.04)	0.51 (0.02)
	1.52 (0.06)	0.76 (0.03)
	2.03 (0.08)	1.02 (0.04)
34.5 (5,000)	1.02 (0.04)	0.76 (0.03)
	1.52 (0.06)	1.27 (0.05)
	2.03 (0.08)	2.03 (0.08)
51.7 (7,500)	1.02 (0.04)	1.52 (0.06)
	1.52 (0.06)	2.54 (0.01)
	2.03 (0.08)	3.05 (0.12)
68.9 (10,000)	1.02 (0.04)	2.29 (0.09)
	1.52 (0.06)	3.05 (0.12)
	2.03 (0.08)	5.08 (0.20)

None of the materials could withstand the pressure of 68.9 MPa (10,000 psi). Therefore, the evaluation of metal and plastic reinforcements that are compatible with liner materials was initiated.

Liner Aging Study -- The chemical effect of drilling fluids can be an important consideration in the selection of liners for flexible drill pipe. Furthermore, drilling fluids may contain small concentrations of O₂ because of the entrainment of air during the pumping process. This entrained oxygen could cause oxidative degradation of the liner. Because of the concern about the possibility of degradation by the drilling fluids and entrained oxygen, an aging study was initiated at Sandia.

In this study, Tefzel, a copolymer of ethylene and tetrafluoroethylene, and EPDM rubber were aged at 125°C (257°F) for 30 days in the following environments:

- 200 ppm O₂
- 10 ppm O₂
- H₂O (no O₂)
- Drilling mud, HTM-1 (no O₂)

The occurrence of degradation was monitored by measuring the tensile properties of the materials before and after exposure and by electron spectroscopy for chemical analysis (ESCA). The latter analysis provides information on changes of surface chemical composition. The results obtained are summarized in Tables 9-5 and 9-6.

Table 9-5

Effect of Drilling Fluid Ingredients on the Tensile Properties of EPDM and Tefzel at 125°C (257°F) for 30 Days

<u>Material</u>	<u>Environment</u>	<u>Change in Tensile Strength, %</u>	<u>Change in Elongation, %</u>
EPDM 267	200 ppm O ₂	-7.5	-16.0
	9 ppm O ₂	-15.4	-25
	H ₂ O (no O ₂)	0	0
	HTM-1 mud (no O ₂)	0	0
	Approximate error, %	4	6
Tefzel	200 ppm O ₂	-5.6	-18.6
	9 ppm O ₂	-3.4	-18.6
	H ₂ O (no O ₂)	-7.2	-24
	HTM-1 mud (no O ₂)	-5.4	21
	Approximate error, %	4.3	5

Table 9-6

Surface Elemental Composition of Liner Candidates before and after Exposure to 200 ppm O₂ at 125°C (257°F) for 30 Days

<u>Liner Material</u>	<u>Element</u>	<u>% Composition by Atomic Weight</u>	
		<u>Before Exposure</u>	<u>After Exposure</u>
Tefzel	Fluorine	42	15
	Oxygen	0	8
	Carbon-- as CF ₂	25	6
	Carbon-- as CH ₂	32	72
	Oxygen	20	22
EPDM 276	Carbon	71	69
	Silicon	9	9

These data indicate that EPDM was attacked by oxygen even at low concentrations but was inert to both water and geothermal mud, HTM-1, at 125°C (257°F). In spite of the loss of tensile properties after the exposure to oxygen, there was no change in the elemental composition of the surface. Bulk analyses of oxygen by neutron activation analysis will be made.

In contrast, Tefzel appeared to undergo degradation in all four types of environments. Furthermore, the exposure to oxygen at 200 ppm markedly altered the surface composition of Tefzel. Oxygen was incorporated into the surface at the expense of fluoride. Somewhat surprisingly, the CH₂ molecules of Tefzel were not attacked. EPDM is still a viable liner candidate.

However, these findings suggest that Tefzel appears to lack the requisite oxidative stability for this application. Further studies are in progress to determine if any synergistic effects occur with combinations of oxygen and water or oxygen and mud.

Meetings — D. Wesenberg and C. Arnold of Sandia reviewed L'Garde's progress on 3 October 1980. There was some redirection of the investigations as a result, which, for the scope defined, can be accomplished within existing resources.

