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GEOTHERMAL TECHNOLOGY DEVELOPMENT PROGRAM
QUARTERLY PROGRESS REPORT

April-June 1981

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ABSTRACT

This report describes the status of ongoing Research and Development (R&D) within the Geothermal 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 research in rock penetration mechanics, fluid technology, borehole mechanics, and diagnostics technology.

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GEOTHERMAL TECHNOLOGY DEVELOPMENT PROGRAM
QUARTERLY PROGRESS REPORT

April-June 1981

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, complete, and log 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 advanced drilling and completion systems. Currently, the program is completing activities which are near commercialization and increasing emphasis on advanced technology development. Research is being conducted in high-risk areas that are not being addressed by private industry due to the lack of near-term payoffs.

Because of the large-scale reduction in resources scheduled for FY 1982, the program was restructured during the second quarter of this fiscal year. Included in the restructuring effort were a reduction in the number of program subelements from six to four and the incorporation into the program of the work in logging and high-temperature instrumentation. The four new program subelements are Rock Penetration Mechanics, Fluid Technology, Borehole Mechanics, and Diagnostics Technology. Work in logging and high-temperature instrumentation is reported for the first time in this quarterly report under the last subelement.

This report contains a brief overview of the activities within the ongoing R&D program for the quarter April-June 1981. Published comprehensive reports on completed projects and presentations made on program work during this reporting period are listed in Appendix A. The reports are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia, 22161.

2. HIGHLIGHTS

Management

- Advisory Panel -- The semi-annual meeting of the Geothermal Technology Advisory Panel is scheduled for 24-25 September 1981 in Austin, Texas.

- Symposium -- A symposium on high-temperature electronics, sponsored by Sandia for DOE/DGE, is planned for 7-8 December 1981 in Houston, Texas.

- International Information Exchange -- J. Kelsey visited European drilling research facilities during this quarter. The purpose of the trip was to discuss drilling technology research being conducted in Europe and to present an overview of the DOE/DGE geothermal program. Organizations visited included Shell International (The Hague, Netherlands), Diamant Boart (Brussels, Belgium), TOTAL-CFP (Paris, France), and the French Petroleum Institute in Paris. Discussions with personnel of these research groups resulted in an up-to-date and lucid understanding of ongoing research activities in the area and will assist in avoiding duplication of effort within the DOE geothermal efforts managed by Sandia. The interest shown by the European researchers in the Sandia/DOE geothermal program tends to validate current activities and should provide the opportunity for a valuable interchange of technical information.

Rock Penetration Mechanics

- Development of Improved Cavijet® Nozzles -- Nozzle tests in the high-pressure cell confirm previous erosion tests indicating that at high values of the cavitation number the optimum standoff distance for rock cutting with cavitating jets is about four nozzle diameters (Section 3.3).

- High-Pressure Fluid Delivery Systems -- A study of high-pressure fluid delivery systems indicates that a system involving pumping low-pressure fluid downhole to power an intensifier that would produce the required high-pressure flow for jet drilling and downhole motor operations is the best technical and economical approach. Consideration is being given to laboratory testing of a half-scale, downhole intensifier model to demonstrate the system feasibility (Section 3.5).

- Improvement of Downhole Drilling-Motor Bearings and Seals -- Seals made of glass-reinforced Aflas, a copolymer of propylene and tetrafluoroethylene, are the first to achieve the goal of a 200-hour

life. Two seal packs, containing two seals of the HTCR-SF design each, ran 200 hours without failure at a ΔP of 10.3 MPa (1,500 psi), using water as the drilling fluid and a 121°C (250°F) starting temperature (Section 3.6).

- Polycrystalline Diamond Compact (PDC) Drill Bits -- Laboratory tests of LS brazed cutters and diffusion bonded cutters under simulated Geysers conditions indicate that the use of diffusion bonded cutters may not appreciably increase the temperature capabilities of PDC bits (Section 3.7).

- Drill Stem Corrosion -- Corrosion fatigue laboratory experiments on a dual-phase steel versus a conventional Grade E steel suggest the superiority of dual-phase steel as a drill stem material under actual drilling conditions (Section 3.13).

- Improved Cutter Materials -- This project was initiated this reporting period. The first samples of tantalum and niobium carbide-nickel/cobalt systems have been prepared and tested (Section 3.14).

Fluid Technology

- Aqueous Foam Drilling Fluids for Geothermal Applications -- Early results of stability tests of foams at elevated temperature and pressure have revealed an unexpected effect of pressure. Foams made at high pressure appear more stable than the same foams made at atmospheric conditions. This finding is attributed to the fact that smaller "bubbles" form at high pressure and drain more slowly (Section 4.1).

- Bit Hydraulics Studies -- Convective heat transfer studies of PDC-stud bits in the Hydraulics Test Stand are identifying the cutters in which cooling is critical and the hydraulic configurations which improve cooling of the studs (Section 4.2).

- Advanced Wellbore Thermal Code -- The development of the Advanced Wellbore Thermal Code for predicting transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells has been completed (Section 4.3).

- High-Temperature/High-Pressure Drilling Mud Research Instrument -- Hydrostatic tests on the pressure vessel and cooling jacket were successfully completed. Construction of the building to house the instrument complex has started (Section 4.5).

Borehole Mechanics

- Lost Circulation Material Screening -- The first series of tests of potential lost circulation materials using a modified API Slot Tester have been completed. Preliminary results show little effect of slot length on maximum sealing capability (Section 5.2).

- High-Temperature Perforator -- A perforator system was designed, fabricated, and laboratory tested at a temperature of 250°C (482°F). Target perforation was satisfactory (Section 5.3).

- Casing Stress Analysis -- A structural analysis of the casing/cement stresses in a typical geothermal well in The Geysers area indicates that a large margin in fatigue life of casing may be expected (Section 5.7).

Diagnostics Technology

- Wellbore Inertial Navigation System (WINS) -- Laboratory checkout of WINS hardware components and software has started. Field testing of the system is planned for October 1981 at the Nevada Test Site (Section 6.1).

- High-Temperature GaP and GaAs Devices -- Several multilayer metal film systems have been used successfully to form ohmic contacts to n-type high-temperature GaP devices (Section 6.4).

- Investigation of Amorphous Metalization for Semiconductor Circuits -- Amorphous metals produced for semiconductor circuits are proving to be much more resistant to failure than conventional polycrystalline metals (Section 6.5).

- Development of a 300°C (572°F) CMOS Process -- A self-aligned silicon gate CMOS process has been selected for use in 300°C (572°F) circuits (Section 6.6).

- Metal Sheath Cable Development -- Metal sheath cable prototype testing has been successfully completed, and the final developmental cable is being fabricated (Section 6.7).

- Upgraded Acoustic Borehole Televiewer -- The upgraded Acoustic Borehole Televiewer has been successfully field tested (Section 6.10).

- Development of 300°C (572°F) Operational Amplifier -- Laboratory tests of prototypes of quad operational amplifiers show the devices to be usable at temperatures up to 350°C (662°F) (Section 6.14).

3. ROCK PENETRATION MECHANICS

Research in Rock Penetration Mechanics is directed toward a basic description of rock penetration by candidate high-speed drilling systems. Understanding the behavior of polycrystalline diamond compact (PDC) drag bits (rock fracture and wear mechanisms) is receiving the major emphasis, but other research areas, including improved materials, cavitating jets, and percussion drilling, will be pursued until they can be accurately evaluated. For effective participation in a coherent geothermal technology development program, this work must have the breadth to identify the most promising concepts and the depth to incisively analyze those concepts.

3.1 Geothermal Polycrystalline Diamond Compact Drill-Bit Development

Contractor: General Electric Company, Corporate
Research and Development (GE/CRD)
Principal Investigator: L. E. Hibbs, Jr. (518) 385-8330
Contract Period: 30 June 1976 to 30 September 1981
Contract Number: DE-AC04-76ET27142
Technical Consultant: E. Hoover (505) 844-7315

Project Objective

The overall objective of this project is to develop and demonstrate the performance of a new type of drill-bit design that will provide increased penetration rates and/or longer bit life with high-pressure, sintered polycrystalline diamond compacts (PDCs) for the cutting edges. The scope of this project 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 Activities

Studies of laboratory and field test results and analyses continued during the quarter with a view to determining whether further redesign and field testing of PDC bits should be planned at this time. A decision had not been reached at the close of the reporting period.

