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James R. Kelsey, Editor

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GEOTHERMAL TECHNOLOGY DEVELOPMENT PROGRAM
ANNUAL PROGRESS REPORT

October 1982-September 1983

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Geothermal Technology Development
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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/Geothermal Hydropower Technology Division (DOE/GHTD), with program management provided by Sandia National Laboratories. The program emphasizes research in rock penetration mechanics, fluid technology, borehole mechanics, diagnostics technology, and permeability enhancement.

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1. SUMMARY

Introduction

The high cost of drilling and completing geothermal wells is an impediment to the timely development of geothermal resources in the United States. The Geothermal Hydropower Technology Division (GHTD) of the U.S. 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/GHTD. 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 is being approached by improvements in conventional, rotary-drilling technology. The long-term goal will require the development of advanced drilling and completion systems. Research is being conducted in high-risk areas that are not being addressed by private industry due to the lack of near-term payoffs and small market potential.

The Geothermal Technology Development Program is organized into five subelements--Rock Penetration Mechanics, Fluid Technology, Borehole Mechanics, Diagnostics Technology, and Permeability Enhancement. Work is conducted under these subelements in accordance with overall program priorities and available resources. System analysis efforts are also undertaken, as necessary, in order to define geothermal technology needs and to evaluate the potential impact of new technologies on the cost of geothermal energy production.

This report encapsulates the activities within the ongoing research and development (R&D) program for the 1983 fiscal year. Appendix A lists published comprehensive reports on completed projects and presentations made on program work during this reporting period. The reports are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

Highlights

Management

- Program Coordination. A review of the Sandia Geothermal Technology Development Program was presented at the DOE Geothermal Coordinating Group Meeting held in Sacramento, California on 8-9 November 1982. Several members of the Geothermal Resource Council Board of Directors were in attendance in addition to the DOE Headquarters staff.

- Program Review. Comprehensive presentations delineating the activities of the Geothermal Technology Development Program were prepared and presented to the Geothermal Technology Industry Review Panel and the Division of Geothermal and Hydropower Technology, Department of Energy, on 14-15 March 1983 in Lafayette, Louisiana. The review described ongoing research and planning of the DOE/SNL program. Panel recommendations have been incorporated into the R&D program. The members of the review panel are listed in Appendix B.

- Technology Transfer. James Kelsey, SNL, presented a paper at the Geothermal Resources Council's short course on "Geothermal Drilling Practices" held in Reno, Nevada on 5-6 April 1983. The presentation described some of the unique problems encountered in geothermal drilling, as well as some of the solutions being researched by the drilling industry and by the national laboratories. Approximately 100 persons attended the course. Throughout the sessions, specific references were made to SNL's Geothermal Technology Development Program, indicating an increasing awareness and appreciation of the government-sponsored research efforts.

- Geothermal Drilling Fluid Test System. The high-pressure/high-temperature drilling fluid test system developed jointly by DOE, SNL, and NL Baroid was officially dedicated on 28 January 1983 at NL Baroid/NL Industries, Inc., Houston, Texas. The facility has the capability to measure drilling fluid rheology, density, corrosivity, and fluid loss parameters at temperatures up to 371°C (700°F) and pressures up to 138 MPa (20,000 psi). The test facility is available to outside users on a fee basis.

Systems Analysis

- Fracture Stimulation Cost Effectiveness Study. A study of the cost effectiveness of fracture stimulation of geothermal wells in the Valles Caldera and the Imperial Valley was completed, and a report of the analyses published. The study results indicated that fracture stimulation costing \$300,000 or less is cost effective assuming that fracture stimulation has an efficiency factor (the expected number of stimulations needed to produce a total flow equivalent to the total flow from an average commercial well) of less than three. The study also suggested that the effectiveness of present technologies for fracturing is more of an issue than their cost. A summary of the study effort is presented in Section 2.

- Advanced Drilling Technology Study. An advanced drilling technology study to identify research work needed to meet future drilling requirements was conducted during this reporting period and was nearing completion as the fiscal year ended. Some of the preliminary findings of the study are discussed in Section 2.

Rock Penetration Mechanics

- Development of Improved Cavijet® Nozzles. Phase III work to extend analytical techniques, to use a numerical model to investigate the feedback mechanism, and to conduct flow visualization studies of the flow field continued throughout this reporting period. The analytical equations describing the collapse of a bubble ring near a solid wall were successfully derived. A numerical program was developed to simulate the flow in the nozzle, its interaction with the nozzle orifice, and the formation of structuring through feedback, and the program was debugged. Flow visualization techniques were improved, and the numerical calculations showed

excellent qualitative agreement with the photographic studies. The FY 1983 activities are summarized in Section 3.1.

- Improvement of Downhole-Drilling Motor Bearings and Seals. The efforts to improve downhole-drilling motor bearings and seals were completed early in this reporting period with the running of the final bearing/seal package test in Phase V of the program. All program objectives were not achieved, but resources were not available to continue the investigations. In addition to a final report, an assessment of the program accomplishments and shortcomings was prepared for publication. A summary of the final Phase V work in FY 1983 and the program assessment is presented in Section 3.2.

- Development of High-Temperature, High-Pressure Seals. A new project was established near the end of FY 1983 to design and test high-temperature, high-pressure piston plunger seals and check valves for use in a downhole pressure intensifier. Conceptual designs of the plunger seal and check valve are illustrated in Section 3.3.

- Rock Mechanics for Polycrystalline Diamond Compact Cutters. Analytical and experimental studies of the drag bit cutting process continued during this reporting period, and a report documenting the recent project results was published. The analytical model has demonstrated the capability to predict overall behavior and the effects of major changes in drag bit loading. The FY 1983 laboratory experiments and an assessment of the analytical efforts are summarized in Section 3.4.

- Improved Cutter Materials. The experimental program to develop a new family of cemented carbides for geothermal drilling applications was completed during FY 1983 with the conduct of proprietary wear tests. A final report on the project results was prepared showing that NbC, the best candidate material, does not quite equal WC in terms of its hardness and toughness, but it does exhibit high wear resistance. A summary of the wear resistance tests and the final report are contained in Section 3.5.

- Thermal Studies of Polycrystalline Diamond Compact Drag Tools. The Phase II work to expand the numerical-analytical model for temperature analysis of PDC drag bits was completed during FY 1983, and a report on the study efforts was prepared for publication. Using available experimental

data, a correlation was found between measured cutter wear rates and computed wearflat temperatures. This correlation indicated that wear rates in sandstone increase dramatically when mean wearflat temperatures exceed approximately 350°C (662°F). This result was used to develop the concept of a critical weight-on-cutter, defined as the value of the vertical cutter force at which the critical temperature is exceeded, leading to greatly increased wear rates. Using numerical modeling to compute the heat transfer through the rock being cut, an equation was developed that includes all the major variables and predicts conditions under which the mean wearflat temperature exceeds 350°C (662°F). The development of the critical weight-on-cutter concept and the major conclusions from the report on the Phase II thermal studies are summarized in Section 3.8.

- Polycrystalline Diamond Compact Single-Cutter Testing. A new project to investigate the PDC cutter/formation interaction under simulated downhole pressures was established late in FY 1983. The project is outlined in Section 3.9 and is expected to begin in FY 1984 following refurbishment of a high-pressure test cell owned by Tulsa University.

Fluid Technology

- Aqueous Foam Drilling Fluids for Geothermal Applications. The studies to expand the knowledge on foam behavior at high temperatures and to understand the physics and chemistry of foams continued throughout FY 1983. Foam-stability experiments were directed at identifying the most promising candidate surfactants, and foam-rheology work concentrated on the development of models to explore the role of various physical parameters on foam drainage. In the heat transfer efforts, problems with the test apparatus in measuring bulk fluid temperatures were encountered, and modification of the test facility was started. A summary of the aqueous foam activities is presented in Section 4.1.

- Drilling Fluid/Cement Studies. Phase II of the study of clay-to-cement conversion was completed in FY 1983 with the investigation of the effects of additives on cement reactions in bentonite drilling fluids. Included among the results of the experiments was the finding that the addition of 1% CaCl_2 to a bentonite/lime fluid resulted in the total conversion of bentonite into the cement mineral tobermorite. In addition, an Australian bentonite was evaluated and found to be similar to U.S. low

yield bentonite. The work performed during FY 1983 and the preliminary conclusions resulting from the Phase II studies are summarized in Section 4.3.

Borehole Mechanics

- Lost Circulation Test Facility. Construction of the facility to test lost circulation materials and techniques under simulated geothermal conditions was completed, and the system was successfully proof-tested. Tests of lost circulation materials were also begun using the material, Thermo-Set Seal. Some 42 tests were run by the end of FY 1983, and the tests confirmed the plugging performance of Thermo-Set Seal in earlier API slot tester screening tests. Efforts to develop an analytic model of the "plugging" mechanisms involved with lost circulation materials were also started. A description of the facility and the preliminary results of the lost circulation material tests are presented in Section 5.1.

- Casing Collapse. A study of planar radial buckling of typical well casing under geothermal conditions was completed during this reporting period. Three commonly used casing sizes were studied under conditions of incomplete cementing. Casing collapse was found to occur when the stresses through the casing thickness exceeded the casing material yield stress. The study is summarized in Section 5.2.

Diagnostics Technology

- Acoustic Cement Bond Diagnostics. The design of an acoustic cement bond logging instrument for operation at temperatures up to 250°C (482°F) was completed, and fabrication of the tool was begun. The prototype cement bond logging tool is described in Section 6.2.

- Geopressured-Geothermal Reservoir Diagnostics. The efforts to develop a high-resolution pressure transducer for use in geopressured-geothermal reservoirs was phased out due to resource limitations. The laboratory investigations indicated that currently available commercial transducers are not suitable for use in the harsh, downhole geopressured-geothermal environment. The results of the laboratory evaluation of commercial transducers are presented in Section 6.3.

- Radar Fracture Mapping. This new project to develop a high-frequency technique for location of fractures in the vicinity of boreholes was

begun with a simple experiment at a granite quarry in Texas. The results of the experiment indicated for the first time the feasibility of developing a downhole VHF radar for locating fractures that do not intersect the borehole. The field experiment is described in Section 6.4.

Permeability Enhancement

- Surface-Electric-Potential Fracture Mapping. The feasibility of using a surface-electrical-potential technique to map fractures intersecting boreholes was demonstrated in a field test. The field experiment was conducted in a geothermal well at the Beowawe site in Nevada. A summary of the field test is presented in Section 7.1.

2. SYSTEMS ANALYSIS

During FY 1983, systems analysis efforts continued to focus on areas of investigation that would assist in defining geothermal technology needs and provide tools for the evaluation of the potential impact of new technologies on the cost of geothermal energy production. In this report period, a cost-effectiveness study of fracture stimulation of geothermal wells and a study of advanced drilling research needs were conducted. Summaries of these activities follow.

Fracture Stimulation Cost-Effectiveness Study

A study of the cost effectiveness of fracture stimulation of geothermal wells in the Valles Caldera and the Imperial Valley was completed in this reporting period, and a report of the analyses was published.¹ The primary tool used in the evaluation of the cost effectiveness of fracturing was the computer model, GEOCOM², developed in previous reporting periods. GEOCOM is a computer code that provides life-cycle cost/benefit analysis of completion technologies applied to geothermal wells. The code accepts cost data for drilling, completion, repair, operation, and maintenance of the well. It also accepts data on the productivity of the well as a function of time and intended utilization. The code then utilizes economic data (inflation rate, discount rate, etc.) to calculate the present value cost of producing useable energy over the life of the well. GEOCOM contains default values for wells in several resource areas. This study modeled stimulation of wells in the Imperial Valley and the Valles Caldera.

In the development of many geothermal reservoirs it has been common to encounter production wells in which either there is insufficient flow of geothermal fluids or flow cannot be started at all, even though the well-bore itself is free of problems that would impede flow. Attempts to increase flow from such wells are categorized as "well stimulation techniques" and commonly include

1. Redrilling the well (e.g., to deepen or underream it, or to drill a new leg),
2. Pumping the well,
3. Treating the producing formation with chemicals (e.g., acid washing), or
4. Fracturing the producing formation.

A sometimes viable alternative is to abandon the existing well (perhaps converting it to an injector) and to drill a new production well. In determining which technique to use, it is important to estimate both the cost and the effectiveness of each option. This study examined the costs and effectiveness of fracture stimulation.

The costs of fracturing a geothermal well can be estimated fairly accurately. The major cost categories for fracture stimulation are (1) expendable materials, (2) equipment leasing, and (3) rig rates. Indirect costs (such as pulling the well liner) can sometimes exceed the direct costs of fracture stimulation. Assuming there are no major indirect costs, the cost of a hydraulic fracturing job typically ranges between \$100,000 and \$500,000. The cost of an explosive fracturing job typically ranges between \$40,000 and \$100,000. The primary reason for cost exceeding the minimum is the length or volume of fracture to be produced.

Information on the effectiveness of fracture stimulation is much less well defined than information on cost. This uncertainty prohibits any definitive comparison of fracture stimulation to other stimulation options. However, it is possible to estimate the minimum effectiveness of fracture stimulation required to lower the cost of energy produced by the well.

The analysis of the results for fracture stimulation modeling yielded the following general conclusions:

1. The cost of fracture stimulation is low enough to make it a viable option compared to drilling a new well.
2. For some liquid-dominated resources, the fracture stimulation must increase flow by at least 4,536 kg/h (5 ton/h) for each \$100,000 invested. In some scenarios, the minimum increase required 18,144 kg/h (20 ton/h) for each \$100,000 invested.

3. Fracture stimulation can be cost effective as a repair procedure on an old well.

These conclusions were considered valid for wells supporting the production of electricity. They may or may not be valid for support of direct use projects.

The results of the analysis also indicated that:

1. As much as \$800,000/\$300,000 could be spent on fracture stimulation of a dry well in the Valles Caldera/Imperial Valley before drilling a new well would be a more attractive option.

2. Fracture stimulation in the Valles Caldera/Imperial Valley must increase flow by 4,536/13,608 kg/h (5/15 ton/h) for each \$100,000 invested in order to be cost effective.

3. Assuming stimulation restored the well to its nominal flow that existed prior to the onset of the problem, a fracture stimulation repair costing \$300,000 would still be cost effective on a Valles Caldera/Imperial Valley well up to 10/5 years into the productive lifetime of the well.

The GEOCOM modeling results placed in perspective the limited results of geothermal fracture stimulation experiments. The field tests that have been conducted have averaged an increase of 3,629 to 6,804 kg (8,000 to 15,000 lb) of fluid in initial flow per \$100,000 invested. This appears to be close to the breakeven point for some of the reservoirs; but for most reservoirs, it is considerably below the level necessary to significantly reduce the costs of producing fluid from a marginal well.

Fracture stimulation is an expensive operation with insufficient geothermal experience to allow high-confidence estimates of its cost effectiveness. Based on the modeling and limited experimental results, it appears that for the most favorable geothermal fields, a successful fracture stimulation can be nearly a breakeven operation (in terms of its effect on total energy costs). However, analysis and experience indicate that the effectiveness of fracture stimulation must be greatly improved before it can be used with confidence to salvage nonproductive wells (by significantly reducing the total energy costs). Fracture stimulation has been used for years in oil and gas wells; and because of the maturity of this technology, the costs of fracture stimulation are not likely to fall.

Instead, the most promising areas for work relative to geothermal wells would be in improving effectiveness (as measured by increased flow) and in increasing the probability of success. A key element in this work will be developing an understanding of the fractures that can be produced and how they interact with geothermal reservoirs.