C. Arnold of Sandia and G. Friese of L'Garde went to Coflexip on 10 October and met with J. McManus and J. M. Gueguen. They answered many of L'Garde's questions and agreed to get additional information from France.

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GEOHERMAL WELL TECHNOLOGY-DRILLING AND COMPLETIONS PROGRAM

FISCAL YEAR 81

LEGEND: ACTIVITY PERIOD PLANNED START PLANNED COMPLETION
 RESCHEDULED STARTED COMPLETED

9.7 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. The conceptual design is being finalized on sealing techniques for high-pressure pumps, swivels, and drill pipe. A program review was held in December 1980. An innovative design has been proposed for concentric drill pipe, and the design is being finalized on a downhole intensifier.

Quarterly Progress

During the past quarter, detailed designs for a high-pressure swivel and mud pump were completed using the concept of a controlled leakage seal. Also, a design has been made for concentric-string drill pipe using a positive connection for both inner and outer strings rather than the more conventional stab connection for the inner string. Figure 9-15 shows diagrammatically how the joints would be constructed. This dual string would allow much more flexibility in the total system design because two separate fluids could be delivered downhole. Work on a downhole intensifier is continuing with emphasis being placed on a sealing technique and on a method of switching the driving fluid within the intensifier.

Figure 9-15. Concentric-String Drill Pipe Using a Positive Connection for Inner and Outer Strings

APPENDIX A

Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Comparative Analysis of Combined Flat-Plate PV/T Collectors with Separate PV/T Collectors, Report No. SAND80-1494, E. R. Hoover, Sandia National Laboratories, Albuquerque, New Mexico, October 1980.

"Investigation of Changes in the Structure of Clays During Hydrothermal Study of Drilling Fluids," L. L. Carney and N. Güven, Texas Tech University, Society of Petroleum Engineers Journal, October 1980.

Continental Drilling in Thermal Regimes: Drilling In-Situ Diagnostics and Sampling, SAND80-2164A, by R. K. Trayer, S. G. Varnado, and A. F. Veneruso, Sandia National Laboratories, to the American Geophysical Meeting of the American Geophysical Union, San Francisco, 8-12 December 1980.

Rock Cutting Technology, by J. M. McClaun, interdepartmental, to Sandia National Laboratories, Albuquerque, New Mexico, 10 December 1980.

APPENDIX B

**Representative Geothermal Rocks:
Rock Specifications and Material Properties**

**H. R. Pratt
A. D. Black
Drilling Research Laboratory**

REPRESENTATIVE GEOTHERMAL ROCKS: ROCK SPECIFICATIONS AND MATERIAL PROPERTIES

Several rock types have been selected to represent either geothermal reservoirs or formations that are drilled in order to reach reservoir depths. The representative rock types selected are available from surface outcrops in the form of quarried blocks, boulders, or cored samples and can be obtained for full-scale laboratory drilling or drilling-related tests.

In order to formulate a framework for selecting appropriate rock, the reservoir characteristics of several geothermal areas have been delineated. (See Table B-1.) The information gathered includes the geothermal area, rock type, reservoir type, reservoir depth, geologic structure, temperature, pressure, salinity, availability of material properties, and companies participating in the geothermal area.

On the basis of the geologic and rock property data available for these geothermal areas, several representative rock types were selected. These include sedimentary rock such as hard low-porosity sandstone, soft porous sandstone, siltstone, and shale; volcanic rock such as tuff, andesite, and basalt; and intrusive igneous rock such as granite and granodiorite. A geologic description of the seven representative rocks follows.