3.2 Continuous Chain Bit

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

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 Activities

Investigation of diamond quality variation as the cause of poor drilling results in Field Tests II and III continued during the quarter. Examination at Sandia of diamonds from the chain links supplied by Christensen, Inc. and Hycalog revealed marked differences in physical appearance. The Christensen diamonds were opaque, approached a spherical shape, and had a frosted finish. They also had many fractures, inclusions, and voids which appeared to weaken them structurally. The Hycalog diamonds were semitransparent, had a smooth finish, and were of blocky construction with sharp edges that fit the classical description of diamonds suitable for drilling hard rock. Inquiries were made to companies knowledgeable in diamond processing. The companies indicated that the Christensen diamonds appeared to be reprocessed stones and that reprocessing can damage diamonds. The process is generally proprietary and can consist of mechanical, chemical, and temperature treatment. Only first run, single crystal West African Brown diamonds were recommended for use in drilling hard rock, the type of formation the chain bit was designed to drill.

Christensen was requested to review its manufacturing records to determine if different types and/or sources of diamonds were used in the fabrication of chain links that drilled successfully (Field Test I), versus those links whose drilling performance was unsatisfactory (Field Tests II and III). A response had not been received by the end of the reporting period.

Further investigation of diamond quality variation as the potential cause of the poor drilling performance in the field tests would require fabrication and testing of additional chain links utilizing high quality, first run diamonds. Such a high cost, time-consuming undertaking is not consistent with the decision to phase out the project in response to FY 1982 budgetary restraints. Hence, the work on the natural diamond chain drill option is virtually complete.

Preparations for fabrication and laboratory test of an all-PDC chain link drill continued during the quarter. Design of the link and tooling was completed. Delivery of the tooling and links is expected

in July. The final laboratory test of this configuration of the chain drill is planned for the latter part of next quarter.

Preparation of the final report covering the complete six-year history of the chain drill development has been initiated.

3.3 Development of Improved Cavijet® Nozzles

Contractor: Hydronautics, Inc.
Principal Investigator: A. F. Conn (301) 776-7454
Contract Period: 18 February 1980 to 30 September 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 Activities

Flow Tests in the Air Facility -- The modified, three-cone roller bit was used during this reporting period as the "feed-plenum" for studies of organ-pipe Cavijet® configurations. One of the standard extended arms, or nozzle tubes, from this 31-cm (12-1/4-in.) bit was removed so that modified tubes for these air studies could be inserted.

The organ-pipe Cavijet® study constraints have included optimum modulation amplifications for Mach numbers which correspond to the typical operating pressure drops across these bits and modified tube designs that required minimal internal modifications to the component.

In the air tests conducted to date, organ-pipe Cavijet® configurations that satisfy the restraints have been established. To confirm that this approach scales to water as found in prior nozzle tests, a one-third segment of a full-scale 31-cm (12-1/4-in.) roller bit was adapted for testing in both the air facility and the high-pressure cell (HPC). The air tests using several organ-pipe Cavijet® nozzle configurations agreed with results obtained earlier using the full-scale 31-cm (12-1/4-in.) bit with two of the three nozzle tubes plugged. The jet modulations with the one-third bit segment were higher than had been observed with the full bit, but the patterns of resonant peaks as a function of Mach number were comparable.

A series of air-tests was initiated during this quarter to examine the effect of certain nozzle design details on the self-resonating phenomena. From the first of these tests, it was clear that self-resonance is sensitive to details of the nozzle exit geometry and that small changes can provide rather large variations in the amplitude and pattern of the jet modulation.

Testing of a half-scale model of a single nozzle tube for a 31-cm (12-1/4-in.) roller bit was also continued this quarter in both the air facility and the HPC. The results in air and in water show fairly

well-defined resonant peaks at the first and third modes, with very little resonance at the even, second mode. These results are typical for the single-diameter organ-pipe Cavijet® configuration. It has been observed that changes in the cavitation number have an effect on the amplitude of the jet modulation, but do not change the value of the Mach number where the resonant peaks occur. The air test peaks tend to occur at somewhat higher values of Mach number than the corresponding water peaks. The question of why this particular half-scale model has shown differences between the Mach numbers for air and water resonances is still under study.

Nozzle Test in the High-Pressure Cell (HPC) -- The photographic techniques for recording jet behavior within the HPC were refined during the reporting period. The details of ring vortex structure can now be seen. With the improved photographs, closer observations of the cavitating jet structure as a function of nozzle pressure drop, cavitation number, Strouhal number, and standoff distance have begun.

Half-scale models of both the existing design and a modified nozzle-tube for a two-step organ-pipe Cavijet® were tested in the HPC. The models represented one-third of a 31-cm (12-1/4-in.) three-cone roller bit and were designed at half-scale so that a wider range of pressures could be used. In comparative slot cutting tests on Indiana limestone, the Cavijet® nozzle produced mean slot depths up to 2-1/2 times deeper than the conventional nozzle.

Using the one-third bit segment which had been adapted for water testing, studies were made of a full-scale organ-pipe Cavijet's® performance in the HPC. The appearance of well-defined vortices was then correlated with pressure transducer measurements of cavitation inception. At a Mach number off-resonance, the value of σ_i (the incipient cavitation number) was only about 0.5. However, at a resonant peak of $\sigma_i \approx 1.2$, a significant improvement could be readily seen in the well-defined structure of the ring vortices. In these tests, no target was provided so that free-flow behavior could be examined. The vortices at resonance tended to be very stable and well defined until a distance of about four nozzle diameters was reached. At that point, the vortices began to waver and started to become unstable. These observations of jet structure confirm previous erosion tests that indicated that, at high values of the cavitation number, the optimum standoff distance for rock cutting with cavitating jets is about four nozzle diameters.

Studies at University of California-San Diego -- Stresses imparted by a Cavijet® to a surface are being examined by Professor Ellis by means of high-speed photoelasticity. Using a high-speed photographic method, a dynamic record will be made of the response of a photoelastic material to jet impingement. Also, the feasibility of using vibratory crystals to further modulate the flow from a cavitating jet nozzle orifice is being studied. In addition, Professor Ellis is assisting in the development of an ultra-high-speed, short-duration flash capability. This capability will allow capture, in either still photographs or high-speed movies, further details of the structuring in the self-resonating cavitating jets.

3.4 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 28 February 1981
Contract Number: 13-8728 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

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 was to gather, analyze, and present these data. In particular, this project supplied 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 were identified.

Project Activities

Work under this project has been closed out, and a final briefing on the project was presented to Sandia this quarter. A draft of the final report was reviewed. Completion of the final report is expected during the next quarterly reporting period.

3.5 High-Pressure Fluid Delivery Systems

Contractor: Flow Industries, Inc.
Principal Investigator: J. Reichman (206) 622-1500
Contract Period: 13 June 1980 to 31 May 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.

Project Activities

The study phase of this project has been completed. The draft final report on the high-pressure fluid delivery systems has been reviewed and is awaiting publication. The study compared three different systems for delivering high-pressure, 103 MPa (15,000 psi), drilling fluid downhole. The systems were (1) a conventional system in which all the necessary fluid would be pumped downhole at the required high pressure, (2) a system in which a concentric dual string would be used with the required amount of high-pressure fluid being pumped down one string and the remaining fluid necessary pumped down the second string at low pressure, and (3) a system involving pumping low-pressure fluid downhole that would power a downhole intensifier that, in turn, would produce the required amount of high-pressure flow. The study indicated that the best system in terms of technical barriers, economics, additional applications, and safety is the downhole intensifier system. Laboratory testing of a half-scale downhole intensifier model to demonstrate the system feasibility was recommended.

Development and analysis of alternative follow-on research options to achieve a suitable downhole high-pressure fluid delivery system are in process. Selection of the best program within forecast resources will be made during the next quarter and start-up activities will be initiated.

3.6 Improvement of Downhole Drilling-Motor Bearings and Seals

Contractor: Terra Tek, Inc.
Principal Investigator: P. DeLafosse (801) 584-2400
Contract Period: 1 November 1980 to 30 November 1981
Contract Number: 74-6607 (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 can soak at 260°C (500°F) and operate at a 121°C (250°F) circulation temperature.

Project Activities

Seal Testing and Evaluation -- The first test to achieve the goal of a 200-hour seal life was completed early in this quarter. Two seal packs, containing two seals each, were used in the test. Each seal was made of Utex compound HTCR, a glass-reinforced copolymer of propylene and tetrafluoroethylene. The test was run at a ΔP of 10.3 MPa (1,500 psi), cooling water flow rate of 0.07 m³/h (18 gal/h), and with a starting temperature of 121°C (250°F). The test was terminated after 200 hours without failure of either seal pack; the upper seal pack had leaked about one-half its available lubricant and the lower seal pack was approaching a one-quarter loss. Although the seal temperature had exceeded 260°C (500°F), posttest inspection showed very little degradation of the seal material and almost no wear on the carburized steel shaft.