Advanced Drilling Technology Study

During this reporting period, an advanced drilling technology study was conducted for DOE's Office of Energy Research to identify promising areas for research work needed to meet future drilling requirements. The study was nearing completion as FY 1983 ended. A summary of some of the elements of the study effort follows.

The study efforts included an analysis of likely future sources of energy and of constraints that those resources would impose on future drilling systems, a literature survey of previous scoping efforts to identify research areas, an investigation of current research--public and private, domestic and foreign--in the drilling area, and identification of systems and capabilities that are likely to be used in the foreseeable future. The findings from these efforts were then combined to identify and define advanced research needs.

Based on current drilling patterns and research emphasis, the study identified four areas in which advanced technology developments are most likely to occur. These areas are drilling hardware, information systems, system control, and automation. The need for advanced technology will be driven by a small portion of wells that are deep or remote or that require long horizontal reach to the intended target. These expensive, high-technology wells motivate much of the research and development and will benefit the most from it. The majority of wells require no new technology, and such wells will comprise the bulk of drilling for the foreseeable future. However, even the cheapest wells will benefit from the technology that will be developed for challenging wells. The major areas of development are closely interrelated and in each an attempt was made to identify significant system changes rather than incremental improvements in components.

Drilling Hardware -- This area is the one in which the effects of new technology will first be felt. A major emphasis of current effort is

development of drilling bits. In addition to improvements in materials and designs for roller-cone bits, significant advances are being made in PDC, or shear, bits. These bits have expanded the performance envelope for bits--especially capabilities for higher rotational speeds. The use of shear bits, with existing or new cutter materials, will grow rapidly over the next few years until a major part of oil and gas drilling will be done using them.

The improvement of motors will not have as widespread an effect as the new bits, but it will change directional deep drilling. Though initially applied in directional work, systems of motors and shear bits designed together to optimize drilling efficiency will also find growing application in the straight portions of deep and deviated wells. Their high rates of penetration and long lifetimes will reduce total well costs.

Use of measurement while drilling (MWD) will expand in the high-technology wells in which the inherent cost of improved information and control are justified. The numbers of sensors and the timeliness of the data will improve in these wells. In addition, lower cost MWD systems will be developed for use in most directional drilling situations, greatly expanding the use of MWD.

Information Systems -- During the next few years, several new instruments and signal processing systems will be developed to provide improved information about the borehole and the formation around it. Some of these will find application with MWD systems to improve drilling efficiency, safety and directional control, and others will be used as logging systems to characterize the formation. A major effort will be undertaken to determine the meaning and value of the measurements that are made. The availability of the improved information and the attempt to evaluate it will require, as well as result in, a much better understanding of the drilling process and the parameters that control it. This understanding will develop through several modeling and analysis efforts in the next several years.

System Control -- The information that has become available through MWD allows improved control of the drilling process, while the expanded use of shear bits demands it. True closed-loop control of drilling parameters--weight-on-bit, torque, RPM--will evolve to maximize rate of penetration, minimize wear, and control deviation. Influx gauges will allow

better control of kicks and wellbore pressures. Improved downlink communications will provide control of downhole tools and bottomhole assembly geometries. With these controls, the system can efficiently produce a desired trajectory. To do so, the system will rely on downhole information sensors and processors, downhole or surface computing, and downhole controllable tools.

Automation -- Software will continue to be developed to provide rig-side help in troubleshooting and problem avoidance. Some of this software will be "hard wired" to provide automatic alerting (e.g., kick indication or bit wear); other systems will be off-line to supplement human control (e.g., "expert systems"). Automation of surface rig functions will continue to grow. Downhole automation for closed-loop control is several hardware generations away, but a first step has been taken by the MWD computer systems that determine and modify the priority of the messages to be sent.

Evolutionary Path -- A projected evolutionary path for technology development helps to put likely technology developments and their interrelationships into context. This path is an extrapolation based on current research, and many of the necessary technologies along this path have been tested and fielded during the past several years.

MWD has made available at the surface information from downhole that previously has been unavailable--for example, real-time indications of wellbore inclination and the orientations of the hole and the bit. Operators will continue to gain competence and confidence in using this information and identifying other information that would be beneficial. Once desirable information has been identified, suppliers will develop downhole tools to collect the information (for example, bit weight and torque sensors and new logging tools) and to respond to it (for example, controllable bent subs and turbine speed controls). The quantity of information passing up and down the transmission channel will also have dictated improved data capacity and two-way communications in the channel, and extensive signal processing, both uphole and downhole, will be commonplace. The controllable components, two-way channel and signal processors, will eventually lead to positive, real-time, closed-loop control of the drilling process and the borehole trajectory. This will lead in one of two directions--either a high-quality data channel will connect the downhole tools

to the surface computer that controls them, or a downhole computer will maintain control and a "weaker" data link will connect to the surface for monitoring purposes. The hardware developments required for this step include downhole-controllable-geometry components and perhaps nondamaging, downhole anchor and thrusting systems to allow complete control of trajectory. At this point the drilling system will supply the capability to efficiently "drive" the bit along a desired trajectory. While the reality of the last steps of this evolution may be questionable, consideration of the path does help to identify likely system improvements.

A final report on the advanced drilling technology study was being prepared for publication as Reference 3 as FY 1983 ended.

3. ROCK PENETRATION MECHANICS

Research in rock penetration mechanics is directed toward a basic description of rock penetration by candidate advanced drilling systems. Understanding the behavior of polycrystalline diamond compact (PDC) drag bits in relation to rock fracture and wear mechanisms is receiving major emphasis, but other research areas, including improved materials and advanced rock penetration concepts such as percussion drilling and cavitating jets, 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 Development of Improved Cavijet® Nozzles

Contractor: Tracor Hydronautics
Principal Investigator: G. L. Chahine (301) 776-7454
Contract Period: 18 February 1980 to 31 May 1984
Contract Number: 13-5129, 68-8419 and 52-3636 (Sandia)
Technical Consultant: D. Glowka (505) 844-3601

Project Objective

The objective of this project is to develop design procedures for cavitating jet nozzles that effectively cut rock at lower pressures than those required with conventional waterjet nozzles.

Background

One of the goals of the Geothermal Drilling and Completion Technology Development Program is the development of an advanced drilling system for hard-rock formations. Mechanical drill bits augmented with high-pressure water jets have been identified as one likely component of such a system. With the recognition that the cutting efficiency of high-pressure water jets is a strong function of nozzle design, we have sponsored work since 1978 to develop procedures for designing nozzles that optimize the use of the erosive power available in high-pressure liquids.

The most erosive water jets have been found to be those that cavitate. Cavitation occurs when turbulent vortices or eddies in a high-speed jet attain circulation velocities high enough to drop the fluid pressure below its vapor point, resulting in the formation of a vapor cavity or bubble. Upon bubble collapse in the presence of a pressure gradient, a high-speed microjet develops. This microjet may contain sufficient energy to produce impact pressures greater than 690 MPa (10^5 psi), which is high enough to fracture rock surfaces. The optimal production of large and, hence, destructive cavitation bubbles with nozzle pressures between 13.8 and 55.2 MPa (2,000 and 8,000 psi) has been adopted as the design goal for nozzles developed in this project.

The project's first phase, which included determining the effects of drilling mud on the cutting performance of cavitating jets (Cavijets®) was completed at the end of FY 1979. The results of this initial phase indicated that augmentation of mechanical bits with cavitating mud jets is feasible and might substantially improve drilling performance, even with conventional rig pressures of <27.6 MPa (<4000 psi).⁴ An associated effort was started in late FY 1979 to determine the feasibility of designing cavitating jet nozzles that resonate passively to produce nozzle-pressure pulsations. Such pulsations produce higher jet impact pressures and structure the jet flow field such that larger cavitation bubbles are produced periodically, thereby increasing cutting efficiency. This work was completed in July 1980, with the findings suggesting that additional research should result in viable pulser-nozzle systems.⁵ Continuation of the investigation of downhole pressure-pulsing nozzles was included in the follow-on Phase II project on cavitating jets, which was initiated in February 1980.⁶ The Phase II work, directed at improving the performance of cavitating jets, continued throughout FY 1981. The work included development of theories for vaned nozzles, organ-pipe nozzle acoustics, jet-structuring mechanisms, and boundary pressures induced by the structured jet. Laboratory rock erosion experiments in air and water were conducted to confirm the theories and to assess the feasibility of the organ-pipe nozzle. The influence of tube geometry, Mach number, and cavitation number on the degree of structuring was also determined experimentally for approximately 30 nozzle shapes. FY 1981 ended with the discovery that the critical Strouhal number can be controlled by nozzle design and that some nozzles apparently depend on cavitation for self-excitation and others do not.⁷

Phase II of the project was completed during FY 1982. This phase of the project resulted in the development of nozzle systems with incipient cavitation numbers two to six times higher (hence, greater jet erosivity at greater hole depth) than those obtained with either conventional Cavijet® nozzles or typical commercial bit nozzles. Also, adaptability of the Organ-Pipe Cavijet® to the physical restraints of existing bits was demonstrated, and the potential of self-resonating structured jets for improved bottomhole cleaning (hence, better drilling) was established. The technology developed in Phase II was transferred to industry and other interested

agencies through presentations at technical conferences.⁸⁻¹⁰ A final report on Phase II was published as Reference 11.

The results of the first two phases indicated that structured cavitating jets can effectively increase drilling rates, but in order to attain improvements required for an advanced drilling system, higher nozzle pressures are necessary. Nozzle-design work aimed at pressures just higher than conventional, 27.6 to 55.2 MPa (4000 to 8000 psi), was begun. An analytical, rather than experimental, approach was taken in Phase III, which was begun in mid-FY 1982. The goals established for this phase were (1) to develop analytical techniques to predict the flow-field characteristics of cavitating jets and the upstream resonance characteristics of pulsing jets, (2) to use high-speed motion and still photography of cavitating jets to evaluate the success of the prediction techniques developed, and (3) to apply the prediction techniques developed to design Organ-Pipe Cavijet® or other nozzles for operation with a high-pressure drop across the nozzle, 27.6 to 55.2 MPa (4,000 to 8,000 psi), and to determine their rock cutting performance in the high-pressure cell (HPC).

By the close of FY 1982, progress had been made in the analytical models efforts. The growth and collapse of an isolated ring vortex, such as that produced by a structured jet, was numerically modeled. It was found that the collapse rate of a cavitation bubble in the center of a ring vortex decreases as the vortex circulation velocity increases. Since cavitation bubble inception more readily occurs at higher circulation velocities, this implies that an optimum circulation velocity should be sought. Progress was also made toward modeling the interaction of ring vortices in the jet and the collapse of toroidal cavitation bubbles near a solid wall, such as the rock surface.¹²

FY 1983 Activities

Phase III project work continued throughout this reporting period with efforts concentrated on (1) extending the analytical techniques for predicting the flow-field characteristics of pulsing jets to include (a) the effects of fluid viscosity on cavity inception in the ring vortices surrounding the jet and (b) the growth and collapse of a ring cavity for a jet

impinging on a wall, (2) using the numerical model developed for simulating jet structuring to investigate the feedback mechanism in organ-pipe nozzle systems, and (3) conducting flow visualization studies of the flow field in the vicinity of the nozzle exit for comparison with numerical predictions. A summary of some of the FY 1983 efforts follows.

Analytical and Numerical Analyses

Due to the complexity and variation of flow-field characteristics internal and external to a pulser nozzle, no single model accurately describes the entire flow field. Various important parts of the flow field have therefore been studied in separate analyses to gain insight into the mechanics involved.

Cavitation bubbles are formed in the center of ring vortices that develop in the shear layer between the jet core and the ambient fluid at the nozzle exit. When a jet is structured, these small vortices coalesce into larger vortices, producing cavitation bubbles of larger diameter and more erosive energy. To study the structuring process, a numerical simulation of the movement of small vortices was undertaken. Some results are shown in Figure 3-1. Here, the flow moves from left to right, exiting the nozzle at a nondimensional axial distance of 5.7. A succession of discrete ring vortices, denoted by the data points, are emitted from the nozzle at a given frequency. The circulation strength of the vortices may be varied in a sinusoidal fashion to simulate the effects of the passive pressure pulsation accomplished by standing pressure waves existing in the specially designed upstream portion of the nozzle. Figure 3-1 shows the computed effects of changing the thickness of the lip at the nozzle exit. Note that the small vortices tend to coalesce into larger ones. Note also that as the lip thickness is increased, a flow separation region forms and grows. It is believed that some flow separation in the orifice is necessary in order to achieve pressure feedback into the upstream resonant chamber; however, large separation regions, such as that shown in Figure 3-2, cause extensive fluid recirculation, which dissipates energy. Some optimal lip thickness thus exists for a given set of jet characteristics. This analysis will provide design guidelines for the nozzle exit geometry.

Figure 3-1. Simulation of Jet Nozzle Interaction--Influence of Lip Thickness for a Separated Nozzle Shape

Figure 3-2. Simulation of Jet Nozzle Interaction--Formation of a Recirculation Region

The effects of modulating the nozzle pressure at a preferred frequency were also studied. It was found that the structuring of small vortices into larger ones was more efficient when the vortex circulation strength was varied sinusoidally at a frequency corresponding to a Strouhal number, $S_d = fd/V$, of 0.3 (f = frequency, d = nozzle diameter, V = jet velocity). This result is confirmed by previous experiments that clearly showed larger and more periodic cavitation bubbles forming when the jet pressure is pulsed at this preferred frequency.

Downstream of the nozzle, the vortices interact with one another and with the wall on which the jet impinges. Flow modeling in this region progressed well in FY 1983, and some results are shown in Figures 3-3 and 3-4. The data points represent vortex positions at a given instant in time.¹³ Due to interaction between adjacent vortices, alternating vortices follow different trajectories for the particular emission frequency assumed in Figure 3-3. For a higher frequency (or smaller standoff distance between the nozzle and the wall), this pattern changes, as seen in Figure 3-4. It is thus seen that the radial location of vortex (and cavitation bubble) impingement on the wall can be controlled by the nozzle standoff distance and pulsation frequency. Impingement of a larger number of bubbles near the centerline of the jet is more desirable because the higher jet-stagnation pressures there cause more violent bubble collapse and, hence, greater erosivity.

The same analysis was used to compute tangential velocities and pressure distributions on the wall as a result of the passage of vortices. It was found that both tangential velocity and pressure at a given point on the wall periodically exhibit large spikes with time. Positive spikes in tangential velocity correlate with negative spikes in pressure. These results indicate that improved bottomhole chip cleaning should result with structured jets due to enhanced shearing action and increased lifting forces. This analysis confirms the mechanisms for this phenomena, which has been previously demonstrated experimentally.¹¹

The process of cavitation bubble collapse was also studied further this fiscal year.¹⁴ The method of matched asymptotic expansions was used

Figure 3-3. Trajectories of Ring Vortices Emitted at Constant Frequency ($S_d = 2f = fd/V_{self_0} = 2$)

Figure 3-4. Trajectories of Ring Vortices Emitted at Constant Frequency ($S_d = 2f = fd/V_{self_0} = 4$)

to analyze the effects of the pressure field near a solid wall on the collapse behavior of toroidal bubbles. An example result is shown in Figure 3-5. Here we see the bubble configuration as a function of time. Note that as the bubble collapses a microjet is formed that is aimed in the direction of the pressure gradient (toward the intersection between the jet centerline and the wall). The numerical analysis is thus capable of predicting the formation of the microjet, which has been shown experimentally to be largely responsible for the destructive power of cavitation bubbles.¹⁵

Figure 3-5. Collapse of a Torus Near a Solid Wall--
Bubble Shape at Different Times

Flow Visualization Studies

A low-pressure test-loop facility was designed, assembled, and operated to provide experimental support to the concepts dealing with jet structuring and vortex-nozzle interaction. The bench-mounted flow loop consists of two pumps, a reservoir tank, an organ-pipe feed line, and a test chamber. The test cell was constructed of a clear acrylic cylinder with aluminum end plates that were held in place by means of threaded tie

rods. The inside diameter of the chamber is 28 cm (11 in.). A small, 0.32 l/s (5 gal/min) positive displacement pump serves to pressurize the test cell, up to 1.0 MPa (165 psia), and is controlled by a bypass valve. The centrifugal jet supply pump takes suction directly from the test cell and discharges through a flexible hose to a short length of plenum pipe. The plenum feeds the 1.1-m (44-in.) long Stratojet organ-pipe and nozzle. The flow through the pump, up to 4.5 l/s (65 gal/min), is regulated by a discharge valve to effect the desired nozzle pressure drop—up to 0.5 MPa (75 psi) for the 10- and 12.5-mm (0.4- and 0.5-in.) diameter nozzles that were used.