1. Crab Orchard Sandstone: a light reddish-brown to gray, fine-grained, quartzose sandstone. The detrital quartz grains, 3.9 mils (0.1 mm) in diameter, form a tight interlocking mosaic without authigenic cement. The grains tend to lie with their long axes parallel to the bedding planes. A small amount of carbonate and muscovite is found throughout the rock. This is a very strong, low-porosity sandstone.
2. Kayenta Formation: a buff to light reddish-brown, medium-grained, quartzose sandstone with carbonate cement. The quartz grains are rounded to subangular. The sandstone is friable and porous with bedding thicknesses ranging from 10 cm to 2 meters (3.9 inches to 6.6 feet).
3. Mancos Formation: a gray to black silty shale to siltstone, fine-grained with clay minerals, montmorillonite percentage ranging up to 10% to 15%. The samples must be preserved to prevent dehydration and air slacking. Siltstone stringers are 0.1 cm (0.39 in.) and larger.
4. Upper Provo Canyon Tuff: a light grayish-pink, heterogeneous, partially welded porous tuff with volcanic rock fragments and glass shards ranging to 1.0 cm (0.39 in.). The matrix is very

Table B-1

Reservoir Characteristics of the Representative Geothermal Areas

Geothermal Areas	Principals	Reservoir Type	Rock Type	Reservoir Depth km (ft x 10 ³)	Geologic Structure	Temp. °C (°F)	Pressure	Material Properties	Salinity
The Geysers, CA	Union Shell Burma	Dry steam	Graywacke (sandstone)	1.5 to 2.1 (5 to 7)	Faulted, fractured	241° (465°)	Subhydro- static 3.4 MPa (500 psi)	Available core tested, some data confidential	Low
Imperial Valley, CA:									
Niland	Phillips, So. Cal. Ed., Union	Hot water	Sandstone and shale, some meta- morphitic, deep	1.5 to 2.1 (5 to 7)	Sed. basin, porous matrix	191° to 371°	Hydro- static	East Mesa Source Book	High, 20% to 30% High
Brawley	Union			1.5 to 2.1 (5 to 7)	Porous, some fracture	(375° to 700°)			
Heber	Chevron, Rep., Rep. Geo., USBR			1.2 to 3.4 (4 to 11)	Porous				
East Mesa				1.2 to 3.4 (4 to 11)	Fracture, faulting				Moderate, 10%
Roosevelt Hot Springs, UT	Phillips	Hot water and steam	Granite	0.6 to 1.2 (2 to 4)	Fractured faulted	204° to 260° (400° to 500°)	Hydro- static-	Available core tested	Low to moderate
Baca Ranch, Valle Grande, New Mexico	Union	Hot water	Tuff, welded and altered; andesite	1.2 to 1.8 (4 to 6)	Fractured, faulted	204° to 260° (400° to 500°)	Hydro- static	Core tested this program	Low to moderate
Raft River, Idaho	INEL	Hot water	Tuff, atzite, quartz mon- zonite	1.2 to 1.8 (4 to 6)	Fractured, faulted	143° to 149° (290° to 300°)	Hydro- static	Data available	Low
Jemez Cal- dera, New Mexico	Los Alamos National Laboratory	Hot dry rock	Granite	1.8 to 2.7 (6 to 9)	Fractured	149° to 204° (300° to 400°)	Hydro- static	Data available Los Alamos National Laboratory and this program	Low
Hawaii, Hawaii	Sandia	Hot water	Basalt	0.3 to 1.2 (1 to 4)	Fractured				

heterogeneous with grain size from 0.1 to 2 mm (3.9 to 79 mils). The rock is generally porous.

5. Poea Andesite: a dark gray to bluish-black, very fine-grained andesite with small phenocrysts of plagioclase feldspar and magnetite in a very fine-grained matrix of less than 0.2 mm (7.9 mils). The rock is massive and nonvesicular. The joint blocks range up to 1.5 meters (4.9 feet).
6. John Day Dam Basalt: a very dark gray to black, massive, nonvesicular olivine basalt with an interlocking texture. The rock is composed of phenocrysts of plagioclase feldspar in a ground mass of olivine, glass, magnetite, and plagioclase feldspar. The phenocrysts range up to 1.0 cm (0.39 in.) in length, and the ground mass averages 0.3 mm (12 mils). All minerals are free of alteration. The joint spacing ranges up to 2.0 meters (6.6 feet) on a side.
7. Granite (Sierra White): a white to light gray, massive, medium-grained granodiorite. The rock is composed of interlocking plagioclase, quartz, and mica with the grain size ranging from 1 to 6 mm (0.04 to 0.24 in.). Only a small amount of potassium feldspar and muscovite is present. The strength properties are typical of a fresh igneous rock. The joint spacing ranges up to 20 meters (66 feet).
8. Granite (Texas Pink): a light to medium pink, coarse-grained, massive granite with large, 2- to 3-cm (0.8- to 1.2-in.) phenocrysts of potassium feldspar. The matrix consists of potassium feldspar, quartz, and biotite with an average grain size of 3 to 5 mm (0.12 to 0.20 in.). The jointing in the granite ranges up to several meters.