Seal testing continued during this quarter using a ΔP of 6.9 MPa (1,000 psi) and abrasive-laden drilling mud. Test periods before seal failure ranged from 8 to 42 hours. The cause of the failures were investigated and seal modifications made to correct the suspected failure modes. This work was in process at the close of the reporting period and will continue next quarter.

Bearing/Seal Package Testing and Evaluation -- The first tests of mechanical face seals in the bearing/seal package were attempted. The first mechanical face seal was installed, but the package would not hold the 2.6 MPa (400 psi) lubricant charging pressure. The face seal was removed, and an inspection revealed that the silicon carbide face was cracked. Since it was unclear whether the failure occurred before the package was pressurized, another seal was inspected, installed, and charged with lubricant. The second seal also failed to hold pressure and was found to have cracked. Discussions with the manufacturer

revealed that the seal was designed to work with external pressure. The actual internal pressure of the bearing/seal package loaded the silicon carbide in tension--a stress mode in which its strength is very low. Even if the material had not failed, the geometry of the seal must be modified for the bearing/seal package operation. The manufacturer is fabricating redesigned parts for the seals. Tests of the redesigned seals are anticipated in September. Seals from another manufacturer will be tested in August.

3.7 Polycrystalline Diamond Compact (PDC) Drill Bits

Sandia National Laboratories
Technical Consultant: E. Hoover (505) 844-7315

Project Objective

The objective of this project is to experimentally evaluate the performance of different PDC drill bit designs under geothermal drilling conditions.

Project Activities

During this quarter two Stratapax™ drill bits, a 22.2-cm (8-3/4-in.) Smith bit and a 16.5-cm (6-1/2-in.) Sandia bit, were tested at ambient pressure conditions at the Drilling Research Laboratory in Salt Lake City using hot air as the drilling fluid. The objective of the test was to compare the performance of LS brazed cutters and diffusion bonded cutters under simulated Geysers conditions.

For comparison purposes, the Smith bit had both LS brazed carbide cutters and diffusion bonded steel cutters in critical wear areas. The Sandia bit had both diffusion bonded carbide cutters and diffusion bonded steel cutters. Both bits were tested first in Crab Orchard sandstone and then in Sierra White granite.

In general, the LS brazed cutters lost their PDC cutting elements before the diffusion bonded cutters. However, with only a slight increase in the cutter loading, the diffusion bonded cutters also failed catastrophically. Based on these tests, it appears that the use of diffusion bonded cutters may not increase the bit's temperature capabilities significantly.

Laboratory tests of 22.2-cm (8-3/4-in.) commercial bits drilling Crab Orchard sandstone are planned for next quarter. In addition, planning for a potential field test of the PDC drill bits in the Imperial Valley of California is underway.

3.8 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 May 1981
Contract Number: 13-8785 (Sandia)
Technical Consultant: J. Finger (505) 844-8089

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 Activities

All the equipment required to complete the modification and extension of the testing capabilities was received during this quarter. Final assembly and checkout of the new facilities are underway and are expected to be completed during the next quarter. A description of the capabilities of the new facilities will be included in the FY 1981 annual report.

3.9 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: B. Caskey (505) 844-8835

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 Activities

Work continued during this quarter on the fabrication of the test apparatus to be used for testing modified flexible drill pipe sections. All parts for the test setup were received by the end of the reporting period, including the 70 MPa (10,000 psi) pressure gage. The entire test system will be checked out, and tests will be started in the next quarter.

The mold to make elastomer test hats (inner thermoplastic test liners for Coflexip Zeta flexible drill pipe sections) was also received. The hat mold was Teflon coated and used to make test parts out of EPDM Y267. Satisfactory elastomer test parts were made after only two developmental attempts. Teflon PFA 350 test hats have been received. Since the Teflon hats are expensive, elastomer test hats will be used to check out the test system and the Teflon parts used in actual tests only.

Problems were encountered in machining and welding the Coflexip Zeta pipe sections to the end fittings for the test, but the work was nearing completion as the quarter ended.

3.10 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. The gathered data will support an economic analysis that can be used to evaluate percussion as a candidate advanced drilling system.

Project Activities

The testing and analysis of conventional percussion drilling devices and the designing and testing of improved percussion systems have been completed. Work on the economic analysis of percussion drilling systems proceeded this quarter and will continue through the next quarter. Future experimental work is dependent upon the results of the economic analysis.

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

Contractor: General Electric Company, Corporate Research
and Development (GE/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: J. Finger (505) 844-8089

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 Activities

The original scope of work under this project has been completed. A procurement action being processed for follow-on work under this project was retracted this quarter. It will be changed to a new scope of work that will reorient future research toward fundamental rock/cutter interaction studies rather than drill bit design. This action is required in order to achieve compatibility of this project with the overall reorientation of the Geothermal Technology Development Program in consonance with the anticipated reduction in FY 1982 funding levels.

3.12 Rock Mechanics for Polycrystalline Diamond Compact Cutters

Sandia National Laboratories

Technical Consultants: J. Finger (505) 844-8089
D. Swenson (505) 844-9398

Project Objective

The project objective is to do research and testing so that the interaction between rock and cutting tools utilizing polycrystalline diamond compact (PDC) cutters can be accurately described.

Project Activities

Frictional Heating of Stud-Mounted PDC Cutters -- Studies of frictional heating in PDC cutters have been completed and will be fully described in the final report, SAND80-2677, which is now in preparation.

The analytical work has been focused on the development of a two-dimensional heat transfer model to predict the average cutter temperature over the surface in contact with the rock. This model has been used to examine three cutter configurations--sharp, worn, and badly worn--with different velocities, cooling rates, friction coefficients, and energy partitions. Although the calculated temperatures in the stud have generally been higher than those observed experimentally, the analysis has demonstrated the sensitivity of the temperature distribution to the various parameters and has identified the coefficients which need better experimental definition.

This experimental work at Sandia and GE (Section 3.11) will enable fine tuning of the heat transfer model and permit more accurate evaluations of the effect of bit design on cutter temperature.

Rock Fracture Modeling -- Work is continuing on a finite element model that displays the stresses in a cutter and in the rock that it is engaging. Current effort is directed to experimental verification of the rock material model and to comparison of the fracture pattern in the model prediction and in the laboratory experiments.

3.13 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 geo-thermal H_2S environment without large sacrifices to its mechanical properties or cost.

Project Activities

Corrosion fatigue laboratory experiments on a dual-phase steel and a conventional Grade E steel indicate a cross-over point in the fatigue crack growth rate as a function of stress intensity level. At maximum stress intensity levels below about 35 ksi $\sqrt{\text{in.}}$, the crack growth rate for the dual-phase steel (step-quench heat treatment) is lower than that for the Grade E material. Above about 35 ksi $\sqrt{\text{in.}}$, the Grade E steel exhibits a lower crack growth rate than the dual-phase steel. Since the stress intensities that result from the applied torque and bending through a "dogleg" during drilling are well below 20 ksi $\sqrt{\text{in.}}$, the test data suggest the superiority of dual-phase steel over conventional Grade E material under actual drilling conditions. Calculations also show that the dual-phase steel (step-quench heat treatment) may be superior to conventional Grade E material for drilling in H_2S -containing environments. Planned tests of other heat treatments of the dual-phase alloy will emphasize measurement of the corrosion fatigue behavior at the lower stress intensity levels.

3.14 Improved Cutter Materials

Contractor: SRI International
Principal Investigator: David J. Rowcliffe (415) 859-5044
Contract Period: 30 March 1981 to 31 March 1982
Contract Number: 74-4755 (Sandia)
Technical Consultant: E. Hoover (505) 844-7315

Project Objective

The objective of this project is to develop a new family of cemented carbides suitable for application in geothermal drilling.

Project Activities

This project started at the beginning of this reporting period. Initial efforts included procurement of carbide and metal powders for fabrication of cemented carbides, obtaining WC-Co specimens for fracture toughness correlations, and discussions with manufacturers and researchers knowledgeable in WC-Co system production and performance characteristics. Fabrication of cemented carbides and toughness evaluations have begun.