High-speed motion pictures of translating vapor cavities in the cores of ring vortices emanating from self-modulated nozzles were taken with a 16-mm camera capable of 10,000 frames/second. Lighting was supplied by a flash lamp with flash durations of 1 to 2 μ s. The pulse generator was triggered by the camera to provide synchronous flashes with the shutter that was driven by the film advancing past the lens. For still pictures, a single flash was triggered while the camera shutter was open.^{16,17}

After resolving several problems related to lighting, excellent photographs were obtained with several nozzle configurations. The example shown in Figure 3-6 illustrates the effectiveness of self-resonating pulser nozzles in creating larger, more destructive cavitation bubbles. The left nozzle, not designed specifically for cavitation, creates a random distribution of small cavitation bubbles. The middle nozzle, designed for cavitation but not jet structuring, creates cavitation bubbles that tend to form periodically but do not coalesce into large structures. The nozzle on the right periodically forms cavitation bubbles that coalesce into very large bubbles even at higher cavitation numbers ($\sigma = P_a / \Delta P$).

The flow-visualization apparatus has also been used to study the formation of bubbles inside nozzles made of clear lucite. With certain nozzle geometries, the bubbles could be seen moving toward the nozzle wall and imploding, causing nozzle erosion. Such bubble movement has also been predicted in the numerical studies.

SMITH NOZZLE

$P_a = 193 \text{ kPa (28 psi)}$
 $\Delta P = 616 \text{ kPa (90 psi)}$
 $\sigma \approx 0.31$

CAVIJET NOZZLE NO LIP

$P_a = 186 \text{ kPa (27 psi)}$
 $\Delta P = 699 \text{ kPa (102 psi)}$
 $\sigma \approx 0.26$

CAVIJET NOZZLE THICK LIP

$P_a = 276 \text{ kPa (40 psi)}$
 $\Delta P = 495 \text{ kPa (72 psi)}$
 $\sigma \approx 0.56$
 $f \sim 700 \text{ Hz}$

NOTE: P_a = AMBIENT PRESSURE, ΔP = NOZZLE PRESSURE DROP, $\sigma = P_a/\Delta P$ = CAVITATION NUMBER

Figure 3-6. Comparison of Cavitation Appearance in Three Nozzle Types
(only the thick lip Cavijet® nozzle is self-resonating)

Further qualitative verification of the numerical studies has been possible with the flow-visualization studies. Figure 3-7 shows a comparison of computed and experimental vortex trajectories between the nozzle and the wall. The numerical calculations show excellent qualitative agreement with the photographic results, thus helping to validate the analyses.

Phase III efforts using the numerical model to study the feedback mechanism in resonating nozzles, flow-visualization studies, and the development of an optimized nozzle design for structured, cavitating jets at 27.6 to 55.2 MPa (4,000 to 8,000 psi) differential pressure, were continuing as FY 1983 came to a close. The project is expected to be completed by mid-1984.

Figure 3-7. Trajectories of Structured Jet Vortices ($S_d = 0.25$)

3.2 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 31 January 1983
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 was 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.

Background

This project was initiated by the Energy Research and Development Administration (ERDA) in 1976.¹⁸ The work was continued under DOE,¹⁹ and in mid-1978, DOE assigned management of the project to Sandia. Under the project, a seal tester, a bearing/seal package, and a bearing/seal package test facility were designed and fabricated. New lubricants, seals, and bearing/seal package designs were developed for testing under simulated geothermal drilling conditions.²⁰⁻²⁴ Lubricant testing was completed in 1979 with the successful development and subsequent commercialization of lubricants exhibiting exceptional high-temperature performance.²⁵ Seal testing continued during FY 1980, checkout of the Bearing/Seal Package Test Facility was completed, and testing of bearing/seal packages was initiated.^{6,26} Testing of the most promising candidate seals in the bearing/seal packages continued during FY 1981. A total of 16 seal tests were conducted, concentrating on the development of the high-temperature, corrosion-resistant (HTCR) SF design (chevron-shaped) and the Variseal® design. For the first time, the goal of a 200-hour seal life was achieved

in the test of an SF-design seal made of Utex compound HTCR, a glass-reinforced copolymer of propylene and tetrafluoroethylene. Four bearing/seal package tests were also conducted in FY 1981, including the first attempt to use a mechanical face seal in the package. The face seal failed to hold pressure, and failure of the floating piston was experienced. As FY 1981 ended, preparations were being made for additional HTCR seal tests and for tests of second-generation floating pistons and new face seals.⁷

Seal testing and evaluation tasks under this project were completed in FY 1982 with the successful test of a second-generation Variseal®. In the final test, the seal was run for 100 hours at a differential pressure of 10.3 MPa (1,500 psi) without failure and with less than 20% leakage of the lubricant reserve. Failure of the floating piston continued to be experienced during FY 1982 in the bearing/seal package testing and evaluation part of the project. Both third-generation HTCR and Variseal® floating piston designs failed at test times of 48 hours or less. At the close of FY 1982, preparations were underway for the conduct of the final bearing/seal package tests.¹²

FY 1983 Activities

The project was completed early in this reporting period with the running of the final bearing/seal package test in Phase V of the program for the improvement of downhole drilling motor bearings and seals. Since resources were not available to continue investigations in this area, a final report was prepared and published on Phase V activities.²⁷ The report also included an overview of previous work conducted under the program. In addition, a report was prepared for publication as Reference 28 to evaluate and assess the program accomplishments and shortcomings. A summary of the final Phase V work and the program assessment follows.

Bearing/Seal Package Tests -- Bearing/seal package test No. 15 used the Gits Brothers-III (third generation) face seal that utilized solid tungsten carbide for both the rotating face and the stationary face. A schematic of the face seal is shown in Figure 3-8. The test was run for 24 hours and terminated so that examination of the seal and floating piston could be made. Posttest analysis showed that, as in the case of most of

Figure 3-8. Face Seal Schematic

the bearing/seal package tests, the floating piston had failed, allowing mud to enter the bearing/seal package. The face seal was in good condition. The bearing/seal package test results and conditions are summarized in Table 3-1. As a result of these tests, it was recommended that a bellows arrangement be used in place of the floating piston because the floating piston requires an ID and an OD seal whereas the bellows requires an ID seal only that seals against a replaceable surface.

Program Assessment -- The focus of this program was the development of a better bearing-and-seal assembly that could be used in different kinds of drilling motors in a geothermal environment. The major tasks were (1) design and construction of seal testing devices, (2) screening and evaluation of candidate seals in a simulated bearing/seal package, (3) tests of the most promising candidates in a full-scale bearing/seal package, and (4) analysis of failed seals after testing.

The basic approach of screening seals in a unique machine with a leakage failure criterion and then moving toward full-scale tests in the laboratory or the field still appears to be valid. The execution of this plan could have been more effective, however, if certain parts of it had been done differently. Those parts chiefly involve the test equipment design, the choice of seals to be evaluated, and the failure analysis of the tested seals.

The three major pieces of test equipment (Seal Test Machine, Bearing/Seal Package, and Bearing/Seal Package Test Facility) had design characteristics that did not necessarily give misleading results, but that made the results more difficult to interpret. During the test program, all of the machines were modified to correct deficiencies that did not require major redesign. The remaining features are those that should be considered by anyone planning a machine of the same kind.

The Seal Test Machine would have provided more useful information if it had had torque measurements for the individual seals and if the thermocouples had been placed nearer the shaft/seal interface. The torque and temperature values actually measured were good averages, but the improved

Table 3-1

Bearing/Seal Package Test Conditions and Results

Test No.	Duration h	Seal Type	Shaft Coating	Δp MPa (psi)	Diametrical Clearance: Shaft to Backup Rings mm (in.)	Failure Analysis
01	Shakedown Test	Style 701 3 pressure rings				
02	Shakedown Test	Style 701 3 pressure rings				
03	5.0	Style 701 3 pressure rings	Chrome	6.2 (900)	0.254 (0.010)	
04	30.9	HTCR SF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Floating piston failed, allowing mud into the bearing pack.
05	0	Gits Bros. I face seal	N/A	N/A	N/A	Seal failed before rotation-pressure caused silicon carbide face to crack.
06	6	HTCR SF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Test terminated because of seizure of bearing pack. Dowel pin sheared allowing backup rings to spin, causing seizure.
07	51.3	HTCR SSF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Test terminated because of excessive bearing temperatures. Floating piston failed, allowing mud to enter the bearing pack.
08	10.0	Gits Bros. II face seal	N/A	6.9 (1,000)	N/A	Lost Δp across seal. Seal failed.
09	4.0	HTCR SSF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Floating piston failed. Mud in bearing pack.
010	11.0	Stein face seal	N/A	6.9 (1,000)	N/A	Seal failed - carbon graphite face destroyed - no parts found.
011	48.0	HTCR SSF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Terminated because of not being able to hold P. Mud in bearing pack. Floating piston and main seals both worn.
012	46.0	HTCR SSF design	Carburized steel	6.9 (1,000)	0.127 (0.005)	Mud in bearing pack. Floating piston ID worn.
013	48.0	Variseal® III	Carburized steel	3.5 (500)	0.127 (0.005)	Mud in bearing pack. Floating seals and main seals slightly worn.
014	24.0	Variseal® III	Carburized steel	6.9 (1,000)	0.127 (0.005)	Mud in bearing pack. Floating piston failure.
015	24.0	Gits Bros. III face seal	N/A	6.9 (1,000)	N/A	Mud in bearing pack. Floating piston failure.

- NOTES: 1. All tests run at 450 rpm except test No. 03 at 400 rpm.
 2. Axial load all tests, 4,536 kg (10,000 lb).
 3. 1,078 kg/m³ (9 lb/gal) water-based mud with 2 to 3% abrasive content (No. 3 blasting sand); pH - 7 to 9.

instrumentation would have shown more about rapid fluctuations that might be correlated with each other and the leak rate to give a better understanding of the failure process.

Redesign of the Bearing/Seal Package would probably have had the most beneficial effect of any hardware change. The Bearing/Seal Package has two major impediments to data collection--lack of information on floating piston performance and lack of temperature measurement anywhere near the shaft/seal interface. These problems would not have been so acute if the floating piston had worked well, but its consistent failure aggravated what might otherwise have been minor shortcomings. The problems were also a consequence of a decision early in the program to trade instrumentation sophistication for the realism of a field-usable Bearing/Seal Package. Again, this decision turned out poorly because of the difficulties with the floating piston, so the obvious summation of recommendations for the Bearing/Seal Package is to redesign or eliminate the floating piston. By having a flexible bellows or diaphragm in the annular space between the rotating shaft and the outer case, the sealing problem could be reduced to that of a nontranslating, low-pressure rotary seal. The redesign could also incorporate a method for signalling when the lubricant was expended and a method for measuring temperatures nearer the shaft/seal surface.

The lack of high-temperature capability in the Bearing/Seal Package Test Facility was not a serious operational handicap because the runs were not long enough for hot fluid to become a significant factor in the seal life. If the Bearing/Seal Package redesign were successful, then curing the facility's high-temperature problems would become important.

The choice of seals to test and the analysis of failed seals are directly related, since the latter frequently influences the former. Until late in the program, the analysis of failed seals was based primarily on macroscopic examination or theoretical calculation. The pronounced unrepeatability of the early tests strongly indicates that there were failure processes that were not seen at the scale of the investigation. It is not guaranteed that a more rigorous examination will clearly define the failure

modes and causes of unrepeatable tests, but it does seem that a more thorough look at the failed seals would have led to a more systematic selection of seals to be evaluated subsequently. This effort seems especially worthwhile when the relatively modest cost of the failure analysis is compared to the cost of testing the seals.

Despite the preceding catalog of things that could or should have been done differently, the program produced a number of useful conclusions and generated much unique information. There is now a large base of raw data concerning seal temperatures and leak rates versus time for a wide variety of seals. Seal materials and designs that are promising candidates for further development were also identified. The most important specific conclusions from this program are

1. Seal Design -- The seal, shaft surface, and lubricant must be considered as a system. Perhaps this is obvious, but when the performance of one of these items is discussed, it must be noted that the performance of the complete system is implied. Given this qualification, the best seals tested were the HTCR chevron seal by Utex Industries and the Variseal® by American Variseal Company when run with a carburized steel shaft and a tungsten-carbide coated shaft, respectively. The chevron-shaped HTCR seal also performed better when only one or two rings were used in the stack. When three rings were used, there seemed to be poor lubrication and excessive wear of the center ring. Some industry experience indicates that a single lip seal with additional body material (such as the Utex double-length SSF design) is the optimum arrangement, but the experiments did not make this direct comparison.

2. Lubricant -- The high temperature, 371°C (~700°F) for many hours, at the shaft/seal interface indicated in some tests that a synthetic lubricant will be necessary for those seal designs. The Pacer PLX-014 lubricant (commercialized by Pacer Industries as DHT-90G) was the best lubricant tested in this program. This lubricant ran in one seal test for 200 hours at high temperature with almost no sign of chemical degradation; however, its load-bearing properties in a real-bearing package under these conditions are still unproven.

3. Bearing/Seal Package -- In the course of debugging runs and seal tests, the Bearing/Seal Package was operated for a total of about 300 hours. Except for the problems with the floating piston, the Bearing/Seal Package worked well. It was disassembled many times for the installation of various seals, and there were few signs of deterioration during this process. Field use of a unit similar to this, but with mud-lubricated bearings, also indicates that the design is structurally sound.

3.3 Development of High-Temperature, High-Pressure Seals

Contractor: Foster-Miller Associates, Inc.
Principal Investigator: Brian J. Doherty (617) 890-3200
Contract Period: 1 October 1983 to 30 September 1984
Contract Number: 47-1095 (Sandia)
Technical Consultant: B. Caskey (505) 844-8835

Project Objective

The objective of this project is to design and test high-temperature, high-pressure piston plunger seals and check valves for application in a downhole pressure intensifier for use in geothermal water-jet drilling.

Background

One of the most promising techniques of breaking rock in geothermal well drilling is the use of a water jet. But, high pressures, 103 MPa (15,000 psi), are required for efficient water-jet cutting, and surface equipment capable of providing the necessary flow rates and pressures are not practical at these high pressures because of safety restraints. Hence, an innovative concept for using a high-pressure water-jet technique in geothermal well drilling is needed. Earlier studies²⁹ have indicated the feasibility of the development of a pressure intensifier (pressure transformer), installed downhole, that would be capable of providing 103 MPa (15,000 psi) from a 21 MPa (3,000 psi) surface source. Standard rig mud pumps can safely produce the necessary surface pressure. The most critical problem in the design of a downhole pressure intensifier is the performance of the seals in the device. Successful development of high-temperature, high-pressure seals would not only provide a sound basis for a downhole intensifier design, but would also advance the state of the art in dynamic seals for other high-temperature, high-pressure applications.