The material properties of the representative rock types are given in Table B-2 along with the known geothermal area that each type represents. A comparison of the material properties of the representative rock type and the rock from the geothermal area is summarized in Table B-3. The properties compared include density, porosity, permeability, and strength.

Table B-2

Representative Rock Formations for Geothermal Drilling Program

Representative Rock Formation	Rock Type	Location	Geothermal Area Represented	Rock Type Represented	Rock Properties of Representative Rock
Crab Orchard	Sandstone	Crab Orchard Quarry, TN	The Geysers, California	Graywacke (Franciscan)	$\rho_b = 2.49 \text{ g/cm}^3$ (155 lb/ft ³) Porosity = 2% Permeability = N/A $\sigma_c(\text{unconf}) = 257 \text{ MPa}$ (37,300 psi) Failure envelope = N/A
Kayenta Formation	Sandstone	Grand Junction, Colorado	Imperial Valley, California	Porous, fine grained sandstone	$\rho_b = 2.08 \text{ g/cm}^3$ (130 lb/ft ³) Porosity = 17% to 25% Permeability = 0.01 to 20 mD $\sigma_c(\text{unconf}) = 28 \text{ to } 41 \text{ MPa}$ (4,000 to 6,000 psi) Failure envelope available
Mancos Formation	Siltstone and shale	Central Utah	Imperial Valley, California	Siltstone and shale	$\rho_b = 2.55 \text{ g/cm}^3$ (159 lb/ft ³) Porosity = 8.3% Permeability < 10 ⁻⁸ darcy $\sigma_c(\text{unconf}) = 62 \text{ MPa}$ (9,000 psi) Failure envelope available
Upper Provo Canyon (Early Tertiary) not named	Partially welded tuff	Upper Provo Canyon, Heber, UT	Baca Ranch, Valle Grande, New Mexico	Partially to fully welded tuff	$\rho_b = 2.12 \text{ g/cm}^3$ (132 lb/ft ³) Porosity = 24% $\sigma_c(\text{unconf}) = 32.8 \text{ MPa}$ (4,750 psi) Failure envelope = N/A
Poea (Early Tertiary) not named	Andesite	Stauffer Potash Plant, Rt. 40 near Park City, UT	Baca Ranch, Valle Grande, New Mexico	Andesite	$\rho_b = 2.44 \text{ g/cm}^3$ (152 lb/ft ³) Porosity = 10.4% Permeability = N/A $\sigma_c(\text{unconf}) = 286 \text{ MPa}$ (41,500 psi) Failure envelope = N/A
John Day	Basalt	John Day Dam site, Oregon	Island of Hawaii, Hawaii	Basalt, olivine	$\rho_b = 2.76 \text{ g/cm}^3$ (172 lb/ft ³) Porosity = 8.36% Permeability = N/A $\sigma_c(\text{unconf}) = 161 \text{ MPa}$ (23,400 psi) Failure envelope = N/A
Sierra Batholith	Granodiorite (Sierra white)	Raymond Granite Quarry Raymond, CA	Roosevelt Hot Springs, Utah	Granite, granodiorite	$\rho_b = 2.65 \text{ g/cm}^3$ (165 lb/ft ³) Porosity $\leq 1\%$ Permeability = N/A $\sigma_c(\text{unconf}) = 194 \text{ MPa}$ (28,200 psi) Failure envelope = N/A
Llano Uplift	Granite (Texas pink)	Quarry, Texas	Fenton Hill, NM, Los Alamos National Laboratory Hot Dry Rock Project	Granite, granodiorite	$\rho_b = 2.63 \text{ g/cm}^3$ (164 lb/ft ³) Porosity $\leq 1\%$ Permeability = 1.0 mD $\sigma_c(\text{unconf}) = 162 \text{ MPa}$ (23,500 psi) Failure envelope = N/A