Both sintering and hot pressing processes for preparing dense cemented carbides are being investigated. Cemented carbides in the TaC-Ni and TaC-Co systems have been prepared using both hot-pressing and sintering techniques. The sintering process consists of the following steps:

1. Addition of binders such as microcellulose and paraffin wax.
2. Cold-pressing of cylinders ~10 by 10 mm (~0.4 by 0.4 in.) in a steel die.
3. Binder removal by low temperature heat treatment at ~300°C (~572°F).
4. Liquid-phase sintering under a controlled atmosphere above 1,200°C (2,192°F).

Highest densities, prior to step 4, were obtained using a binder of paraffin wax in cyclohexane. Densities of ~90% of theoretical were reached by sintering for 2 hours at 1,650°C (3,002°F). Examination of the sintered cylinders suggested that higher densities could be reached by improving the initial distribution of the binder phase and lowering the sintering temperature.

From the point of view of cost, sintering is the preferred method for producing cemented carbides on a large scale. At this stage of the project, however, it is more practical to make test samples by

hot-pressing because this process requires fewer steps and less refinement to yield high density specimens. Cylinders of TaC-10 wt% Ni and TaC-10 wt% Co were hot-pressed close to theoretical density at 1,800°C (3,272°F) and 41.4 MPa (6,000 psi) in graphite dies. Metallographic examination of the samples showed carbide grains between 10 and 50 μm (0.4 and 2.0 mils). In addition, a substantial quantity of the binder metal was pressed out of these samples. Both observations suggested that the hot-pressing temperature was too high.

Theoretically dense NbC-10 wt% Ni was produced by hot pressing dry-milled powders for 10 minutes at 1,200°C (2,192°F). Metallographic observations confirmed the absence of pores but indicated occasional islands of Ni, probably due to incomplete milling. The carbide grain size was about 6 μm (0.24 mils), indicating some grain growth had occurred. The Vicker's hardness of this material was 1,040 kg/mm^2 (1,479 ksi), which is similar to that of WC-10 wt% Ni alloys but slightly lower than that of WC-10 wt% Co. For indentation loads up to 2 kg (0.9 lb), NbC-10 wt% Ni showed multiple intergranular cracking without the formation of individual radial cracks. The significance of this observation with respect to the fracture toughness of this material is not yet understood.

Samples of NbC-10 wt% Co pressed under the conditions described above reached densities approximately 97% of the theoretical value. The temperature for liquid phase formation appears to be about 50°C (90°F) higher in this system than in the NbC-10 wt% Ni system. The Vicker's hardness of this material was about 1,250 kg/mm^2 (1,778 ksi). Production of theoretically dense NbC-10 wt% Co is expected by hot-pressing at 1,250°C (2,282°F).

Experiments in carbide fabrication and toughness evaluation will continue during the next quarter.

3.15 Drill String Dynamics

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

Project Objective

The objective of this project is to develop a computer program for use in solving the drill string dynamics problem, including the interaction of the drill bit and the formation.

Project Activities

An exploratory study by Jordan, Apostol, Ritter Associates has established the technical feasibility of satisfactorily developing a finite element computer model to solve the drill string dynamics problem. Also, a three-year development program has been outlined for planning purposes. Efforts are underway to establish a cost sharing-joint development program with industry. Details of the program are expected to be worked out during the next quarterly reporting period.

4. FLUID TECHNOLOGY

The general goal of Fluid Technology research is to develop drilling fluids specifically tailored to reduce problems commonly encountered in geothermal drilling. The projects include extensive study of properties of aqueous foams used in drilling applications and development of methods for generating large quantities of inert gas to be used as a drilling fluid. Foam and inert-gas-based fluids have very low densities and, thus, can be helpful in avoiding lost circulation and can help to reduce corrosion problems. Additional projects are directed toward improvements in more conventional drilling fluids and toward understanding the behavior of fluids in the drilling environment.

4.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories

Technical Consultants:

P. Rand (505) 844-7953

A. Kraynik (505) 844-0780

L. Mondy (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 Activities

High-Pressure/High-Temperature Stability -- Stability tests of foams at elevated temperature and pressure in the autoclave are being conducted. Early tests indicate a strong effect of temperature on stability (foams being less stable at high temperatures) and an unexpected effect of pressure. Foams made at high pressure appeared more stable than the same foams made at atmospheric conditions. Subsequent investigation led to two conclusions. First, foams made at high pressures have smaller "bubbles" than do foams with the same liquid volume fraction made at low pressures, and second, foams with smaller bubbles drain more slowly. Neither of the conclusions was obvious, although both can be explained using basic theoretical models of foam and foam stability.

Thermal Conductivity -- A bench-scale foam generator was used to generate foams for measuring foam thermal conductivities. Conductivities were measured for foams of different densities and made with different gases. These measurements were used to evaluate various foam conductivities analytical models. The results indicate closer agreement with a model for parallel conduction through the liquid and gaseous phases than with a series conduction model.

Test Facilities -- Two new test facilities were designed: a foam heat transfer facility and a foam rheology facility. The required components were ordered and some parts had been delivered by the end of the reporting period. Assembly and checkout of the facilities and initial experimentation are anticipated during the next quarter.

4.2 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 are being conducted to determine the optimal position, size, and placement of nozzles used for cooling and cleaning purposes. A bit hydraulics laboratory has been 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 capability.

Project Activities

Bit hydraulics research during this quarter was concentrated on (1) analyzing the bit blank dye flow tests reported last quarter, (2) completing and analyzing dye flow tests for the Sandia 16.5-cm (6-1/2-in.) PDC-stud test bit, (3) obtaining high-speed motion photography of the test bit flow fields using plastic tracers, and (4) measuring convective heat transfer coefficients for the test bit.

The dye injection technique used to define fluid flow patterns in the bit blank tests proved impractical for investigation of the flow patterns of the PDC-stud test bit. The increased turbulence in the flow field caused by the cutters greatly increased turbulent diffusion of the dye. A tracer tracking technique using small, 3 mm (0.12 in.), spherical acrylic beads in the fluid system and high-speed motion photography was devised and used successfully to delineate flow patterns with the PDC-stud test bit. The high-speed photography records the movement of the tracer beads and subsequent frame-by-frame analysis of the film allows definition of the tracer bead trajectories, or pathlines.

The Sandia PDC-stud test bit, instrumented with 28 convective heat transfer gages to measure convective heat transfer coefficients, was tested in the Sandia Bit Hydraulics Test Stand at different rotational speeds. Three bit hydraulic configurations were used: (1) all 10 nozzles open, (2) outer 6 nozzles on the bit face plugged--inner 4 nozzles open, and (3) inner 7 nozzles plugged--outer 3 nozzles open. Analysis of the test data indicate that:

1. There was no simple trend in the effect of bit rotation speed on cutter cooling; some cutters cooled better at high speeds while others cooled better with the bit stationary.

2. Configuration 2 cooled all cutters better than configuration 1.
3. Configurations 2 and 3 exhibited cooling patterns which, although different, were considered about equally advantageous for cooling. Configuration 2 appeared to be the best overall configuration since it did not have chip removal problems evident in configuration 3.
4. The bit gage cutters received less cooling than other cutters; cooling these cutters is probably more critical than cooling the others since they travel faster and generate more frictional heat.

During the next quarter, work will include (1) analysis of tracer tracking results for the PDC-stud test bit, (2) identification and tracer testing of other hydraulic configurations for the PDC-stud test bit that have high performance potential, (3) measurement of bottom-hole pressure gradients for all configurations identified, and (4) tracer testing of commercial PDC bits.

4.3 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 31 December 1981
Contract Number: 46-5670 and 74-2300 (Sandia)
Technical Consultants: J. Kelsey (505) 844-6968
L. Mondy (505) 844-0284

Project Objective

The objective of this project was 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 encompassed

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.

A series of technical articles illustrating the practical use of the computer code will also be prepared and published under this project.

Project Activities

Development of the Advanced Wellbore Thermal Code has been completed and preparation of the final report is proceeding. Technical articles describing the practical use of the code are also being written.

4.4 Inert Gas Generation

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

Project Objective

The objective of this project is to develop a cost-effective method for on-site generation of an inert (anaerobic) gas for use as one component of a drilling fluid to control geothermal drill pipe corrosion.

Project Activities

The major project activities include (1) laboratory tests and analyses to define the relationship between corrosion rates and gas composition and (2) investigations of two gas generation schemes, cryogenic air separation, and diesel exhaust purification.