The goals of this development effort include the design and test of candidate high-temperature, high-pressure piston plunger seals and check

valves capable of functioning satisfactorily in a downhole pressure intensifier under geothermal drilling conditions. The components must operate in a water-based drilling mud containing 2% abrasive sand particles (larger than 74 microns) at a fluid temperature of 149°C (300°F). A minimum operating life of 200 hours and survival for 60 days at temperatures in the 260°C (500°F) range is also prescribed for the components. The seals will be designed for a piston plunger that is 2.5 cm (1.0 in.) in diameter, has a 61-cm (24.0-in.) stroke, reciprocates at 60 strokes per minute, and pumps the drilling fluid at 103 MPa (15,000 psi). The maximum leak rate through the seal will not exceed $0.63 \times 10^{-5} \text{ m}^3/\text{s}$ (0.1 gal/min) at a pressure drop across the seal of 103 MPa (15,000 psi). The check valve will also have a pressure drop across it of 103 MPa (15,000 psi) and must accommodate, when open, a flow rate of $25 \times 10^{-5} \text{ m}^3/\text{s}$ (4.0 gal/min) with less than a 0.69-MPa (100-psi) pressure drop. The valve must operate at 60 open/close cycles per minute and have a maximum leak rate, when closed, of no more than $0.63 \times 10^{-5} \text{ m}^3/\text{s}$ (0.1 gal/min). Preliminary conceptual designs of the plunger seal and the check valve are depicted in Figures 3-9 and 3-10, respectively.

FY 1983 Activities

The procurement actions required to establish this project were begun in the latter part of this reporting period. By the close of FY 1983, the project contractor had been selected, and work on the seal development was scheduled to begin in early FY 1984.

Figure 3-9. High-Temperature, High-Pressure Plunger Seal Concept

Figure 3-10. High-Temperature, High-Pressure Check Valve Concept

3.4 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 understand the rock/cutter interaction well enough to predict and optimize the performance of polycrystalline diamond compact (PDC) bits. The approach to this goal has been to conduct analytical and experimental investigations of a single drag cutter in virgin rock.

Background

This project was begun in November 1978. Initial efforts included the modification of a two-dimensional, finite-difference model, designated TOODY, to investigate the rock/cutter interaction problem.³⁰ Work continued during FY 1979 on (1) the calculation of cutter stresses including the effect of rake angle, depth of cut, and confining pressure of drilling mud and (2) the rock failure mechanism, using the biaxial fracture model available in the TOODY code.³¹ In FY 1980, code modifications--dealing with finer zoning, larger rock, and longer run time--improved calculations that identified four steps in the rock fracturing process.⁶

During FY 1981, work on rock fracture modeling was directed to experimental verification of the rock material model and to comparison of the fracture pattern in the model prediction and in laboratory experiments. The model was transferred from the TOODY finite-difference code to the HONDO II finite-element code in order to lower costs and provide for greater flexibility, for boundary conditions, and for shear as well as tensile failure. Verification of the material model was attempted by using the constitutive relations for Berea sandstone in HONDO and by loading sandstone blocks in the laboratory under different confining stresses. The verification tests showed good qualitative agreement, although calculated failure loads were considerably less than the experimental failure loads.

This discrepancy was attributed to the granular behavior of the material model after failure.⁷

Analytical and experimental work to understand the drag-bit cutting process continued during FY 1982. A series of single-cutter experiments were conducted at a fixed cutter speed and at three depths of cut in Tennessee marble and Westerly granite. Although there were similarities in the extent and type of damage that developed in the two rock types, some subtle variations that reflect differences in the rock type, structure, and mechanical behavior were apparent. Development of the two-dimensional, finite-element code also continued during FY 1982 in the effort to model the rock-cutter interaction and the chip formation process. Features added to the model included plastic deformation and formation shear cracks in compression. In this evolutionary stage, the model predictions remained quite sensitive to the assigned structures of the cutter/kerf interface. Nonetheless, the model predicted that chip formation is produced by the development of tensile fractures and that subsurface tensile fractures should be produced that dip in the direction of tool displacement. The latter prediction was in good agreement with the observations noted in the marble and granite experiments.¹²

FY 1983 Activities

Analytical and experimental work to understand the dragbit cutting process continued during this reporting period, and a report was prepared and published documenting the recent analytical and experimental efforts under the project.³² In addition, experimental data were produced for use in the development of the Drill String Dynamics Model (Section 3.6). A summary of these project activities follows.

Laboratory Experiments -- The laboratory rock-mechanics work focused on providing experimental information on the nature of rock failure during cutting. Experiments to investigate the development of damage as a function of depth of cut during drag-bit tests were conducted. The objective of the effort was to investigate the size and shape of damage zones and to correlate these observations with code predictions of stress distributions within test specimens. Two different rock types, Tennessee marble and

Westerly granite, were selected for the test series. These rock types were selected because both have a very low porosity yet have quite different compositions and mechanical properties that will be reflected in cutting behavior and damage development. Low porosity was important because a vacuum impregnation technique was used to draw dyed epoxy into the fractures created by cutting the rock. The cut zone was then sectioned to show the colored epoxy in the cracks.

In early work, fracture patterns in the marble compared favorably with the predictions of the code, and fracture patterns in specimens of Westerly granite tested at three different depths of cut were in agreement with those in the marble samples and with the predictions of the code. However, it was suspected that the dyed-epoxy decoration technique was not revealing the full extent of the damage in either type of rock. As an alternative method, tested specimens of both marble and granite were imbibed with a fluorescent dye penetrant, sectioned, and examined. The results of this study indicated that the full extent of the damage was indeed not made clear by the first decoration technique. Furthermore, although there were similarities in the extent and type of damage that developed in the two rock types, some subtle variations that reflected differences in the rock type, structure, and mechanical behavior were apparent.

The modeling of the bit/formation interaction in the Drill String Dynamics Model (GEODYN) required the definition of force inputs to individual PDC cutters. In order to provide the required data, singlecutter tests with both sharp and worn cutters were performed in sandstone and granite. Three depths of cut, 0.635, 1.27, and 2.54 mm (0.025, 0.050, and 0.100 in.), were made with each rock/cutter combination, and three-axis force measurements were recorded on magnetic tape. In addition to straight cuts in virgin rock, penetration tests (in which the cutter plunged vertically into the rock with no movement parallel to the rock surface) and offset cuts (in which the cutter was partially engaged in a previous cut) were conducted. The force records were digitized, and some statistical analysis was done. The data were provided to Jordan, Apostol, Ritter Associates for use in the qualification of the GEODYN model.

Project Assessment — The analytical work to date has met with mixed success, being able to capture some features of the cutting process, but not all. Part of the difficulty lies with modeling the material behavior. The response of Berea sandstone in even relatively simple uniaxial and triaxial tests is complex and highly nonlinear. The "elastic" properties are load dependent and failure is progressive, beginning at relatively low loads.

The constitutive models used to represent the material are necessarily simplifications of actual behavior. They also include some theoretical shortcomings, such as use of a stress criterion for crack propagation. However, despite these limitations, verification analyses of indentation tests correlated fairly well with observations, Figures 3-11 and 3-12. Fracture patterns matched those obtained experimentally, and loads calculated with both Coulomb and plasticity failure criteria bounded the measured values.

The analysis of drag bit cutting has the added complication of requiring assumptions about contact between the cutter and the rock. It was shown that the results were sensitive to this assumption. This necessity of assuming a contact geometry appears to be the major stumbling block to developing analysis methods that can model the cutting process in detail. Even if all the other limitations of the model were removed, this problem would still remain. The only apparent way to eliminate the need to assume a constant contact area is to have the cutter move a significant distance in the analysis. This requires the ability to form and eject chips and to include the crushing of the rock under the cutter. Conceptually, this is achievable with either a remesh capability or Eulerian approach, but the problem size and required computing time is formidable.

The present analysis is not without value, however. The model has the capability to predict overall behavior and the effects of major changes in loading.

a. Predicted Fracture Pattern

b. Experimental Fracture Pattern

Figure 3-11. Comparison of Predicted and Experimental Fracture Patterns, Unconfined Indention Conditions

a. Predicted Fracture Pattern

b. Experimental Fracture Pattern

Figure 3-12. Comparison of Predicted and Experimental Fracture Patterns, Confined Indentation Conditions

The most significant result with respect to overall behavior is the prediction that vertical loads form fractures. This leads to the conclusion that indentation-type loading is probably one of the major fracture forming mechanisms during drag bit cutting, not only contact between the front of the cutter and the rock. It thus appears that cutter life could be extended by improving the capability of cutters to withstand significant vertical and bottom shear loads, with a reduced emphasis on the front face of the cutter.

With respect to the effects of changing loading conditions, the most important result is the effect of in situ stresses and pressure on the rock surface. The model predicts a change in the cutting process from a tensile fracture process to a shear (plasticity) process when confined. This change in behavior appears intuitively correct and is also supported by the demonstrated successful application of the model to the confined indentation test. The change in cutting process has implications for both testing and design. If the cutting process at atmospheric pressure is not the same as when confined, the applicability of atmospheric test data is questionable. Tests under confined conditions would most closely represent actual conditions.

Hence, with respect to research into the mechanics of cutting, the present situation is such that laboratory tests do not simulate actual cutting conditions, and the model is least reliable at laboratory test conditions (atmospheric pressure). It is expected that the present model is most applicable to actual drilling conditions, where the rock is confined by drilling mud. Therefore, a primary objective should be to bring the laboratory test conditions closer to actual drilling conditions. Comparisons should then be made between the model and tests under simulated cutting conditions.

In consonance with the above conclusions, a new project was being established to test single drag cutters under simulated downhole pressures as FY 1983 came to a close (Section 3.9).

3.5 Improved Cutter Materials

Contractor: SRI International
Principal Investigator: David J. Rowcliffe (415) 859-5044
Contract Period: 30 March 1981 to 31 December 1982
Technical Consultant: J. Finger (505) 844-8089

Project Objective

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

Background

This project was started during FY 1981. Initial efforts included procuring carbide and metal powders for fabrication of cemented carbides, obtaining WC-Co (tungsten carbide-cobalt) specimens for fracture toughness correlations, and discussing WC-Co system production and performance characteristics with knowledgeable manufacturers and researchers. Fabrication of cemented carbides and toughness evaluations were initiated. Both sintering and hot-pressing processes for preparing dense cemented carbides were investigated. Cemented carbides in the NbC-Ni (niobium carbide-nickel), NbC-Co (niobium carbide-cobalt), TaC-Ni (tantalum carbide-nickel), and TaC-Co (tantalum carbide-cobalt) systems were prepared using hot-pressing techniques. Sub-stoichiometric samples of some systems, e.g. NbC_{0.83}-Co, were also prepared. The density, microstructure, and hardness of the samples produced were determined and compared with the properties of rock-cutting grades of cemented WC-Co. By the end of FY 1981, suitable fabrication and testing techniques had been established, and preparation of test specimens of NbC-Ni, NbC-Co, TaC-Ni, and TaC-Co systems was under way.⁷

Experiments with a broad range of cemented carbides consisting of NbC and TaC with Co and Ni binders were conducted during FY 1982 to develop a new family of cemented carbides that would provide an alternative to WC-Co materials for geothermal drilling. Test results showed the most promising

systems were those based on NbC-Co. Hardness and toughness tests indicated that the NbC-Co systems have a qualitative dependence on binder content similar to that found in WC-Co. In addition, examination of wear surfaces by scanning electron microscopy suggested that surface plastic deformation of the carbide phase occurs in the carbide grains of NbC-Co materials, in contrast to surface fracture in the carbide grains of WC-Co. The tendency to deform plastically rather than to initiate microfracture could improve the wear resistance of hard grades of NbC-Co. Additional wear resistance testing of NbC-Co compositions was planned for FY 1983.¹²

FY 1983 Activities

The project was completed in the first part of this reporting period with the conduct of additional wear resistance testing, and a final report on the project was prepared for publication as Reference 33. A summary of the wear resistance tests conducted in FY 1983 and of the final report follows.

Wear Resistance Tests -- Wear resistance was measured in a bit manufacturer's (Security Dresser) proprietary wear test that has a history of accurately predicting field performance from laboratory test data.

Table 3-2 shows the results of wear tests made at Security Dresser. The wear resistance number, W, reflects the volume of material lost from a standard 12.7-mm (0.5-in.) diameter cylinder abraded on a rock surface under controlled conditions; the larger the value of W, the higher the wear resistance. The W values can be ranked approximately in order of increasing hardness and decreasing toughness. For a given cobalt content, the NbC_{0.83} materials are generally harder, tougher, and considerably more wear-resistant than their stoichiometric counterparts. Examples of wear-resistance values for commonly used rock-cutting grades of WC-Co, determined by the same test, are given in Table 3-3. These examples show that the wear resistance of the NbC_x-based cemented carbides lies within the range of the grades of WC-Co commonly used in rock drilling. The high wear resistance values found in NbC_{0.83}-10 Co can be achieved in grades of WC-Co with a lower Co content. Such grades are not currently used for rock cutting because of their low fracture toughness. However, no wear resistance data on low Co grades of cemented WC were available for comparison.

Table 3-2

Hardness and Wear Resistance of Cemented Carbides

<u>Composition</u>	<u>Hardness, GPa</u>	<u>Fracture Toughness, MPa m^{1/2}</u>	<u>Wear Resistance, W</u>
NbC-10Co	12.70	-	784
NbC-10Co	-	-	669
NbC-10Co	12.16	5.98	1098
NbC-10Co	13.25	5.39	878
NbC-20Co	11.05	8.28	376
NbC _{0.83} -10Co	14.40	5.30	2065
NbC _{0.83} -10Co	14.28	6.47	1866
NbC _{0.83} -20Co	12.52	8.54	536

Table 3-3

Examples of Wear Resistance Values for Commonly Used WC-CO

<u>Wear Resistance, W</u>	<u>Co, %</u>
1076	10.35
872	12.35
803	12.35
611	10.35
581	10.35
565	10.35
448	10.35
267	16.51
258	15.13
236	16.51

Several processes can occur separately or in combination that will cause loss of material in an abrasive wear test. If the cobalt is attrited away, the carbide grains can be pulled out; they can also fracture and fall out if they are not supported by cobalt. This type of uneven wear can be expected if the cobalt regions are relatively large compared with the carbide grain size. This would arise either for large cobalt contents or in nonhomogeneous microstructures. Alternatively, poorly bonded carbide grains might exist if the overall binder content is low or if local shortages of cobalt exist due to nonhomogeneities. In either case, loss of individual grains is expected to result in high wear rates. On the other hand, if the cobalt is lost gradually and the grains are well supported, the surface should wear more evenly. If the carbide has the right properties, it may wear by a process of plastic rounding rather than fracture. In this case, wear rates will be low. The wear mechanisms of individual cemented carbides are probably more complex than this description, and it is likely that several mechanisms of loss of material will contribute to the abrasive wear of specific grades of carbide.