Note: ρ_b = density
 σ_c = unconfined compressive strength
 N/A = not available

Table B-3

Comparison of Material Properties between Representative Rock and Rock from Geothermal Areas

Representative Rock	Properties	Geothermal Rock	Properties
Crab Orchard sandstone	$\rho_b = 2.49 \text{ g/cm}^3$ (155 lb/ft ³) Porosity = 2% Permeability = N/A σ_c (unconf) = 257 MPa (37,300 psi) Failure envelope = N/A	The Geysers graywacke sandstone (Union Oil sample)	$\rho_b = 2.67 \text{ g/cm}^3$ (167 lb/ft ³) Porosity = 5% to 7% Permeability = 0.02 mD Perm (fract) = 40 mD σ_c (unconf) = 230 MPa (33,350 psi) Failure envelope available
Kayenta sandstone	$\rho_b = 2.08 \text{ g/cm}^3$ (130 lb/ft ³) Porosity = 17% to 25% Permeability = 0.01 to 20 mD σ_c (unconf) = 28 to 41 MPa (4,000 to 6,000 psi) Failure envelope available	Imperial Valley-- East Mesa sandstone	$\rho_b = 2.00 \text{ g/cm}^3$ (125 lb/ft ³) Porosity = 10% to 30% Permeability = 0.01 to 20 mD σ_c (unconf) = 75.8 MPa (11,000 psi) Failure envelope available
Mancos siltstone and shale	$\rho_b = 2.55 \text{ g/cm}^3$ (159 lb/ft ³) Porosity = 8.3% Permeability < 10 ⁻⁸ darcy σ_c (unconf) = 62 MPa (9,000 psi) Failure envelope available	Imperial Valley-- East Mesa and elsewhere, siltstone	Properties not available
Upper Provo Canyon tuff	$\rho_b = 2.12 \text{ g/cm}^3$ (132 lb/ft ³) Porosity = 24% Permeability = N/A σ_c (unconf) = 4,750 psi Failure envelope = N/A	Bandelier tuff, Baca Ranch, New Mexico	$\rho_b = 2.20 \text{ g/cm}^3$ (137 lb/ft ³) Porosity = 17% to 20% Permeability = 0.1 to 0.3 mD σ_c (unconf) = N/A Failure envelope = N/A
Poea andesite	$\rho_b = 2.44 \text{ g/cm}^3$ (152 lb/ft ³) Porosity = 10.4% Permeability = N/A σ_c (unconf) = 286 MPa (41,500 psi) Failure envelope = N/A	Andesite below Bandelier tuff at Baca Ranch site, Valles Calders, New Mexico	No data available
John Day basalt	$\rho_b = 2.76 \text{ g/cm}^3$ (172 lb/ft ³) Porosity = 8.36% Permeability = N/A σ_c (unconf) = 161 MPa (23,400 psi) Failure envelope = N/A	Olivine basalt, Island of Hawaii, Hawaii	$\rho_b = 2.93 \text{ g/cm}^3$ (183 lb/ft ³) Porosity = 11.14% Permeability = N/A σ_c (unconf) = N/A Failure envelope = N/A
Sierra white granodiorite	$\rho_b = 2.65 \text{ g/cm}^3$ (165 lb/ft ³) Porosity $\leq$ 1% Permeability = N/A σ_c (unconf) = 194 MPa (28,200 psi) Failure envelope available	Granodiorite, Mineral Range, Roosevelt Hot Springs, Utah	$\rho_b = 2.62 \text{ g/cm}^3$ (164 lb/ft ³) Porosity < 1% Permeability = N/A σ_c (unconf) = 120.9 MPa (17,545 psi) Failure envelope available
Texas pink granite	$\rho_b = 2.63 \text{ g/cm}^3$ (164 lb/ft ³) Porosity $\leq$ 1% Permeability = 1.0 mD σ_c (unconf) = 162 MPa (23,500 psi) Failure envelope = N/A	Quartz monzonite, Raft River, Idaho	Little data available
		Granite, granodiorite, Fenton Hill Site, Los Alamos National Laboratory, hot dry rock, New Mexico	$\rho_b = 2.70 \text{ g/cm}^3$ (169 lb/ft ³) Porosity = 0.5% Permeability = 0.015 mD to 0.001 mD σ_c (unconf) = 207 MPa (30,000 psi) $\sigma_T = 8.0 \text{ MPa}$ (1,160 psi) Failure envelope available