Corrosion Rate/Gas Composition Relationship -- A series of laboratory tests are underway to measure steel corrosion rates when exposed to simulated drilling conditions. The test variables include salt concentration, temperature, pressure, pH, and oxygen concentration. In tests to date, low corrosion rates were measured when solution oxygen concentrations were 50 ppb or less, or when the pH was high (>11) and salt content was high (>22%). Additional tests are expected to produce data to more completely define the relationships among the variables.

A report¹ has been published which provides gas composition specifications for the required inert gas. Functions are also presented in the report that relate corrosion to oxygen and salt concentrations, temperature, flow rates, and pH. The effect of NO_x, SO₂, CO₂, CO, and H₂O concentrations on corrosion during mist drilling is also discussed in the report.

Cryogenic Gas Generator -- A portable cold box which can supply about one million standard cubic feet of nitrogen per day has been fabricated by Yearout and Associates of Torrance, California. The industry developed unit is approximately 2.4 m wide, 3.7 m high, and 6.4 m long (~8 by 12 by 21 ft) and is presently undergoing shakedown trials. The unit, although expensive, is capable of producing gaseous nitrogen with less than 2 ppm of oxygen. Firm operating and maintenance costs are dependent upon final checkout and operational experience, but the overall cost is currently estimated at \$7,000 to \$10,000 per day.

Diesel Exhaust Gas Purification -- Three proposals to design and cost a full-scale, diesel exhaust gas purification unit were received

and evaluated. Foster-Miller Associates, Inc. of Waltham, Massachusetts, was selected to perform the work which will begin in the next quarter. The project is expected to be completed before the end of 1981.

Reference

¹T. E. Hinkebein and T. L. Snyder, "Corrosion Inhibition by Control of Gas Composition During Mist Drilling," Report No. SAND81-0973, Sandia National Laboratories, Albuquerque, New Mexico, May 1981.

4.5 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
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 down-hole conditions of up to 371°C (700°F) and 138 MPa (20,000 psi).

Project Activities

Construction of the building for the Geothermal Drilling Fluid Test System (GDFTS) began in April and continued during the quarter. Completion of the building is expected in the late September-early October 1981 time frame.

Work continued on the design, fabrication, and checkout of GDFTS components. Hydrostatic tests on the pressure vessel, 190 MPa (27,500 psi) internal pressure, and the cooling jacket, 152 MPa (22,000 psi) external pressure, were successfully completed by National Forge Company. Design of the filter modifications was completed and the required parts ordered or fabrication initiated. Other subsystem work included checkout of the Petrolite corrosion rate detector electronics package, furnace soldering of probes, and machining of parts for the new corrosion probe holder.

The Control System Operator's Manual, part of the overall GDFTS Operator's Manual, was completed. As work proceeded on the operator's manual, a few software problems were discovered and will be resolved at a later date. Checkout of the computer operation continued with some problems traced to the printer. Resolution of these problems is continuing.

A forecast of time and funding required to complete the project was submitted to the Department of Energy contracting officer, along with a request for additional DOE funding.

4.6 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 1 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 both of various chemical species and elevated temperatures similar to the conditions encountered during geothermal drilling activities. On the basis of this understanding, clay-based, geothermal drilling-fluid systems, complete with the additives dictated by downhole conditions, will be designed for use in geothermal drilling.

Project Activities

Rheological measurements of drilling fluids following hydrothermal treatments continued this quarter. Rheological properties of pure attapulgite and of attapulgite/chloride systems were recorded at room temperature and after heating in the autoclave at 204°, 260°, 316°, 371°, and 427°C (400°, 500°, 600°, 700°, and 800°F). Tests of sepiolite/hydroxide systems were conducted at room temperature and at 204°, 260°, and 316°C (400°, 500°, and 600°F). Evaluations of pure sepiolite and sepiolite/chloride systems were carried out last quarter. The overall viscosities of attapulgite muds were very low, exhibiting poor gel strength and pore filtrate properties. The sepiolite/hydroxide based muds produced higher viscosities than the previously tested muds. This finding was predominant in the sepiolite/Mg(OH₂) and the sepiolite/NaOH systems. Rheological measurements will continue next quarter using attapulgite/hydroxide systems.

A Sandia high-temperature/high-pressure viscometer was provided to Texas Tech University to assist in the ongoing research. Two additional units with improvements in speed and temperature controls are being fabricated at Sandia.

5. BOREHOLE MECHANICS

The Borehole Mechanics program emphasizes research into completion and well maintenance problems. Specific areas of interest include lost circulation, lining and cementing the well, perforating, and scale removal.

5.1 Lost Circulation/Cementing Test Facility

Sandia National Laboratories

Technical Consultants:

V. Behr (505) 846-0301

J. Kelsey (505) 844-6968

E. Hoover (505) 844-7315

Project Objective

The first objective of this project is to construct a facility that will provide the capability to test lost circulation/completion materials and techniques at simulated geothermal conditions. Following the construction of the facility, the evaluation of materials and techniques used for problems in completion and 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 Activities

Hardware procurement and fabrication of components continued during this quarter. Prefabrication machining of the test vessel parts is underway at Sandia. Several components have been received and are ready for assembly or additional fabrication work. Building modifications to accommodate the facility at Sandia have begun and are expected to be completed by the end of September 1981. Preliminary shakedown tests of the facility are currently forecast for late 1981.

5.2 Lost Circulation Material Screening Apparatus

Sandia National Laboratories

Technical Consultants:

V. Behr (505) 846-0301

J. Kelsey (505) 844-6968

Project Objective

The objective of this project is to fabricate an economical screening apparatus that will be simple enough to permit the testing of a large matrix of materials in a short period of time. The apparatus will be used to evaluate the relative performance of a large number of lost circulation materials to determine which materials should be tested first in the Lost Circulation/Cementing Test Facility (see Section 5.1). This preliminary evaluation procedure will allow work in the Lost Circulation/Cementing Test Facility to be concentrated on the most promising materials, conserving both time and material in the operation of the facility.

Project Activities

During this quarter, checkout of the screening device was completed, and the first series of tests on three lost circulation materials using a modified API Slot Tester were completed through the API orifice tests. The tests are continuing with extended parallel slot tests. Preliminary results show little effect of slot length on maximum sealing capability. Further tests are planned to clarify these preliminary findings. Tests to investigate the effects of slot taper are also planned.

5.3 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 temperatures of 250° to 300°C (482° to 572°F) for 45 minutes.

Project Activities

A perforator system consisting of a conical-shaped charge containing the explosive HNS-II, an ignition train made with a rectangular cross section aluminum jacket surrounding the same explosive, and a low-voltage detonator loaded with HNS-II was fabricated this quarter. The assembly was heated in an oven maintained at 250°C (482°F) for two hours and then fired at that temperature. The system functioned properly, and a target was perforated in a satisfactory manner. The system is now under patent consideration.

5.4 Completion Equipment Study

Contractor: Foster-Miller Associates, Inc. (FMA)
Principal Investigator: B. Doherty (617) 890-3200
Contract Period: 1 August 1980 to 31 July 1981
Contract Number: 49-8367 (Sandia)
Technical Consultant: C. Carson (505) 844-6477

Project Objective

The objectives of this project are to study the equipment and practices currently used to complete geothermal wells and to identify problem areas that might benefit from development of new technologies.

Project Activities

The survey of completion activities and assessment of problem areas were completed during this quarter. A qualitative ranking system was developed to assign priorities to areas for technical development. In addition, engineering analyses of centralizer bows and of cementing plugs were carried out. The remaining project activities include limited hardware analysis but consist largely of compilation of data and the preparation of the final report. Completion of these activities is expected during the next quarterly reporting period.

5.5 Completion Technology Life Cycle Cost Model

Contractor: The BDM Corporation
Principal Investigator: A. Mansure (505) 848-5320
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 can be used to evaluate (1) the cost of current completion technology, (2) the areas needing development, and (3) the cost benefit of new technology.

Project Activities

Development of a set of intermediate variables to allow a mathematical representation of completions and their life cycle costs was finished this quarter. In addition, approximately 40 different cost categories requiring characterizations in terms of the intermediate variables were identified.

Development of the mathematical relationships between the intermediate variables and life cycle cost/benefit is continuing. The mathematical relationship between the benefit of the completion activity and the time history of production was completed during the quarter. Studies of the costs for completion operations are in process.

Identification of the required subroutines for the computer code as well as subroutine specification in terms of function, inputs, and outputs using program design language was completed. Programming has begun on all of the subroutines, and completion of the model is expected during the next quarterly reporting period.