Figure 3-13 shows examples of the abraded surfaces of materials with the lowest wear resistance in the NbC_x series. In NbC-20Co (Figure 3-13a), the cobalt is heavily attrited away, and some of it can be seen as approximately spherical debris. The relatively soft carbide grains show evidence of considerable rounding. There are no microfractures, but many grains have been pulled out. Consequently, the wear number is relatively low. In the example shown in Figure 3-13b, the attrition of cobalt is similar to that shown in Figure 3-13a, but there is less loss of carbide by plastic rounding. Many grains have been pulled out and there is evidence for microfracture.

Figure 3-14a shows considerable microfracture and pullout but little plastic rounding of the stoichiometric NbC grains. The materials shown in Figure 3-14a contain 10% Co so there is less binder to be lost by attrition. On the other hand, if insufficient cobalt is present, this can affect the degree of support given to the carbide grains. Figure 3-14b illustrates the wear surface of $\text{NbC}_{0.83}\text{-10 Co}$, the material with the highest W value. It shows many rounded carbide grains and some pullout, but

a. NbC-20Co; W = 376

b. NbC_{0.83}-20 Co; W = 536

Figure 3-13. Wear Surfaces of Cemented Niobium Carbide

a. NbC-10Co ; W = 669

b. $\text{NbC}_{0.83}\text{-10 Co}$; W = 2065

Figure 3-14. Wear Surfaces of Cemented Niobium Carbide

virtually no microfracture. This micrograph suggests that relatively uniform wear of both phases is occurring and that the main wear mechanisms are related to plastic flow. This could be an important observation because there is no evidence that the wear resistance is limited by the relatively low fracture toughness of $\text{NbC}_{0.83}\text{-Co}$ compared with WC-Co.

In comparing the properties of cemented carbides, it must be appreciated that hardness, toughness, and wear resistance are all considered when selecting a grade of carbide for a particular drilling application. It is clear that these experimental cemented carbides are extremely wear resistant, but the corresponding levels of toughness are below those that are usually required in WC-Co. The relative importance of hardness, toughness, and wear resistance in determining the drilling behavior of an insert might be different in WC-based and NbC-based materials, and drilling tests will be necessary before a valid comparison can be made.

Summary and Conclusions -- This project was a screening study to fabricate and evaluate a range of cemented carbides based on niobium carbide, NbC_x , and tantalum carbide, TaC_x , (where x is 0.83 to 1) with cobalt and nickel binders for use as rock-bit inserts in geothermal drilling. A major goal was to explore the influence of carbon content on selected mechanical properties of the cemented carbides. Most test materials were made by hot pressing, but exploratory work indicated that these cemented carbides could also be produced by cold pressing and sintering. Processing variables that were studied included milling conditions, hot-pressing time, pressure, and temperature. The fabrication studies showed that the lowest porosities and most uniform microstructures were obtained in the $\text{NbC}_x\text{-Co}$ system, and much of the study focused on these materials.

The range of hardness that can be obtained in $\text{NbC}_x\text{-Co}$ alloys is comparable to that found in rock-cutting grades of WC-Co, and harder materials can be made using substoichiometric NbC. The fracture toughness of the experimental carbides was lower than that of WC-Co of the same hardness. The most significant toughness result was that, for a given hardness, the fracture toughness of $\text{NbC}_{0.83}\text{-Co}$ was greater than that of stoichiometric NbC-Co. From these data, it can be concluded that carbon content exerts a

strong influence on the properties of $\text{NbC}_x\text{-Co}$ materials and that, by adjusting the carbon content of the carbide, it is possible to obtain simultaneous improvements in hardness and toughness in this system.

Observations made during toughness and wear tests suggest that residual stresses are present that might affect resistance to cracking. The presence of residual compressive stresses raises the apparent fracture toughness by as much as 40%. The residual stresses probably arise in hot pressing, and it is likely that such stresses could be controlled either by heat treatment or in a fabrication procedure based on cold pressing and sintering. The latter procedure would also eliminate microstructural and compositional nonhomogeneities that arise if the cobalt phase is extruded at the surface during hot pressing.

Abrasive wear tests provided a valuable insight into the potential usefulness of cemented NbC_x . The abrasion resistance of the $\text{NbC}_x\text{-Co}$ compositions is in the range of the WC-Co compositions that are currently in use for rock cutting, and cemented carbides with higher wear resistance values can be made using $\text{NbC}_{0.83}$ cemented with Co. Examination of wear surfaces indicated that both phases in $\text{NbC}_{0.83}\text{-10 Co}$ wear at a relatively even rate and that material is removed by a process related to plastic flow, rather than microfracture. These observations suggest that the relative role of plastic flow and fracture in determining resistance to abrasive wear might be different in $\text{NbC}_x\text{-Co}$ and WC-Co. Whereas the wear resistance results are encouraging, the fracture toughness levels are significantly below those used in current WC-Co insert grades. Thus, the high levels of wear resistance that can be developed in $\text{NbC}_x\text{-Co}$ might be difficult to utilize if the corresponding fracture toughnesses are insufficient to prevent macroscopic fracture during drilling.

Niobium carbide is also attractive because of its cost and relative abundance. The current price for NbC is \$25/lb for 100-lb lots. Since the density of NbC is only about half that of WC, the cost of carbide per insert could be very low, depending on the composition. Further work that would focus on improved fracture toughness and on drilling tests is clearly

required to establish the technical merits of $\text{NbC}_x\text{-Co}$ for geothermal drilling applications.

Recommendations -- This program has established that cemented niobium carbides have some unique properties that make them an attractive alternative to conventional WC-Co rock bit materials. However, further work is required to improve the fracture toughness and to evaluate performance in controlled rock drilling tests. A program containing the following tasks could accomplish these goals:

1. Establish the conditions to produce $\text{NbC}_{0.83}\text{-10Co}$ by cold pressing and sintering.
2. Determine the fracture toughness, hardness, transverse rupture strength, and abrasive wear resistance of sintered $\text{NbC}_{0.83}\text{-10Co}$.
3. Select a drilling system, conditions, and insert design appropriate to the properties of $\text{NbC}_{0.83}\text{-10Co}$ and fabricate the inserts.
4. Perform drilling tests using a cutting structure containing inserts of $\text{NbC}_{0.83}\text{-10Co}$.
5. Determine the wear mechanism by examination of inserts after the drilling tests.

3.6 Drill String Dynamics

Contractor: Jordan, Apostol, Ritter Associates, Inc.
Principal Investigator: Jerold A. Baird (401) 294-4589
Contract Period: 1 March 1982 to 15 October 1983
Contract Number: 68-3061 (Sandia)
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. The wellbore/drill string simulation is being developed in order to specify the dynamic environment near the bit sufficiently for design of advanced downhole equipment.

Background

An exploratory study by Jordan, Apostol, Ritter Associates, Inc. has established the technical feasibility of satisfactorily developing a finite-element computer model to solve the drill string dynamics problem. During FY 1981, the planning of a program to develop the drill string model was completed. The program concept was structured into three phases: (1) development of subsystems and assembly into a bit/formation interaction model, (2) refinement and extension of the model, and (3) incorporation of the bit/formation model into a complete wellbore/drill string simulation. Efforts were initiated to establish a cost-sharing/joint-development agreement with industry for carrying out the program. These efforts were still under way as FY 1981 came to an end.⁷

Agreement was reached by mid-FY 1982 among industry participants for the cost-sharing/joint development of the drill string dynamics computer model. The bit/formation interaction phase of the drill string system model was begun during the latter part of FY 1982 with the subsystem formulations for stiffness, mass, damping, body-force description, bit rotation, formation, and solution algorithm being completed by the end of the reporting period.¹²

FY 1983 Activities

Phase I of the drill string dynamics program, bit/formation interaction, was at the point of completion as this reporting period ended. Figure 3-15 is a graphic representation of the program phases and the drill string segments that are included in each phase of the development of the computer program for use in solving the drill string dynamics problem. Phase I efforts included (1) the development of the finite elements and associated algorithms necessary to provide a polycrystalline diamond compact (PDC) bit-bit sub model idealization, (2) the characterization of the geometry, boundary conditions, and phenomenological description of the PDC bit-formation interaction, (3) the idealization of the formation response, and (4) the integration of these tasks into a computer program whose main solution algorithm provides the capability of modeling transient dynamic bit motions to account for the nonlinear, time-dependent, loading, and boundary-condition response characterizing the problem. The bit/formation model is identified by the acronym, GEODYN. A summary description of GEODYN follows.

Bit-Drill String Model -- A finite element model is employed to characterize the structural response of the bit-drill string assembly. The PDC bit body model is constructed using 8-node, three-dimensional, isoparametric brick elements with three translational degrees-of-freedom (d.o.f.) associated with each node point. The bit body is assumed to behave in a linear elastic manner. A three-dimensional linear beam element was selected for modeling the drill collar sections above the bit. Each beam node utilizes three translational and three rotational d.o.f. to characterize the structural response. These beam elements are also assumed to behave in a linear elastic manner.

Constraint equations relating translational brick displacements to beam rotations are utilized to enforce a plane section condition at the juncture of the bit and drill string. Boundary conditions are imposed only at the top of the drill string. Six springs that limit both translational and rotational movements are utilized. This permits loads to be applied at the top of the drill string with attendant displacements occurring. A simple model utilized to verify the Phase I GEODYN code is shown in Figure 3-16.

Figure 3-15. Drill String Dynamics Program Phases

Figure 3-16. Simple Bit-Bit Sub Verification Model

Although this model does not truly characterize a bit, it is adequate to demonstrate the capabilities of the modeling technique. The PDC cutters are ignored in the generation of the finite element mesh.

Cutter Model -- A major aim of the Phase I development was the modeling of the interaction between the formation(s) and the individual PDC cutters on the bit. This was made possible (i.e. minimizing the required d.o.f. necessarily accounted for in the dynamic solution process) by adopting a "ghost cutter" idealization. This idealization treats each cutter as a rigid body element that moves in accordance with prescribed bit body motions. All PDC studs, gauge cutters, and wear buttons are modeled in this manner. The stiffness and mass of the cutters do not enter into the assembly of the finite element structural matrices (i.e. stiffness, mass, and damping) on which the solution of the equations of motion are based. The geometric position of each cutter is, however, tracked during the bit's rotation and compared directly with the formation's surface description to assess if contact has occurred. If contact occurs, interactive formation forces are computed, applied to the cutter geometry sub-nodes, and interpolated to the bit body finite element nodal force equivalents. The solution of the equations of motion for the finite element model is performed utilizing these equivalent nodal formation forces, in addition to gravity, inertial, and externally (i.e. weight-on-bit, etc.) applied forces.

Formation Model -- The final component necessarily addressed in this developmental effort was the downhole formation(s) model. A simple "discrete point" model was adopted for this purpose. A combination of discrete points, conveniently regarded as the center point of a surface area (i.e., mosaic tile), is used to define the surface contours of the formation. A bottom surface, a side-wall surface, and an inclined surface lying between the bottom and side wall are modeled in the code. The assumed direction of allowable penetration for the three subsurfaces differs. Figure 3-17 illustrates an idealized cross-sectional view of the formation surface and depicts the assumed penetration directions allowed.

The code interactively facilitates the definition of these surfaces and permits both topology and material characterizations to be modified

Figure 3-17. The Three Surface Portions of the Formation Model

from prescribed default conditions. To facilitate actual penetration of the formation by "ghost cutters" a linear spring was incorporated to model penetration resistance. A friction force is also computed and applied to the cutter. This friction force is a function of both the penetration resistance and the absolute velocity of the cutter relative to the formation surface. The code, therefore, utilizes the geometric interaction between cutters and formation to describe transient, nonlinear responses necessary for solution.

Solution Algorithm -- The solution algorithm employs a modified Newton-Raphson iterative procedure in concert with a Newmark-Beta numerical integration scheme. To affect an even greater savings in time, the solution process incorporates a modally reduced bit-drill string idealization. The code is written in FORTRAN 77.

Verification -- Verification of the capability of GEODYN to model the bit/formation interaction was begun in the latter part of FY 1983 using simple test runs and Sandia National Laboratories test data. Representation results are shown in Table 3-4 for modal frequencies of a Smith 22.2-cm (8-3/4-in.) bit with a 1.5-m (5-ft) sub.

Table 3-4

Modal Frequencies of a Smith 22.2-cm (8-3/4-in.)
Bit with a 1.5-m (5-ft) Sub

Source	Modal Frequency, Hz					
	First Bending	Second Bending	Third Bending	Fourth Bending	First Torsional	First Axial
Laboratory test	155	442	870	1392	679	1291
GEODYN full model lumped mass	147	426	866	1446	654	1261
GEODYN* full model consistent mass	148	437	903	1543	667	1270

*Averaged value X-bending and Y-bending
natural frequencies

Verification of the model was continuing as FY 1983 came to a close, and preparations were underway to install the code on Sandia's VAX 11/780 and Cray 1 computer and to begin laboratory qualification of the code. Documentation of the Phase I work to include a user instruction manual was also in process as FY 1983 ended. Publication of the documentation was expected in FY 1984. The start of Phase II, bottomhole assembly analysis, to develop and integrate a transient, dynamic bottomhole assembly capability into the GEODYN model was scheduled to begin early in FY 1984.

3.7 Thermal Spallation Drilling System

Contractor: Resource Technology, Inc.
Principal Investigator: R. Rinaldi (918) 743-2985
Contract Period: October 1983 - July 1984
Contract Number: 68-3057 (Sandia)
Technical Consultant: James R. Kelsey (505) 844-6968

Project Objective

The objective of this project is to assess the feasibility, economics, and technical problems of applying thermal spallation techniques to drilling deep holes in various types of rocks.

Background

Thermal spallation drilling techniques have been widely applied in the past and continue to be used extensively for the formation of shallow blast holes needed in the removal of taconite ore and in hard-rock quarrying operations. Recently, efforts to apply the technique to achieve greater borehole depth have had some success. Drilling experiments in granite have produced a 22.9-cm (9-in.) diameter borehole 335 m (1,100 ft) deep at an average penetration rate of 16 m/h (52 ft/h) and a 38.1-cm (15-in.) diameter borehole 131 m (430 ft) deep at an average penetration rate of 7.6 m/h (25 ft/h). These results, especially the high penetration rates, suggest significant benefits if the thermal spallation technique could be applied to the drilling of deep boreholes for hot-dry-rock, geothermal, and oil/gas wells.

Although the effectiveness of thermal spallation in drilling shallow holes in hard rock presents an attractive potential for drilling deep holes, the feasibility of adapting the technique to deep well drilling remains unclear. Many technical and economic issues such as the mechanics of the spallation process, the range of rock types subject to spallation, the compatibility with current drilling equipment and procedures, the requirements for new devices and procedures, the technical limitations, and

costs in comparison to conventional drilling are unknown or not adequately defined. Hence, a thorough analysis, on a total system basis, of extending the spallation technique to deep well drilling is warranted. Since available background information indicated technical data existed that could be used to assess the applicability of the spallation technique to deep hole drilling, a decision was made in FY 1983 to conduct a system analysis of spallation drilling using a high-temperature flame before committing significant resources to any R&D effort to extend the technology to deep well drilling.

FY 1983 Activities

Establishment of this project was begun in the latter part of this reporting period. Resource Technology, Inc., Tulsa, Oklahoma was selected to conduct the system analysis, and by the close of FY 1983, contractual arrangements had been completed. Work was scheduled to begin with the new fiscal year. The basic tasks of the analysis include background studies, a conceptual design, identification of technology limitations, recommendations for solving the identified problems, utility studies that include identification of sites suitable for the spallation technique, and a detailed economic analysis of the conceptual system.

3.8 Thermal Studies of Polycrystalline Diamond Compact Drag Tools

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

Project Objective

The objective of this project is to develop a numerical-analytical model to analyze temperatures in polycrystalline diamond compact (PDC) drag bits and to determine the effects of these temperatures on bit life.