Note: ρ_b = density
 σ_c = unconfined compressive strength
 σ_T = tensile strength
N/A = not available

APPENDIX C

Revised GEOTEMP Input Format

REVISED GEOTEMP INPUT FORMAT

Introduction

A necessary beginning for a thermal simulation is a complete definition of the geometry of the well to be modeled. Casings, tubing, and drill pipe are all defined by specifying the inside and outside diameters and the setting depth. In addition, the cement interval length is specified for each casing.

A tubing string with as many as ten intervals, for which different tubing dimensions can be specified, is described for the well. As many as four casing strings outside the tubing can be specified. Tubing intervals are numbered from the top to the bottom of the well. Casing strings are numbered from the inside (smallest diameter) to the outside (largest diameter). Figure C-1 illustrates a completed injection well having one uniform tubing string and four casing strings. Note that the setting depth for each casing string must be less than that for the string immediately interior to it; i.e., an outer casing string is always shorter than those inside it. The tubing depths, however, may be freely specified.

Fluid properties are specified for the primary flowing fluids, secondary flowing fluids, and the annular fluid between casings. Each fluid is defined by three properties--density, plastic viscosity, and yield point. For compressible flow simulations, all primary-flowing gas properties are defined by the program, and so no special input is necessary. The specific heat capacity and thermal conductivity for each fluid are computed from the density. This computation and the use of the viscosity parameters are discussed in detail in sections IV-3 and IV-5 of the original GEOTEMP report.

Other data defined as input to the computer model are well dimensions, temperatures, and flow rates. The initial and final hole depths are defined as is the surface borehole diameter. Of course, the initial and final hole depths are identical for production, injection, and circulation. However, for drilling, the initial depth may be zero and the total depth thousands of feet. It is possible to analyze the resumption of drilling by setting the initial depth at some point downhole and estimating the downhole temperatures at the time drilling is resumed.

For deviated wells, additional information is needed: (1) the depth at which the well is deviated and (2) the measured vertical depth. The final hole depth noted previously is interpreted to mean the true vertical depth.

GEOTEMP2 TEST DATA : COMPRESSIBLE FLOW						
CONTROL CARD	1	4	2			
TUBING CARD	1	3.9580	4.500	5000.0	2000.0	
CASING CARD	1	8.6810	9.625	5000.0	2200.0	
CASING CARD	2	12.3470	13.370	3000.0	2200.0	
CASING CARD	3	19.1240	20.000	1000.0	1000.0	
CASING CARD	4	29.0000	30.000	100.0	100.0	
GEOMETRY CARD		5000.	5000.	4500.	2000.	40.00
INITIAL TEMPERATURE		70.0	145.00	70.	20.	
FLUID CARD	1	10.	15.	5.	PRIMARY	
FLUID CARD	2	10.	15.	5.	ANNULAR	
INITIAL FLUID	1	1	2	145.0	0.0	
CHANGE CARD	5 0 1	70.	2000.	10.		
CHANGE CARD	5 0 2	70.	100.	20.		

Figure C-1. GEOTEMP2 Revised Input Test Data: Compressible Flow

An initial temperature distribution in the well and surrounding soil is specified. The geothermal gradients are approximated with two constants, which yields a temperature distribution like that given in Figure C-2. Two linear temperature functions are computed from the surface temperature, the bottomhole temperature, and an intermediate temperature and depth. This temperature distribution is used to set the initial distribution, the surface boundary temperatures and boundary temperatures 400 feet below the bottomhole depth, and the downhole boundary temperatures at the maximum radius.

Inlet fluid temperatures and flow rates are specified. During circulation, it is possible to account for fluid influx at the bottom of the hole. Fluid properties, inlet temperature, and flow rate may all be defined for this secondary fluid independent of the circulation. The parameters for the primary flowing fluid are allowed to change at any time and as often as necessary. A flowing option is specified at each change as one of the following:

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

Also needed is the inlet temperature, volume flow rate, and fluid type. Each of these variables is held constant through every time step until the next change occurs at a specified time.