Initial selection of cases and data gathering for sensitivity studies have begun.

5.6 Wellbore Descaling Using Cavitating Jets

Sandia National Laboratories
Technical Consultant: C. Carson (505) 844-6477

Project Objective

The objective of the project is to develop and demonstrate a capability for descaling geothermal wells using high-pressure water jets.

Project Activities

In a previous project, Daedalean Associates developed and conducted preliminary tests of a cavitating jet descaling device. An attempted field test of the unit was cut short by difficulties in delivering high-pressure water to the cleaning head. The purpose of the current effort is to carry out a successful full-scale field test of a descaling system, including the necessary fluid delivery subsystems. During this reporting period, various possible combinations of tubing and pump units for delivering high-pressure fluids to the bottom of a well have been investigated. It appears that a commercial capability exists for high-pressure jet cleaning of slots in oil wells, and that this capability can be extended to solve the problem of downhole delivery of high-pressure water for descaling. Test plans will be finalized early next quarter, and a field test may be conducted either late next quarter or early in FY 1982.

5.7 Casing Stress Analysis

Sandia National Laboratories
Technical Consultant: C. M. Stone (505) 844-5113

Project Objective

The objective of this project is to demonstrate that existing analytical techniques for thermal stress analysis can be applied to geothermal casing applications. Finite element analysis using existing state-of-the-art techniques will be applied to generic geothermal casing problems. Results from these studies will demonstrate how the analytical techniques can impact well completion.

Project Activities

In The Geysers, geothermal production may periodically be interrupted and the well shut-in to a 10% flow rate to satisfy environmental requirements. These shut-in periods cause increases in wellbore temperature and pressure. A structural analysis of the casing/cement stresses due to increased temperature and pressure was performed this quarter. Several production/shut-in cycles were studied to determine the stress and displacement histories. The stresses show that yielding of the casing will occur during the initial completion/start-up phase of the well. After this initial yielding, the cyclic stresses were found to be elastic with a compressive mean stress. Available material data for the casing steel indicate that, for the expected cyclic stresses, more than a million cycles may be experienced without fatigue failure. The well is expected to experience only a thousand cycles during its 30-year life; hence, a large safety margin in fatigue life is anticipated.

An analysis was started to study the casing stresses developed in Imperial Valley geothermal wells. The Imperial Valley well temperature/pressure operating history is different from the conditions which exist at The Geysers. An assessment will be made of fatigue life for casing in the Imperial Valley environment during the next quarterly reporting period.

5.8 Polyurethane Foam Tests

Contractor: Southwest Research Institute
Principal Investigator: Emil Tschoepe (512) 684-5111
Contract Period: 4 December 1980 to 30 June 1981
Contract Number: 74-3379 (Sandia)
Technical Consultant: J. Kelsey (505) 844-6968

Project Objective

The objective of this project was to evaluate the suitability of using polyurethane foam as a lost circulation material. Specific emphasis was placed on the determination of the material properties of foam formed under simulated geothermal conditions.

Project Activities

The laboratory tests to evaluate the use of polyurethane foam as a lost circulation material during drilling were completed this quarter. Three polyurethane formulae, designed by Poly Plug, Inc., were mixed, in turn, in a 122-cm (48-in.) diameter pressure vessel at four pressures, ranging from 0.1 MPa to 6.2 MPa (15 psi to 900 psi), and at four temperatures, ranging from 38°C to 149°C (100°F to 300°F). The density of the prefoam constituents was 1,201 kg/m³ (75.0 lb/ft³). An inert atmosphere of nitrogen was maintained in the pressure vessel during production of the foam, and the two components of the formulae were reacted within canvas bags suspended in the nitrogen environment. The exotherm temperature of the foam was measured continuously while the foam was being made under the simulated geothermal well conditions. Subsequently, samples of the foam formed were removed from each test specimen, and the physical properties and permeability of each sample were measured. The physical properties measured were density, compressive strength, and closed cell percentage. Permeability was measured by recording the volume of IMCO gel solution, under 0.69 MPa (100 psi) pressure, that passed through a 12.7-mm (0.5-in.) thick section of foam in four hours.

The test data show that the the best results were obtained under the most severe conditions, 149°C (300°F) and 6.2 MPa (900 psi). In general, the foam reacted at the higher temperatures was lower in density, but had equal or better compressive strength, regardless of the pressure during reaction. In most cases, no significant difference in compressive strengths of the three formulae was noted at 38°C or 93°C (100°F or 200°F). No exotherm burns were observed on any samples.

Preparation of the final report has been initiated and completion is expected during the next quarterly reporting period. Consideration is being given to field trials of polyurethane as a lost circulation material.

6. DIAGNOSTICS TECHNOLOGY

The central goal of Diagnostics Technology research is the development of high-temperature capabilities for well-logging equipment and instrumentation. This program element also includes research into areas aimed at increasing the capability to measure and evaluate downhole conditions, thus optimizing the performance of the drilling system.

6.1 Wellbore Inertial Navigation System (WINS)

Sandia National Laboratories

Technical Consultants: S. Kohler (505) 846-0421
R. Wardlaw (505) 844-4978

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. The first stage of this project is aimed at developing a tool that operates at moderate temperatures, 150°C (302°F). A capability to operate at higher temperatures, 250°C (482°F), will be pursued as the second phase of the project.

Project Activities

A series of tests were conducted this quarter using the RIMS-II Prototype Inertial Measuring Unit (IMU), which is the functional equivalent of the WINS IMU. The tests were conducted in two phases, the first to examine inertial instrument performance and the second to assess overall IMU/navigation software compatibility.

In the first phase, one of the two axis gyros did not perform at the expected bias repeatability level of 0.1 deg/h. In addition, rather large misalignments existed between the gyro input axes and the IMU axes, and the maximum parameter stability was not achieved until the IMU was in operation for at least 30 minutes to allow temperature stabilization.

During the second phase, navigation software was executed by the Eclipse computer using IMU instrument outputs delivered through an existing IMU/Eclipse interface. These tests identified several error sources not currently modeled by the navigation software. The error sources were associated with gyro angular acceleration sensitivity, accelerometer size effect, accelerometer angular acceleration sensitivity, and scale factor temperature sensitivity.

Work is proceeding to correct the gyro misalignment and to incorporate software compensation for the error sources identified. System testing using the RIMS-II unit will continue next quarter with testing of the WINS IMU scheduled to start in August.

Most of the mechanical parts for three WINS assemblies have been received. Wiring of two servo module interconnection packages is complete, and wiring of similar packages for the I/O module is underway. Laboratory checkout of the first WINS platform, power converter, and servo electronics module is nearly complete. An oven test of the platform is planned for early July to verify operation in the ambient temperature/time profile expected during well surveying. Checkout of

the second WINS power converter and servo electronics module is under-way. Fabrication of printed circuit boards for the I/O module is expected to be completed in July. When sufficient I/O and interface circuitry is available, a test of data transmission reliability will be performed using a seven conductor cable.

Field test of WINS is planned for October at the Nevada Test Site's Pahute Mesa Exploratory Hole No. 1. The hole is essentially vertical, 2,286 m (7,500 ft) deep, and cased with 27 cm (10-5/8 in.) o.d. casing.

6.2 High-Temperature Operation of Active Devices

Contractor: Clemson University
Principal Investigators: Professor L. Fitch
Professor J. Prince (803) 656-3379
Contract Period: October 1980 to September 1981
Contract Number: 28-7356 (Sandia)
Technical Consultant: Bruce L. Draper (505) 844-2132

Project Objective

The objective of this project is to characterize commercial and experimental integrated circuits (linear and digital) and RF devices up to 325°C (617°F) and to correlate these test results in order to produce design rules for high-temperature ICs and RF transistors.

Project Activities

Testing of various commercially available devices for potential use in high-temperature applications continued this quarter. Test results include (1) the Intel M2908 PROMs retained their memory contents to above 310°C (590°F), but military and industrial versions failed in latch-up mode at about 160°C and 150°C (320°F and 302°F), respectively, and (2) the Fairchild 93421 Isoplanar memory showed the highest temperature capability of any memory circuit tested, remaining functional at 215°C (419°F), but lost its memory content when raised to 220°C (428°F). Testing of analog-to-digital converters, RF switching diodes, RF bipolar transistors, RAMs, etc., has been carried out.