Background

The frictional heating studies of PDC cutters were begun in the latter half of FY 1979 using a conduction code, CINDA³¹, and continued during FY 1980.⁶ By the end of FY 1981, development of the preliminary analytical model was completed and comparisons of calculated temperatures and experimental data had been made. Analytical work 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 was used to examine three cutter configurations--mildly worn, moderately worn, and severely worn--with different velocities, cooling rates, friction coefficients, and rock properties. The analysis demonstrated the sensitivity of the temperature distribution to the various parameters and identified the coefficients that needed better experimental definition.⁷

Phase I of this work was completed in FY 1982, and the results were published in References 34 and 35. The model developed was found to be in reasonable agreement with experimentally measured wearflat temperatures. Analysis of the data showed that the cutter temperatures vary directly with the friction force on the wearflat and approximately as the one-half power of the sliding velocity. The data also showed that the ability of liquid drilling fluids to reduce friction is far more important in reducing operating temperatures than is their ability to provide cutter cooling.¹²

Phase II of the project to expand the numerical-analytical model was also begun during FY 1982, employing different boundary conditions in the study of the effects of such factors as a thicker PDC diamond layer, bit bounce, and cyclic heating and cooling. The different boundary conditions included enlargement of the thermal models to contain a portion of the bit body, thus removing the assumption of constant-temperature surfaces used in Phase I. Transient thermal modeling and thermal stress modeling were under way by the end of FY 1982, along with the sensitivity studies of various parameters that control cutter temperatures.¹²

FY 1983 Activities

The Phase II work to expand the numerical-analytical model for temperature analysis of PDC drag bits was completed during this reporting period, and a report of the studies was prepared for publication as Reference 36. The work in this phase was a refinement and extension of the studies reported earlier in Reference 35. More generalized boundary conditions were employed for the finite element thermal modeling of single PDC cutters. In addition, a more restrictive maximum safe-operating temperature to prevent rapid wear of PDC cutters was identified and the concept of a critical weight-on-bit was introduced. The effects of several design and operating parameters on the critical weight-on-bit were analyzed, as were transient effects associated with events such as bit bounce and making a drill string connection. Finally, the thermal stresses induced in PDC cutters under downhole conditions were computed and analyzed. A summary of some of the investigations and the major conclusions resulting from the studies follow.

The process studied in this investigation was frictional heating and convective cooling of PDC cutters under downhole drilling conditions. Figure 3-18 is a graphical representation of this process. Due to the relative motion between the cutter and the rock, frictional heat is generated at the interface. Cutter temperature distributions under simulated downhole conditions were computed with two-dimensional numerical models of the three cutter configurations shown in Figure 3-19. The wearflat of the mildly worn cutter extends across the diamond layer of the PDC element. The wearflat of the moderately worn cutter includes the diamond layer and the tungsten carbide compact to which the diamond is bonded. The severely

Figure 3-18. Representation of Process Modeled in Baseline Analysis

Figure 3-19. Finite Element Meshes for the Three Cutter Configurations Modeled

worn cutter has a wearflat that extends well into the cutter stud. These three models thus span the range of cutter wear normally encountered in practice.

The portion of the numerical models surrounding the cutter stud represents approximately that segment of the bit body that is thermally affected by the single cutter. In other words, a full bit could be represented by a series of cutter models placed side by side. The vertical sides of the bit body segments are thus surfaces of approximate symmetry and were modeled as adiabatic for the baseline calculations. The upper surface of each model represents the inside cavity of the bit body and was therefore modeled as being convectively cooled. The bit body segments surrounding the cutters represent a generalization of the models used in earlier work, where the tops of the cutters were assumed to be maintained at the fluid temperature.

Numerical simulation was performed with a two-dimensional finite element code.³⁷ Steady-state solutions were obtained for each wear condition, assuming for the baseline case, grade 55B WC-Co studs and grade 883 WC-Co compacts and bit bodies. The effects of different thermal conductivities were also investigated.

New experimental data³⁸ were used to test the validity of the following equation for predicting the mean wearflat temperature of a PDC cutter,

$$\bar{T}_w - T_f = \frac{\alpha \mu F V}{A_w} f, \quad (1)$$

where,

- $\bar{T}_w$ = mean cutter wearflat temperature
- T_f = fluid temperature
- α = energy partitioning fraction
- μ = friction coefficient between cutter and rock
- F = weight-on-cutter
- V = cutting speed
- A_w = cutter wearflat area
- f = thermal response function (numerically determined)

Mean wearflat temperatures for the conditions used in the laboratory tests are plotted in Figure 3-20, comparing the predictions of the equation with the measured data. The agreement was good enough for the predictive method to be used with confidence, at least for identifying trends. The effects of certain design and operating parameters on wearflat temperature manifest themselves in the equation through changes in the cutter thermal response function. These effects were explored in connection with the concept of critical weight-on-cutter.

Critical Weight-On-Cutter -- There are a number of ways in which Equation 1 could be used, but perhaps the most useful is in establishing the maximum weight-on-cutter that can be used in practice without causing an excessive rate of cutter wear. Equation 1 shows mean wearflat temperature rise to be directly proportional to weight-on-cutter. If high wearflat temperatures lead to increased cutter wear rates, then bit life can be expected to be generally reduced at higher weight-on-bit. Since the penetration rate generally increases with weight-on-bit, this suggests a trade-off between bit life and penetration rate.

The primary mode of wear of PDC cutters below wearflat temperatures of 750°C (1382°F) is microchipping of the diamond layer. Above 750°C (1382°F), the wear mode changes to a more severe form in which thermal deterioration and whole-grain pullout occur. Hence, the cutter wearflat temperature should at least be maintained below 750°C (1382°F) to prevent catastrophic wear rates. However, it was subsequently found that cutter wearflats should probably be maintained at a lower temperature in order to prevent inordinately rapid wear in the microchipping mode.

In laboratory cutting of Jackfork sandstone, the wear rate of PDC cutters has been shown to be a function of cutter speed. It has also been suggested that this increase is due to the fact that higher sliding speeds cause elevated wearflat temperatures, which in turn cause a decrease in the hot hardness of individual diamond crystals. Tungsten carbide also experiences a drop in hardness with increasing temperature. Since abrasive wear depends primarily upon the relative hardness of the cutter and the work-piece, a relative decrease in cutter hardness will cause an increase in the

Figure 3-20. Comparison of Computed and Measured Wearflat Temperatures

failure rate of asperities on the cutter surface and, hence, a higher wear rate. This hypothesis is supported by the conclusions of metal machining research that shows that the wear of machine tools is strongly temperature-dependent, even though other factors such as workpiece characteristics do play a role.

Assuming that wearflat temperature is a controlling factor in cutter wear rate for at least a given rock type, experimental wear rates were correlated with computed wearflat temperatures under the same conditions. Two sources of experimental data were used. In the first, Jackfork sandstone was cut at atmospheric pressure with a jet of 40:1 (water:oil) coolant directed at the cutter face. In the second, Nugget sandstone was cut, both with and without this coolant. Data were obtained at several cutting speeds and at a fixed depth of cut.

All the parameters required by Equation 1 to compute wearflat temperatures were recorded, except the friction coefficient with the water:oil coolant. This was determined indirectly from cutter wearflat temperature measurements in which the same type coolant (40:1 water:oil) and Nugget sandstone were employed. Figure 3-21 shows wearflat temperature rise as a function of a group of measured and computed variables, with friction coefficient as a parameter. In Figure 3-21, the computed temperature rise agrees with the experimental data when a friction coefficient of $\mu = 0.15$ is assumed.

Using this value for μ with the coolant and using available air/sandstone data⁹ ($\mu = 0.2$) with the dry tests, the mean wearflat temperatures corresponding to the experimental conditions for the wear tests were computed and are shown in Figure 3-22. The results indicate that wear rates under dry cutting conditions are one to two orders of magnitude higher than those obtained with cooling and lubrication. Figure 3-22 further shows that even with cooling and lubrication, wear rate begins to increase significantly above a temperature of approximately 350°C (662°F). Although other surface properties affected by cutter environment undoubtedly play a role in controlling cutter wear, these data lend support

Figure 3-21. Data Used to Determine PDC-Sandstone Friction Coefficient with Water/Oil Coolant

Figure 3-22. Experimental Wear Rates as a Function of Computed Wearflat Temperature

to the suggestion that temperature effects on wearflat hardness may be a leading cause of the increased wear rates.

Although based on a limited data base for a single family of rock, it was assumed for purposes of the study that 350°C (662°F) is the critical mean wearflat temperature, above which wear rate increases dramatically. The trends observed as a result of this assumption should be valid even if the magnitude of the critical temperature is somewhat in error.

The critical weight-on-cutter can now be derived by solving Equation 1 for F at the critical wearflat temperature:

$$F_{cr} = \frac{A_w}{\alpha f \mu V} (\bar{T}_w - T_f)_{cr} \quad (2)$$

For purposes of illustration, a typical downhole fluid temperature of $T_f = 50^\circ\text{C}$ (122°F) is assumed for the baseline case. In order to generalize the curves used to illustrate various effects, Equation 2 is plotted in the form,

$$\mu F_{cr} = \frac{300 A_w}{\alpha f V} \quad (3)$$

Values for the wearflat area A_w are required in order to plot Equation 3 for the three wear conditions evaluated in this study. The computed wearflat area, based on geometry for a -20° backrake, stud-mounted PDC cutter, is given approximately by the equation

$$A_w = 0.8d^{1.46} \quad (4)$$

The results are presented in Figures 3-23, 3-24, and 3-25, respectively, for the mildly, moderately, and severely worn cutters. The scales on the righthand side of these graphs represent the total weight-on-bit for a 22.2-cm (8-3/4-in.) bit with 40 cutters, assuming a friction coefficient of 0.10. The lower horizontal scales represent the bit rotational speed

corresponding to V , assuming the cutter to be near the periphery of the 22.2-cm (8-3/4-in.) bit.

The curves in the figures show the effects of convective cooling on the critical weight-on-bit. The higher cooling rates associated with water drilling ($h = 0.1 - 1.0 \text{ W/cm}^2\text{°C}$) allow a much greater cutter weight to be employed than those associated with air drilling ($h = 0.01 - 0.1 \text{ W/cm}^2\text{°C}$), especially at the lower cutter speeds. This detrimental effect of air drilling is compounded by the fact that friction coefficients are generally higher with air than with water.

Figure 3-23. Critical Weight-On-Cutter for the Mildly Worn Cutter Under Baseline Conditions

Comparing the curves of Figures 3-23, 3-24, and 3-25, it is noted that higher bit weights can be used as the cutters wear. This suggests that under certain operating conditions, reduced weight-on-bit should be employed when the cutters are sharp in order to prevent thermal damage and, consequently, unacceptably high wear rates.

Figure 3-24. Critical Weight-On-Cutter for the Moderately Worn Cutter Under Baseline Conditions

Figure 3-25. Critical Weight-On-Cutter for the Severely Worn Cutter Under Baseline Conditions

The effects of several design, operating, and environmental parameters (including cutter design, hydraulic design, formation characteristics, cutter cooling rate, downhole fluid temperature, depth of cut, bit balling, commencement of drilling, lifting the bit off bottom, and bit bounce) on critical weight-on-cutter were examined and compared with the baseline calculations. The results of these investigations are reported in detail in Reference 36.

Conclusions -- The major conclusions resulting from the Phase II temperature analyses of PDC drag bits were as follows:

1. A method was developed for predicting mean wearflat temperatures of PDC cutters under simulated steady-state and transient downhole conditions. The method has been shown to produce results that compare favorably with available experimental data.
2. Cutter wear rates correlate with mean wearflat temperatures, and available experimental data indicate greatly increased wear rates above 350°C (662°F).
3. A relation was developed for determining the critical weight-on-bit, above which cutter wearflat temperatures exceed 350°C (662°F).
4. The use of steel cutter studs and bit bodies does not significantly increase wearflat temperatures, even though the thermal conductivity is about one-half that of the WC-Co grade normally used in PDC bits.
5. A diamond layer thickness twice that conventionally used can significantly increase the weight-on-bit that can be tolerated by mildly worn cutters.
6. Efforts to design fluid ports for increased cooling of the bit body or internal cooling of cutter studs are not worthwhile since they do not significantly reduce wearflat temperatures.

7. Formation characteristics have a significant effect on cutter wearflat temperatures. Due to the large range of friction coefficient and rock thermal conductivity that may be encountered in normal drilling practice, actual downhole cutter temperatures and critical weight-on-bit cannot be accurately predicted unless specific data on formation characteristics are obtained.

8. Within the range of cutter cooling rates achievable in practice, increased cooling rates lead to significant reductions in wearflat temperatures.

9. Even minor bit balling substantially reduces effective cutter cooling rates.

10. Bit bounce resulting from drill string vibration can significantly increase cutter temperatures from their steady-state values during the critical fraction of the cycle when the cutters are in contact with the rock.

11. Thermal stresses induced in cutters under downhole conditions can reach levels high enough to cause yielding of the cutting structure.

As FY 1983 ended, the Phase II studies were being extended to investigate in greater depth the relationship of temperature to the wear mechanism.

3.9 Polycrystalline Diamond Compact Single-Cutter Testing Under Simulated Downhole Pressures

Contractor: John F. McLaugh, Consulting Engineer
Principal Investigator: John F. McLaugh (918) 749-7888
Contract Period: December 1983 - 30 November 1984
Contract Number: 58-0395 (Sandia)
Technical Consultants: D. Glowka (505) 844-3601
J. Finger (505) 844-9398

Project Objective

The objective of this project is to characterize the polycrystalline diamond compact (PDC) cutter/formation interaction under simulated downhole pressures.

Background

Comprehensive research on PDC cutter performance and formation interaction was begun in FY 1979 and has continued through this fiscal year, both by outside contractors and within Sandia laboratories. Efforts during FY 1983 are reported in Sections 3.4 and 3.8. The research work has addressed fabrication processes, thermal studies of the cutter, cooling of the cutter, full-scale PDC-bit laboratory and field experiments, modeling of the cutter/formation interaction, measurement of friction coefficients between the cutter and the formation, and PDC-bit design. The results of this earlier work has been reported in References 6, 7, 12, 30, 31, 32, 34, 35, and 38. The technical data generated by these research efforts have been especially valuable, as well as appropriate as a Sandia task, since industry has not invested any significant resources in investigating these aspects of drilling technology.

In the basic research efforts to date, experiments on the PDC cutter/formation interaction have been conducted at atmospheric pressures. In order to study the cutter/formation interaction under simulated field conditions and generate data for comparison with earlier tests, a decision

was made in FY 1983 to test the PDC cutter under high pressures in the laboratory.

FY 1983 Activities

Establishment of the project to test single PDC drag cutters under simulated downhole pressures was begun in the latter part of this reporting period. Specification of the test matrix, parameters, and procedures was completed, and contractual arrangements were nearing completion as FY 1983 ended. The experiments will begin early in the next reporting period and will be performed by John F. McLaugh, a Tulsa, Oklahoma consulting engineer. A high-pressure test cell owned by Tulsa University Drilling Research Projects will be used to measure triaxial cutter forces while cutting rock subjected to various combinations of borehole, pore, and confining pressures up to 35 MPa (5,000 psi). Friction coefficients between the cutter and the rock will be determined, and cut rock samples will be returned to Sandia for examination of rock damage and chip morphology.