Drilling requires additional input information but uses essentially the same format. In addition to flow direction, inlet temperature, and flow rate, drilling requires the depth to which the well is drilled under these conditions and the number of hours per day that fluid is circulated. All of these variables may be changed at any specified time. Based on this information, a drilling rate is computed for the period during each day that fluid is circulated. Of course, depth does not change with time during the shut-in period of a day.

Thermal properties for all solid materials are defined in the program. The solids that are modeled in the computer code are

- Cement
- Soil
- Steel

Although several types of each material exist, the thermal properties are not expected to vary significantly between types and are therefore not part of the input data. Of course, for several applications, a user may enter the program to redefine thermal properties for solids. The three thermal properties needed are

SET VARIABLES AT TIME = 0.000 DAYS
 FLOWING OPTION = FORWARD CIRCULATION
 AIR INJECTED INTO TUBING
 INLET TEMPERATURE= 70. F
 FLOW RATE = 2000. SCF/MIN
 TIME TO CHANGE DATA = 10.000 DAYS

TIME = 10.000 DAYS

ITERATIONS = 3

TEMPERATURE DISTRIBUTION

DEPTH, FT	RADIAL POSITIONS, FEET					
	0.1	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	70.0	73.0	73.0	73.0	73.0
400.	70.0	70.0	76.4	76.4	76.4	76.4
600.	70.0	70.0	79.7	79.7	79.7	79.7
800.	70.0	70.0	83.1	83.1	83.1	83.1
1000.	70.0	70.0	86.4	86.4	86.4	86.4
1200.	70.0	70.0	89.8	89.8	89.8	89.8
1400.	70.0	70.0	93.1	93.1	93.1	93.1
1600.	70.0	70.0	96.5	96.5	96.5	96.5
1800.	70.0	70.0	99.8	99.8	99.8	99.8
2000.	70.0	70.0	103.1	103.1	103.1	103.1
2200.	70.0	70.0	105.9	105.9	105.9	105.9
2400.	70.0	70.0	108.7	108.7	108.7	108.7
2600.	70.0	70.0	111.5	111.5	111.5	111.5
2800.	70.0	70.1	104.0	109.1	112.2	114.3
3000.	70.0	70.2	102.0	109.5	114.0	117.1
3200.	70.0	70.5	102.3	111.0	116.3	119.9
3400.	70.0	70.7	104.1	113.3	118.9	122.7
3600.	70.0	70.9	106.0	115.6	121.5	125.5
3800.	70.1	71.2	107.9	118.0	124.1	128.3
4000.	70.1	71.4	109.8	120.3	126.7	131.0
4200.	70.1	71.7	111.7	122.6	129.3	133.8
4400.	70.2	72.0	113.6	125.0	131.9	136.6
4600.	70.2	72.2	115.5	127.3	134.5	139.4
4800.	70.2	72.5	117.4	129.6	137.2	142.2
5000.	70.3	72.8	123.0	133.9	140.6	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-2. Temperature Distribution Output Resulting from
 the Compressible Flow Problem Given in
 Figure C-1

- Density
- Specific heat capacity
- Thermal conductivity

These properties are discussed in more detail in section IV-4 of the Part I report. The quantities presently employed by the thermal simulator are listed in Table II-1 of the same report.

Data Formats

This section describes in detail how to input 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, 15, 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, 15, 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, 15, 3F10.0, 6A4)

- Columns 21-25 Fluid I.D. number
- 26-35 Density, lb_m/ft³
- 36-45 Plastic viscosity, centipoise
- 46-55 Yield point, lb_f/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 are 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
 5 = forward circulation compressible flow
22-23 Secondary flow option
 0 = no flow
 1 = secondary flow
24-25 Primary fluid I.D. number
 If flowing option 5, the fluid
 I.D. numbers are defined
 1 = air
 2 = nitrogen
26-35 Primary fluid inlet temperature, °F
36-45 Primary fluid volume flow rate, gal/min
 If flowing option 5, gas volume flow
 rate, SCF/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).

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