6.3 High-Temperature Thick Film Development

Contractor: Purdue University
Principal Investigator: Professor R. W. Vest (317) 749-6244
Contract Period: October 1980 to November 1981
Contract Number: 28-7200 (Sandia)
Technical Consultant: Bruce L. Draper (505) 844-2132

Project Objective

The objective of this project is to develop a family of ceramic, thick film materials (conductive, resistive, dielectric, and semiconductive) which retain useful electrical and mechanical characteristics for both extended periods, 10^5 h, at 300°C (572°F) and short periods, 1,000 h, at 500°C (932°F).

Project Activities

The study of various compositions of ceramic materials for use in high-temperature applications continued this quarter. Among the materials being studied are $\text{BaTiO}_3/\text{SnTiO}_3$ in various ratios together with a frit for use as a medium k dielectric. Stability of characteristics at temperature and over extended periods of time is being studied to determine the optimum mix and curing technique. Various compositions of RuO_2 and Rh_2O_3 in a frit were studied for use as a thick film resistance material. Studies of stability as a function of mix and firing are continuing.

6.4 High-Temperature GaP and GaAs Devices

Contractor: Texas A&M University
Principal Investigator: Professor O. Eknayan (713) 845-7030
Contract Period: October 1980 to September 1981
Contract Number: 62-9929 (Sandia)
Technical Consultant: B. L. Draper (505) 844-1910

Project Objective

The objective of this project is to investigate metallization, passivation, and doping techniques to establish a technological basis for the fabrication of high-temperature (GaP and GaAs) diodes and controlled rectifiers, and the eventual design of JFETs/MESFETs.

Project Activities

The aging of silicon nitride (Si_3N_4) passivated platinum (Pt) and chromium (Cr) Schottky GaP diodes was performed up to 2,488 hours at 275°C (527°F). Temperature cycling experiments involving cooling the diodes to room temperature and heating back to 275°C (527°F) have also been carried out. The devices continued to exhibit good characteristics, barrier height and leakage current density at reverse bias, after the extended exposure to high temperature.

Several multilayer metal film systems have been used successfully to form ohmic contacts to n-type GaP. These systems are Au-Sn/Ni, Au-Si, and Au-Te/Ni. Both laser annealing and thermal annealing have been employed, with laser annealing generally outperforming thermal annealing in both ohmic behavior (linearity) and surface morphology.

6.5 Investigation of Amorphous Metalization for Semiconductor Circuits

Contractor: University of Wisconsin
Principal Investigator: Professor J. D. Wiley (608) 262-3736
Contract Period: January 1980 to September 1981
Contract Number: 74-2536 (Sandia)
Technical Consultant: Roger J. Chaffin (505) 844-2609

Project Objective

The objective of this project is to investigate the related phenomena of diffusion and electromigration in amorphous metals and to obtain experimental data needed to assess the feasibility of amorphous metal films as metallization on high-temperature semiconductor integrated circuits to improve reliability.

Project Activities

This project, directed toward the development of metal systems for semiconductors that can withstand very high temperatures without failure, has produced amorphous metals that have proved to be much more resistant to failure than conventional polycrystalline metals. For example, the diffusion coefficient for Au in amorphous Ni-Nb at 450°C (842°F) is six orders of magnitude lower than it is in polycrystalline Ni. Studies have continued this quarter on amorphous Ni-Nb, Ni-Mo, and Si-W. Si-W films have remained amorphous for one hour at 700°C (1,292°F). A new vacuum annealing furnace has been obtained to allow precise measurement of the recrystallization temperature of these films. Over 100 amorphous samples have been delivered to Sandia this quarter for measurement of diffusion versus temperature in the Sandia backscattering facility.

6.6 Development of a 300°C (572°F) CMOS Process

Contractor: Harris Corporation, Semiconductor Products Division
Principal Investigator: Jim Beasom (305) 724-7567
Contract Period: September 1980 to September 1982
Contract Number: 28-1345 (Sandia)
Technical Consultant: B. L. Draper (505) 844-2132

Project Objective

The objective of this project is to develop a dielectrically isolated (DI) CMOS logic integrated circuit technology capable of operation at 300°C (572°F).

Project Activities

A self-aligned silicon gate CMOS process has been selected for use in the 300°C (572°F) circuits to be developed by Harris Corporation. Several methods of circuit realization were considered, including field-programmable logic, uncommitted gate arrays connected by user-specific metalization, and multifunction dedicated MSI chips with function-select pins. The last method is the one which has been selected for exploitation. A wide variety of functions (2-, 3-, and 4-input AND/NAND and OR/NOR gates, inverters, transmission gates, multivibrators, VCOs, 4-bit shift registers, counters, dual JK flip-flops, etc.) can be implemented with an inventory of only 3 or 4 different kinds of chips.

Reports on the evaluation of aluminum versus self-aligned silicon-gate processes and on the selection of the best method of circuit realization have been completed and delivered to Sandia.

6.7 Metal Sheath Cable Development

Contractor: Halpen Engineering Inc.
Principal Investigator: Arthur Halpenny (716) 856-3185
Contract Period: January 1980 to August 1981
Contract Number: 13-5163 (Sandia)
Technical Consultant: R. W. Eifert (505) 844-4153

Project Objective

The objective of this project is to develop a metal sheath, single-conductor electromechanical logging cable for continuous operation in geothermal wells at temperatures up to 350°C (662°F).

Project Activities

Cable testing was successfully completed. The mechanical testing of the second prototype cable involved 331 cycles at a tension of 136 kg (300 lb), 581 cycles at 454 kg (1,000 lb), 831 cycles at 680 kg (1,500 lb), and 38 cycles at 817 kg (1,800 lb). Each cycle subjected the cable to six straight-bent-straight bending cycles over a 127-cm (50-in.) sheave and two bent-straight-bent bending cycles over a 152-cm (60-in.) drum.

The 4,572-meter (15,000-foot) developmental cable is being fabricated using 304 L stainless steel for the three inner sheaths and Inconel 600 for the two outer sheaths. Inconel 600 has a higher tensile strength and will withstand the hostile environments found in geothermal wells better than stainless steel. All the required materials for fabrication of the cable have been received at the Manufacturing Innovations Company plant in Tulsa, Oklahoma and the inner core for the cable is 95% complete. Delivery of the completed cable to Sandia is expected in September 1981.

6.8 High Temperature Components

Sandia National Laboratories
Technical Consultant: T. Zipperian (505) 844-6407

Project Objective

The objective of this project is to develop very high-temperature diodes, transistors, and SCRs for application at temperatures up to 500°C (932°F).

Project Activities

Liquid-phase epitaxial (LPE) $\text{Ga}_{(1-x)}\text{Al}_x\text{P/GaP}$ (with $x \approx 0.44$) p^+n heterojunction diodes were successfully fabricated by Sandia and were tested at temperatures up to 400°C (752°F). These devices had 23°C (73.4°F) and 400°C (752°F) extrapolated saturation current densities of approximately 2×10^{-16} A/cm² and 1×10^{-4} A/cm², respectively. Measured reverse saturation current densities with $V_R = 3.0$ V at 23°C (73.4°F) and 400°C (752°F) were approximately 3×10^{-9} A/cm² and 2×10^{-3} A/cm², respectively. Breakdown voltages at $I_R = 100$ μ A exceeded 50 V for all diodes tested at temperatures up to 300°C (572°F) and exceeded 30 V for temperatures up to 400°C (742°F). The data suggest that heterojunction diodes in the GaAlP system can be fabricated with high-temperature electrical characteristics quite similar to GaP homojunction devices. The eventual application is expected to be in the fabrication of heterojunction bipolar junction transistors for use at high temperature.

A GaP bipolar junction transistor under test at Sandia has shown that high-temperature, $T > 300^\circ\text{C}$ ($T > 572^\circ\text{F}$), operation of the device was limited mainly by emitter and base ohmic contact resistance. Problems with the emitter contact resistance were accentuated by the high sheet resistance of the intrinsic base. Common-base output characteristics of the device revealed that collector bulk and contact resistances for this one device were negligible and that collector-base leakage was less than 100 μ A for temperatures up to 450°C (842°F). It is anticipated that contact resistance problems may be alleviated somewhat by geometrical changes in the transistor.

6.9 High-Temperature Geothermal Logging and Caliper Tools Development

Sandia National Laboratories
Technical Consultant: R. W. Eifert (505) 844-4153

Project Objective

The objective of this project is to develop tools and cableheads for continuous operation in geothermal wells at temperatures up to 275°C (527°F) and pressures up to 48.3 MPa (7,000 psi). Development of a downhole caliper tool for geothermal well application is also included in this project.