3.10 Evaluation of the Effects of Electrical Currents on Drill Bit Wear

Sandia National Laboratories
Technical Consultant: J. Finger (505) 844-8089

Project Objective

The objective of this project is to investigate the effect on bit wear of electrical currents generated during drilling.

Background

Laboratory work by Professor S. A. Hoenig at the University of Arizona has suggested that drill bit wear decreases with reduced drilling current. In order to explore this phenomenon further, full-scale bit tests were planned, in conjunction with Professor Hoenig, in FY 1983 to test two identical milled-tooth, roller-cone bits; one to be run with an insulating collar and one without the collar. The bits were to be used to drill granite, and tooth wear was to be measured at regular intervals. After completion of the drilling, the bearing wear of each bit was to be measured and compared.

FY 1983 Activities

Work on this project was suspended during FY 1983, pending modification and renovation of Sandia's laboratory drilling rig. Upon completion of the drilling rig refurbishment, efforts under this investigation will be rescheduled.

4. FLUID TECHNOLOGY

The general goal of Fluid Technology research is to develop drilling fluids specifically tailored to solve problems commonly encountered in geothermal drilling. The projects include extensive study of properties of aqueous foams used in drilling applications and development of analytical tools modeling fluid flow in the wellbore. Research into high-temperature clay morphology, methods to convert clay to cement, and techniques to improve bit cleaning and cooling is also being conducted.

4.1 Aqueous Foam Drilling Fluids for Geothermal Applications

Sandia National Laboratories

Technical Consultants: P. Rand (505) 844-7953

A. Kraynik (505) 844-0780

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Project Objective

This project will identify or develop aqueous foams for use as drilling fluids in the underpressured formations characteristic of many geothermal areas. The foams will be capable of operating in elevated temperature environments and will exhibit chemical and foaming stability and anticorrosive and antioxidant properties.

Background

The laboratory development phase of the foam project was begun in mid-FY 1979 after publication of a survey report that outlined the technical approach to development of the foam. A laboratory apparatus was built for conducting surfactant screening tests, and during FY 1980 surfactant screening was carried out at 260°C (500°F) and at 310°C (590°F).³¹ The effects of NaCl, HCl, brines, and deionized water on the drainage time, cell structure, and pH of the surfactants at the test temperatures were observed. More than 100 surfactants were evaluated, and several, representing all general classes, demonstrated stable characteristics in all test environments. At the close of FY 1980, preparations were under way to acquire an autoclave in order to test the most promising surfactants at high pressure and high temperature.⁶

During FY 1981, the effects of temperature and pressure on the behavior and stability of foam were extensively investigated in the autoclave. In addition, stability of individual foam bubbles was investigated by studying bubble coalescence using a spinning drop interfacial tensiometer, and thermal conductivities of foams were determined using a bench-scale foam generator and thermal probes. Test facilities were also assembled to study the rheological properties of aqueous foams and the heat transfer

characteristics of flowing foam. The high-pressure/high-temperature stability tests led to the discovery that increasing the pressure caused a large increase in the liquid drainage time, i.e., increased stability.

Investigation revealed that this effect arose from the decreased average bubble size, even at constant liquid/gas volume ratios, in foams made at high pressures. Rheological models of the liquid drainage in foams as well as experimental data established that cell size has a large effect on liquid drainage times. Also, all foams showed a large decrease in stability as temperature was increased. In the spinning drop interfacial tensiometer tests, all surfactant systems tested were affected adversely by elevated temperatures, and none of the systems produced stable thin films at temperatures above 98°C (208°F). The studies of foam thermal conductivity were completed and reported in Reference 39. By the end of FY 1981, a simple model had been developed for predicting the wellbore temperature distribution for drilling a geothermal well with drilling foam, and assembly of hardware to conduct rheology and flowing foam heat transfer tests was nearing completion.⁷

Research to develop aqueous foams for geothermal drilling continued during FY 1982. High-temperature/high-pressure stability tests of foams using additives to improve stability identified a biopolymer, Kelco K1D-97, that increased the drainage time of a C₁₂₋₁₄ alpha olefin sulfonate surfactant by three to five times at 140°C (284°F). Construction of the foam flow heat transfer loop was completed, and verification of the experimental facility was begun. Construction of the foam rheology test facility was also completed, and shakedown experiments with the facility were started. Development of an aqueous foam rheological model was also begun by the end of FY 1982.¹²

FY 1983 Activities

The studies of aqueous foams, aimed at overcoming the paucity of knowledge on foam behavior (especially at high temperatures) and understanding the physics and chemistry of foams continued throughout this reporting period. The three primary areas of investigation during FY 1983 remained (1) foam stability at high temperatures, (2) rheology of foams,

and (3) heat-transfer characteristics of foam. Reports on the efforts in each of the areas were prepared and published in References 40, 41, and 42. A summary of some of the work in each area follows.

Foam Stability -- Stability measurements and the study of viscosity increasing additives on the most promising surfactants continued during FY 1983. Foaming and stability measurements have been made on a comprehensive number of surfactants at ambient conditions, at high temperatures and pressures, and in different chemical environments. Alpha olefin sulfonates performed well in all environments except the sodium chloride/calcium chloride brine, and the 310°C (590°F), 0.1 M hydrochloric acid. Other surfactants including the quarternary ammonium chlorides, coco betaines, alkyl aryl sulfonates, alkyl ethoxylates, and several proprietary surfactants have also shown promise.⁴⁰ Qualitative performance ratings of some of the most promising surfactants are shown in Table 4-1. As this reporting period ended, efforts to develop a surfactant with broader capabilities than the alpha-olefin sulfonates and suitable for a field test were still in progress.

Table 4-1
Surfactant Performance Ratings

Surfactant Type and Class	Chemical Environment				
	H ₂ O	NaCl	BRINE	HCl	NaOH
Test Temperature	260°C (500°F)				
Alpha Olefin Sulfonate-Anionic	E	E	U	E	E
Quat. Ammonium Chloride-Cationic	E	E	E	E	U
Coco Betaine-Amphoteric	E	E	P	E	P
Alkyl Ethoxylate-Nonionic	E	E	P	U	E
Test Temperature	310°C (590°F)				
Alpha Olefin Sulfonate-Anionic	G	E	U	P	E
Quat. Ammonium Chloride-Cationic	E	E	E	E	U
Alkyl Ethoxylate-Nonionic	E	U	P	U	P

E=Excellent, G=Good, P=Poor, U=Unsatisfactory

Foam Rheology -- Work in the rheology of aqueous foam continued during FY 1983 to include investigations of compressibility, shear-thinning viscosity, yield stress and slip at the wall, and development of theoretical models to explore the role of various physical parameters on foam drainage and to provide guidance for the design of drainage experiments. The structural parameters studied include liquid volume fraction, cell size, film thickness, and liquid-volume-fraction distribution.

An unexpected foam stability phenomenon was observed in which the drainage rate of foams (made with the same surfactant and having the same liquid content by volume) decreased by more than an order of magnitude as the foam generation pressure was increased to 10 MPa (100 atmospheres). This decrease in drainage rate was attributed to a decrease in the foam cell size with increasing generation pressure. In order to examine the observed phenomenon further, theoretical models were developed to explore the role of various physical parameters on foam drainage. The basic model contains no empirical parameters and provides a simple description of transient drainage from a column of persistent foam. With the model, the flow through an interconnected network of Plateau borders that define the edges of cells assumed to be regular pentagonal dodecahedrons can be analyzed. The derivation is based upon the following simplifying assumptions:

1. The foam is persistent, i.e., the films are stable and do not rupture during drainage.
2. The cell-size distribution is monodisperse and does not change due to intercellular gas diffusion.
3. The foam is dry, i.e., the liquid volume fraction is less than 0.1.
4. The gas-liquid interfaces of the Plateau borders are rigid and therefore the no-slip boundary condition is used.
5. Liquid holdup in the films is negligible because the fully drained films are thin.
6. The initial liquid-volume-fraction distribution is uniform.
7. The film drainage kinetics are fast and therefore are not rate determining.

These assumptions are obviously restrictive but the basic model provides a logical basis for comparison with experimental data. Each of the last four assumptions was relaxed in further analysis and their influence explored. Many literature drainage studies do not provide sufficient information for comparison with theory. But, the model provides guidance for the design of drainage experiments by indicating important parameter dependences.

The theoretical foam drainage analysis using the model included (1) study of liquid holdup in the films separating adjacent cells, nonuniform initial liquid volume fraction distribution, and interfacial mobility and (2) analysis of simultaneous film drainage and flow through the Plateau borders. The study showed that the predicted half life, the time required for one half of the liquid to drain from the foam, is inversely proportional to the square of the cell diameter, illustrating the importance of foam structure in drainage. Also, it was found that border suction due to reduced pressure in the Plateau borders provides a mechanism for film drainage. Hence, it was concluded that improved foam stability is related to small cells, liquid holdup in the films, and slow film drainage kinetics. A report on the details of the analysis was prepared for publication as Reference 41.

As this reporting period ended, preparations were being made in the rheology area to address high flow-rate behavior of foams above the yield stress where bulk deformation of the foam becomes an important flow mechanism.

Heat Transfer -- Checkout and verification of the experimental foam heat-transfer facility was completed, and foam heat-transfer rate measurements were attempted during this reporting period. However, problems were encountered early in the experiments.

The test facility consists of two concentric tubes, about 3.1 m (10 ft) long, mounted horizontally in a counterflow, heat exchanger configuration. Heat is supplied from hot water circulating within the annulus. The apparatus and data reduction scheme were qualified for air flow; however, measurements of foams in the shakedown tests presented

several difficulties. The heat-transfer rate measurement requires a knowledge of the bulk fluid temperature, and, for foams, the temperature profile must be measured within the tube. At liquid volume fractions greater than or equal to 0.1 during the early testing, foam drainage within the tube produced an asymmetric temperature profile that was unacceptable for the heat-transfer calculations. In addition, difficulties were encountered in producing a steady, pulsation-free flow of foam using a positive displacement pump for the water/surfactant mixture. The variation in flow also affected the measurement of the temperature profile.

Modification of the apparatus to correct the above problems was started in this reporting period. The concentric tubes and the insulated box that contains them will be redesigned to allow a vertical orientation, eliminating the adverse effects of gravity-induced foam drainage. The pulsations of the liquid flow caused by the pump will be eliminated by producing the required flow with a pressurized 0.6-m^3 (150-gal) tank. The modification of the apparatus was still in progress as FY 1983 came to a close. Qualification testing of the modified apparatus will be conducted before measurements of the average heat-transfer rate as a function of foam flow rate and liquid volume fraction begin next year.

In conjunction with the experimental efforts, a quasi-steady model was developed for predicting the temperature profiles of aqueous foams circulating in geothermal wellbores. In the analysis, the foam is assumed to be incompressible allowing an analytical solution of the energy equation after the energy equation has been decoupled from the momentum equation. The term "quasi-steady" comes from assuming that in the energy equation, flow in the wellbore is steady, while conductive heat transfer within the formation is time-dependent. The rate of conductive heat transfer from the formation into the wellbore was computed from an analytical solution for the response of an infinite region bounded internally by a hole and subjected to a convective boundary condition.

Solutions for linear and bilinear geothermal temperature profiles were obtained, and the appropriate dimensionless parameters governing the solution were identified. The quasi-steady model was compared to the more

sophisticated finite-difference computer code GEOTEMP, with good agreement obtained for times longer than 24 hours.

Aqueous foams have a very high Prandtl (Pr) number (1000 to 5000). Large Pr fluids require great distances for full development of the temperature profile. Entry length heat-transfer solutions available in the literature were adapted for use with aqueous foams. Both plug-flow and laminar Newtonian flow models were considered. Sample calculations were performed for both plug and laminar flow models with various lengths over which the heat-transfer coefficient was averaged. A representative result for a 1,524-m (5,000-ft) wellbore with a bottom hole temperature 191°C (375°F) indicated that the maximum foam temperature can be as high as 149°C (300°F). It was also demonstrated analytically that tool joints have the potential for appreciably enhancing the local convective heat-transfer rate. However, the separating flow from the trailing edge of the tool joints is complicated enough that experiments will need to be run to better quantify the degree of enhancement on the local rate of heat transfer. These experiments will be carried out in the modified Foam Flow Heat Transfer Loop during FY 1984. A detailed report on the development of the quasi-steady model was published in Reference 42.

4.2 Wellbore Thermal Code

Sandia National Laboratories
Technical Consultant: L. Duda (505) 844-2377

Project Objective

The objective of this project was to correct, revise, and update the advanced Wellbore Thermal Code, GEOTEMP2.

Background

The development of the thermal wellbore simulator, GEOTEMP2, for prediction of transient wellbore temperatures during drilling, circulating, injection, and production in geothermal wells was completed in FY 1981. Complete documentation of the code and the final research report were published as References 43, 44, and 45. The key features of the GEOTEMP2 Code are (1) a finite difference scheme using cylindrical geometry and axial symmetry and (2) fully transient heat conduction for both the wellbore flowing stream and the formation. The wellbore fluid flow options include injection and production, forward and reverse circulation, inlet temperature change, flow rate change, fluid properties, multiple fluids in the wellbore, different drilling fluids (mud, air, or nitrogen), and two-phase steam injection or production.

FY 1983 Activities

Since the code's publication, several problems and errors were detected during exercise of the simulator. These included the following:

1. The code produced inconsistent results when output was requested at short time intervals (less than one day). The cumulative output at short time intervals did not match output at longer intervals.
2. The sample problem output in the user manual did not match the actual output of the code.
3. The equation for the bubble rise velocity in slug flow for steam production/injection in the research report and implemented in the code was incorrect.

4. The implementation of a deviated wellbore in the code was incorrect, resulting in the same temperature for the bottom two formation layers.

During this reporting period, the problems and errors detected were corrected, and preparation of a revised, second generation GEOTEMP2 user manual and code listing incorporating the changes was underway as FY 1983 ended. Publication of the revised GEOTEMP2 documentation is anticipated during FY 1984. Planning was also underway at the close of this reporting period for further work on the computer code to include benchmarking gas drilling and steam injection/production and the possible addition to the code of radiation, foam drilling, and convective transport within the rock matrix.

4.3 Drilling Fluid/Cement Studies

Contractor: Texas Tech University
Principal Investigator: N. Guven (806) 742-3110
Contract Period: 1 October 1981 to 31 December 1983
Contract Number: 68-4752 and 37-2331 (Sandia)
Technical Consultants: C. Carson (505) 844-6477
L. Duda (505) 844-2377

Project Objective

The objective of this project was to study the formation of cement minerals in drilling fluids by observing the rheological changes in bentonite-based muds before cement formation.

Background

This project is a follow-on effort to the extensive studies previously conducted to develop 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, were designed for use in geothermal drilling. The results of this earlier work were published as Reference 46.

Phase I of the study of the formation of cement minerals in drilling fluids was completed in FY 1982. The study included experiments on the effect of additives on the viscosity of bentonite drilling fluid, and the data showed that salts and hydroxides of potassium provide excellent control of the fluid viscosity at high temperatures. The addition of lime was found to increase the fluid pH and promote the high-temperature reaction between bentonite and lime, with the precipitation of tobermorite, the common cement mineral. Phase II was begun near the end of FY 1982 to study the factors that control cement setting in bentonite drilling fluids and to investigate the accelerating and retarding effects of additives on the conversion of clay minerals to cement minerals.¹²

FY 1983 Activities

Phase II of the study of clay-to-cement conversion was completed in FY 1983, and preparation of a final report on Phases I and II was begun. The results of Phase I that addressed the effects of additives on the viscosity of bentonite drilling fluid and the early work in Phase II that investigated the in situ conversion of bentonite fluids into cement minerals was reported in Reference 12. The remaining efforts performed during this reporting period under Phase II were concerned with the effects of additives on cement reactions in bentonite drilling fluids. A summary of the FY 1983 work follows.