Project Activities

Development of the following 275°C (527°F) logging tools is continuing: temperature tool, flow tool, pressure tool, and combination color tool (flow, temperature, and pressure). These tools, including compatible cableheads, are in various stages of fabrication or development. During the reporting period work continued on the development of stable electronics for these tools, and parts for the combination tool were fabricated. Redesign of the flow tool incorporates a spring mounting for the impeller jewel bearing to prevent shock-induced fracturing. Fabrication of parts for a seven-conductor 275°C (527°F) cablehead was ordered. Preliminary design of a sheath cable cablehead was completed, and detail drawings were initiated. Parts for the downhole caliper tool have been fabricated and delivered to Sandia.

6.10 Upgraded Acoustic Borehole Televviewer

Sandia National Laboratories
Technical Consultant: F. Heard (505) 844-2377

Project Objective

The objective of this project is to upgrade the Acoustic Borehole Televviewer (ABT) for operation in temperatures as high as 275°C (527°F) and pressures to 41.4 MPa (6,000 psi).

Project Activities

A successful field test of the Acoustic Borehole Televviewer (ABT) in the Los Alamos GT-2 well was conducted on 21 May 1981. No problems were experienced during the three hours the tool was in the hole at temperatures to 190°C (374°F) and pressures to 31.0 MPa (4,500 psi). Logs in the open hole zones showed fracturing in agreement with the Los Alamos temperature and spinner log predictions. In addition, the individual fractures and their orientations were clearly visible in the ABT log. The next test of the ABT will be in the very hot, 320°C (608°F), Los Alamos EE-2 well to verify operation to the 275°C (527°F) design goal.

6.11 High-Temperature Electronics

Sandia National Laboratories
Technical Consultant: B. L. Draper (505) 844-2132

Project Objective

The objective of this project is to develop high-temperature electronic component technology for 275°C (527°F) geothermal borehole instrumentation.

Project Activities

Failure analysis on both the Micropac +15 volt high-temperature regulator and the Teledyne Philbrick 275°C (527°F) hybrids was carried out. Energy Dispersive X-Ray Analysis of the die attach areas in the Micropac hybrids revealed large amounts of silver, suggesting that silver-loaded epoxy was used. This die attach method has previously been shown to be the cause of failure in several Sandia and Teledyne Philbrick parts. A quick set of experiments run at Sandia and Teledyne during April 1981 on epoxy versus eutectic die attach once again implicated the epoxy. More detailed comparisons, including various methods of epoxy curing, are underway.

Work on identifying commercial chip capacitors usable up to 300°C (572°F) is continuing. Capacitance changes for several components were measured at 25°C (77°F) with $t=0$ and at 300°C (572°F) after 500 hours of aging. Capacitance, insulation resistance, and dissipation factor versus temperature for a Johanson NPO capacitor look promising for high-temperature applications. Additional tests will be carried out on these types of capacitors before a final report is issued.

6.12 275°C (527°F) Pressure Transducer

Sandia National Laboratories
Technical Consultant: T. McConnell (505) 844-7185

Project Objective

The objective of this project is to develop a high resolution pressure transducer capable of operating in geothermal well environments at temperatures to 275°C (527°F).

Project Activities

The quartz pressure transducer research has been terminated. Before termination, several more disks were slotted and assembled to end caps. Some difficulty was encountered with fracturing of the assemblies as they cooled down after the high-temperature bonding process. From this problem and subsequent measurements of the response characteristics of the transducer, it was concluded that the quartz crystal supplier had not cut the disks in the correct crystallographic orientation. A final report will describe in detail the measured responses of these transducers.

6.13 Upgraded Casing and Cement Inspection Tools

Sandia National Laboratories
Technical Consultant: Hsi-Tien Chang (505) 844-7588

Project Objective

The objective of this project is to upgrade casing and cement inspection tools for operation in geothermal well environments.

Project Activities

Work continued during the quarter to upgrade casing and cement inspection tools. An acoustic transmitter circuit for an acoustic cement bond logging tool was oven-tested at 250°C (482°F) for two hours. Temperature-caused variations in output voltage, current, and frequency are expected to be reduced with circuit refinement and the use of selected electronic components. With operation of the magnetostrictive transducer in the magnetic saturation region, the acoustic signal output may, however, not be markedly affected by such temperature-caused variations. A redesigned Spryton tube using bismuth for anode and cathode in a new trigger circuit design has been successfully operated for approximately 150,000 cycles at 10 pulses per second.

6.14 Development of 300°C (572°F) Operational Amplifier

Contractor: Harris Corporation, Semiconductor Products Division
Principal Investigator: Jim Beasom (305) 724-7567
Contract Period: September 1980 to June 1981
Contract Number: 49-2759 (Sandia)
Technical Consultant: Bruce Draper (505) 844-2132

Project Objective

The objective of this project is to develop a quad, general purpose solid state operational amplifier for use at 300°C (572°F).

Project Activities

Work continued this quarter on a 300°C (572°F) operational amplifier. Tests performed on prototypes of the Harris 300°C (572°F) Quad Op-Amp showed the devices to be usable up to 350°C (662°F) although some drifting was evident at that temperature. At 300°C (572°F) the amplifiers were found to be stable with input offset voltages near 2 mV, input bias and offset currents less than 1 μ A and 0.1 μ A, respectively, open loop voltage gain of 83 dB, power supply rejection ratio equal to 82.5 dB at 324°C (615°F), and common mode rejection ratio of 83 dB, also measured at 324°C (615°F).

6.15 Instrumentation for Downhole Pump Motors

Sandia National Laboratories

Technical Consultant: B. L. Draper (505) 844-2132

Project Objective

The objective of this project is to develop high-temperature components for downhole pump motor instrumentation.

Project Activities

Final V/F circuit changes were made for the downhole pump instrumentation, and hybrid mask design began in June. Older versions of this circuit, used in the Deep Steam project, were usable only up to 180°C (356°F). With minor circuit changes and the addition of one component, df_{out}/dT has been decreased to less than 200 ppm/°C up to temperatures above 200°C (392°F). Careful selection of components at the time of hybrid assembly will further decrease the temperature coefficient and increase the useful temperature range. One of the limiting factors in this design is the monotonically increasing temperature dependence of $V_{CE(SAT)}$, the saturation voltage of the bipolar switching transistors used in the circuit. In redesigning the V/F circuit, it was found that a VMOS device was needed both as a cable driver and as a buffer/switch on an op-amp output. The International Rectifier HEXFETs IRF123 and 322 were both found to be usable. At 200°C (392°F) both devices continued to operate in the enhancement mode and retained low on-resistance of 1-5 Ω . I_{DSS} for both devices is near 125 μA at 205°C (401°F) and 800-1000 μA at 240°C (464°F). Both are available in chip form.

APPENDIX A
Publications and Presentations

PUBLICATIONS AND PRESENTATIONS

Phase IV Final Report Program for the Improvement of Downhole Drilling Motor Bearings and Seals, Report No. SAND81-7066, G. A. Tibbets, P. H. DeLaFosse, A. Black, and S. J. Green, Terra Tek, Inc., Salt Lake City, Utah, Contract No. 46-3053, April 1981.

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Corrosion Inhibition by Control of Gas Composition During Mist Drilling, Report No. SAND81-0973, T. E. Hinkebein and T. L. Snyder, Sandia National Laboratories, Albuquerque, New Mexico, May 1981.

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Evaluation of Equipment and Methods to Map Lost Circulation Zones in Geothermal Wells, Report No. SAND80-7057, W. J. McDonald, P. A. Leon, and G. Pittard, Maurer Engineering, Inc., Houston, Texas, Contract No. 49-1458, May 1981.

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The DOE/DGE Geothermal Program, by J. Kelsey, Sandia National Laboratories, to Shell International, The Hague, Netherlands; Diamant Boart, Brussels, Belgium; TOTAL-CFP, Paris, France; and The French Petroleum Institute, Paris, France, 22 June-3 July 1981.

Temperature Histories in Geothermal Wells: Survey of Rock Thermo-mechanical Properties and Drilling, Production, and Injection Case Studies, Report No. SAND81-7128, M. A. Goodman, Enertech Engineering and Research Company, Houston, Texas, Contract No. 13-8769, July 1981.

Lost Circulation in Geothermal Wells: Survey and Evaluation of Industry Experience, Report No. SAND81-7129, M. A. Goodman, Enertech Engineering and Research Company, Houston, Texas, Contract No. 13-8769, July 1981.

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