In these experiments, the fluid preparations were autoclaved in a temperature range of 149° to 316°C (300° to 600°F) under a pressure of 110 MPa (16,000 psi) with a systematic addition of various additives. FANN 50C and 35A viscometers were used to measure the high-temperature rheology of the fluids before and after aging in an autoclave cell for 16 hours under the above conditions. Other properties of the fluids such as plastic viscosity, gel strength, yield point, pH, CEC (cation exchange capacity), fluid loss, and filter cake thickness were also measured. The mineral reactions in these autoclaved fluids were studied with x-ray diffraction and electron microscopy. The changes in the physical properties and in the rheology of the fluids were then correlated with the high-temperature mineral reactions in the fluids.

Bentonite/Lime/CaCl₂ Fluid -- A fluid composed of 2% bentonite/1% lime/1% CaCl₂ was autoclaved at high temperatures with the purpose of increasing Ca²⁺-concentration in the fluid with regard to the formation of tobermorite. The characteristics of the fluid are described by the rheograms in Figure 4-1. These data show that the viscosities of the fluid were extremely low at all temperatures, similar to the other bentonite fluids with high Ca²⁺-concentrations. The fluid pH steadily decreased from 12 at 21°C (70°F) to 8.9 at 316°C (600°F), thus remaining always alkaline. The CEC (cation exchange capacity measured in milliequivalents per 100 grams) values drastically decreased from 75 meq/100g at 21°C (70°F) for the untreated fluid to 12.5 meq/100g for the fluid autoclaved at 316°C (600°F).

Figure 4-1. Viscosity Versus Temperature of the 2% Bentonite/1% Lime/1% CaCl₂ Fluids After Autoclaving at the Temperatures Indicated on Each Curve

This indicated most of the smectite dissolved in these alkaline solutions at high temperatures.

Calcite, halite, and tobermorite occurred as the main reaction products in this fluid. Calcite readily forms by the carbonization of lime in the air. Halite crystallizes when the chloride solution has dried. Sodium is supplied from the smectite by the ion exchange reaction between the Ca^{2+} in the solution and Na^+ in the original clay. Tobermorite, the cement mineral, first appeared at 149°C (300°F) and became a major component of the mud at higher temperatures. A calcium feldspar also formed while autoclaving the fluid at 316°C (600°F). Smectite disappeared entirely from the fluid at 204°C (400°F). Thus, the addition of CaCl_2 to the bentonite/lime fluid favored the total replacement of smectite by tobermorite.

Bentonite/Lime/Gypsum Fluid -- A new fluid was prepared having the composition, 2% bentonite/1% lime/1% gypsum. The properties of this fluid were measured, and the viscosity results are depicted in Figure 4-2. This fluid exhibited low viscosities similar to other bentonite/lime fluids. The fluid pH and CEC values decreased significantly with higher temperatures.

The main reaction products of the bentonite/lime/gypsum fluid were calcite, tobermorite, and anhydrite. Gypsum seemed to convert to anhydrite by simple dehydration during the autoclaving of the fluid at temperatures of 149° to 260°C (300 to 500°F). Tobermorite first formed in small quantities at 149°C (300°F) and appeared in larger amounts at higher temperatures. Gypsum did not appear to give any special benefits in bentonite/lime fluids.

Bentonite/Lime/Lignosulfonate Fluid -- A fluid with the composition of 2% bentonite/1% lime/0.25% lignosulfonate exhibits extremely low viscosities at all temperatures as shown by the data in Figure 4-3. The fluid pH evolved from 12.0 at 21°C (70°F) to 8.5 at 316°C (600°F), similar to other bentonite/lime fluids. Again, the CEC values of the fluid showed a reduction from 100 meq/100g at 21°C (70°F) to 14 meq/100g at 316°C (600°F).

Figure 4-2. Viscosity Versus Temperature of the 2% Bentonite/1% Lime/1% Gypsum Fluids After Autoclaving at the Temperatures Indicated on Each Curve

Figure 4-3. Viscosity Versus Temperature of the 2% Bentonite/1% Lime/0.25% Lignosulfonate Fluids After Autoclaving at the Temperatures Indicated on Each Curve

Tobermorite appeared in small quantities at 149°C (300°F) and in larger amounts at higher temperatures. Calcite formed again due to the carbonization of lime in the air. A calcium-feldspar developed at 260° and 316°C (500° and 600°F) in the fluid. Some of the smectite remained in the fluid even after autoclaving at 316°C (600° F), whereas a large portion of smectite dissolved in the alkaline solution fluids subjected to high temperatures. Although lignosulfonates can be expected to give a temporary retardation to the formation of cement minerals, such an effect was not seen in the bentonite/lime fluid.

Bentonite/Lime MgO Fluid -- A fluid with the composition of 2% bentonite/1% lime/1% MgO showed interesting features. The viscosity changes of this fluid are shown in Figure 4-4. The viscosities of the fluid remained rather low at all but the highest temperatures. The fluid pH remained highly alkaline without significant changes at higher temperatures in contrast to the other fluids tested. The CEC values, however, showed an unusually low value of 75 meq/100g at 21°C (70°F) with a decrease to 25 meq/100g at 149°C (300°F).

The addition of MgO to the bentonite/lime mud resulted in unusual reaction products. MgO readily hydrated to brucite, $\text{Mg}(\text{OH})_2$, in the fluid at 21°C (70°F), whereas lime similarly reacted with CO_2 in the air to calcite. Both calcite and brucite occurred as reaction products at higher temperatures, 149° to 416°C (300° to 600°F), indicating that the fluid was saturated with respect to Ca^{2+} and Mg^{2+} . At higher temperatures, some of the brucite appeared to react with CO_2 (in the fluid) and form magnesite (MgCO_3). It is interesting to note that magnesia readily reacted at 149°C (300°F) with smectite and formed a serpentine mineral (possibly amesite). In fact, all the smectite was replaced by this serpentine mineral when the fluid was autoclaved at and above 204°C (400°F). Thus, no smectite remained in the fluid at and above 204°C (400°F). Furthermore, no cement mineral (tobermorite) crystallized when MgO was added to the fluid, instead a garnet-like phase was found. The addition of MgO maintained the fluid pH at high alkaline values, thus providing a buffering agent for the water-base fluids.

Figure 4-4. Viscosity Versus Temperature of the 2% Bentonite/1% Lime/1% MgO Fluids After Autoclaving at the Temperatures Indicated on Each Curve

Electron microscopic examination showed the common reaction product in the fluid after autoclaving at and above 204°C (400°F) was a serpentine mineral. This phase is not a swelling clay mineral like smectite, and it therefore depresses the viscosity of the fluid. At higher temperatures, after autoclaving the fluid at and above 260°C (500°F), a garnet-lime mineral appeared to develop instead of tobermorite. Typical serpentine and garnet particles are shown in Figure 4-5. Garnets occurred as micron-sized spherical crystals whereas the serpentine developed hexagonal platelets with submicron dimensions. A closeup view of the serpentine platelets are displayed in Figures 4-6 and 4-7. The x-ray spectra gave strong spectral lines of Mg, Al, and Si. This suggested an amesite or aluminum lizardite variety of serpentine with the general chemical formula:

Figure 4-5. General View of the Commonly Observed Reaction Products Consisting of Serpentine and Garnet. Magnification: 13,000 X

Figure 4-6. Newly Formed Serpentine Platelets Showing Well-Developed Hexagonal Outlines. Magnification: 44,000 X

Figure 4-7. A Clay (Chlorite) Platelet with Hexagonal Outlines. Magnification: 65,000 X

From the selected area electron diffraction pattern, cell parameters of 5.37 Å and 9.27 Å were calculated and were considered compatible with the above serpentine species. The addition of MgO in the fluid prevented the formation of cement minerals, but the new phases (serpentine, garnet, magnesite, etc.) did not lend any viscosity to the fluid.

Conclusions -- Preparation of the final report on the drilling fluid/cement studies was nearing completion as FY 1983 came to a close. The report will be published in FY 1984. The preliminary conclusions of the investigation of the formation of cement minerals in drilling fluids are:

1. Pure Na-bentonite fluid becomes highly viscous (gelation) in the temperature range, 121° to 232°C (250 to 450°F).

2. Low-molecular-weight polymer controls viscosity only in a limited temperature range of 149° to 204°C (300 to 400°F).

3. High-molecular-weight polymer enhances the fluid viscosity only for untreated mud. It reverses its function when the fluid is autoclaved at and above 149°C (300°F).

4. Sodium hydroxide, especially NaCl, at 1% concentration in the fluid markedly enhances the fluid viscosity (gelation) up to 260°C (500°F). The addition of 1% silica to the fluid significantly reduces the viscosity but leads to the precipitation of Na-silicates (analcime and albite) that may cause permeability damage.

5. Salts and hydroxides of potassium provide excellent control of fluid viscosity at high temperatures. This feature is related to the conversion of smectite to illite/smectite mixed-layers at and above 204°C (400°F).

6. Salts and hydroxides of calcium depress the fluid viscosity to very low levels at all temperatures.

7. The addition of lime increases the fluid pH and promotes the high-temperature reaction between bentonite and lime with the precipitation of tobermorite, the common cement mineral.

8. The addition of free silica to the bentonite/lime fluid does not promote the formation of cement minerals in the fluid.

9. The addition of 1% CaCl₂ to the bentonite/lime fluid leads to the total conversion of bentonite (smectite) into the cement mineral tobermorite. Gypsum, on the other hand, does not give any benefits for the mud-to-cement conversion.

10. Lignosulfonates do not appear to cause any appreciable retardation for the conversion of the bentonitic mud into cement.

11. The addition of MgO to the bentonite/lime fluid prevents the precipitation of cement minerals and, instead, leads to the formation of a serpentine mineral. The latter phase is a nonswelling layer silicate and does not lend any viscosity to the fluid. The addition of magnesia becomes detrimental to the fluid viscosity. Magnesia provides, however, a reliable buffer for maintaining a high pH in the fluid at increasing temperatures.

Australian Bentonite -- At the conclusion of the clay-to-cement conversion studies, a parallel task was performed to evaluate the mineralogical and rheological properties of three different samples of bentonite from a new source. The samples, supplied by Cometals, Inc., were Gurulmundi crude bentonite, Trugel Red bentonite, and standard grade bentonite from Queensland, Australia.

X-ray diffraction analysis of the bulk sample of the crude bentonite showed it was composed of about 55% smectite (montmorillonite), 10% kaolinite (+ halloysite), 15% quartz, and 20% cristobalite. The mineral composition of the processed sample of Trugel Red bentonite was very similar to that of the crude bentonite. Trugel Red was made up of about 60% smectite (montmorillonite), 10% kaolinite (+ halloysite), 15% quartz, and 15% cristobalite. Examination of the standard grade bentonite sample showed that its mineral composition was similar to the other two bentonite samples. In summary, the X-ray diffraction studies of the samples indicated that

1. There was little or no mineralogical difference among the three samples.
2. All samples had a smectite content less than commercial U.S. bentonites such as Wyoming or Cheto bentonite.
3. In comparison to Wyoming bentonite, the Australian bentonite had a high silica content.
4. The Australian bentonite was formed in an acidic environment.

Electron microscopic examination of the samples revealed morphological features of smectite particles in the crude bentonite. Smectites occurred

as thin films and some thin lamellae that were barely visible, mostly in diamond-shaped forms. The thin smectite films folded and crumbled into aggregates as large as 4 to 5 microns. The morphological features of the smectites in the Australian crude bentonite are very similar to those in Wyoming bentonite. The x-ray spectra obtained from the smectite films gave Al and Si as the major elements and Mg and Fe as the minor constituents in the chemistry of these smectite species. Thus, they appeared to be morillonite varieties similar to the smectite species in Wyoming bentonite.

Kaolinite and halloysite were the other clay minerals in the Australian crude bentonite. Halloysites occurred mainly as tubular units and sometimes as spheroids. They ranged in length from 1 to 3 microns, and their x-ray spectra showed some excess silica and a little iron impurity. The spheroidal halloysite consisted of cabbage head-like aggregations of halloysite tubes. The chemistry of the spheroidal halloysite was very similar to that of the tubular halloysite. Kaolinite was found in the form of hexagonal platelets in the micron-size range. The x-ray spectra showed Al and Si as the major constituents of the kaolinite with some Fe-impurities. The intensity ratio Al/Si lines was 0.67 as expected from a kaolinite composition. This Al/Si intensity ratio for the x-ray spectra was found to be lower in halloysites. This result can be attributed to the presence of amorphous silica associated with halloysites. The pure silica phase (cristobalite) occurred as aggregates of extremely fine grains in the order of 100 to 300 Å.

Electron microscopic examination of the Trugel Red bentonite showed very similar morphological features for the mineral components in the samples. Thus, the mineral composition of the Trugel Red and crude bentonite was very similar both in quantitative distribution, and morphological and chemical characteristics. In other words, the smectite concentration was not enhanced or the silica concentration was not lowered during the processing of the crude bentonite. In summary, electron microscopic examination of the Australian samples showed the smectites present were similar to the smectite species in Wyoming bentonite but that nonsmectite constituents were different. In some aspects, the Australian bentonites were similar to U.S. low-yield bentonites.

Despite the close similarity in mineral composition, the high-temperature rheology of the three bentonites showed some significant differences. The rheological properties of a 6% Trugel Red bentonite was first measured with a FANN 35A viscometer. The plastic and apparent viscosities, yield point, and gel strength of the 6% Trugel Red before and after autoclaving were rather good. However, the CEC of these fluids was rather low. These low CEC values were considered directly related to the actual amount of smectite component in Trugel Red. Thus, the smectite content of 6% Trugel Red was equivalent to about 3% Wyoming bentonite fluid. The high-viscosity of the 6% Trugel Red was measured with a FANN 50C viscometer before and after autoclaving at 204°C (400°F). The rheograms showed a rather satisfactory behavior without any high-temperature gellation that is commonly associated with a 6% Wyoming bentonite fluid. A more realistic comparison, however, could only be made if the concentration of the Trugel Red fluid was increased so that its smectite content was comparable to that of Wyoming bentonite. For this purpose, a 12% Trugel Red bentonite fluid was prepared. In addition, 10% fluids were prepared with the crude bentonite and with the standard grade bentonite. The high-temperature viscosities of these fluids are displayed in Figure 4-8, as measured with a FANN 50C viscometer.

The Trugel Red bentonite showed a steady but small decrease in viscosity from about 96×10^{-3} Pa·s (96 cp) at room temperature to 51×10^{-3} Pa·s (51 cp) at 204°C (400°F). The crude and standard bentonites showed much higher viscosities between 38° and 121°C (100° and 250°F) as indicated in Figure 4-8. This result indicated that the crude bentonite and the standard have high-temperature gellation just like the Wyoming bentonite. The crude bentonite fluid reached a viscosity "hump" at 172×10^{-3} Pa·s (172 cp) at 93°C (200°F), and the viscosity drastically decreased beyond that temperature. The crude bentonite fluid became extremely thin between 204° and 260°C (400 and 500°F) so that it was not possible to measure its viscosity. The standard grade bentonite fluid had a viscosity hump above 300×10^{-3} Pa·s (300 cp) at 121°C (250°F), and it showed a sharp decrease in viscosity with increasing temperatures up to 260°C (500°F). In summary, although the mineral composition of the three bentonites were similar, the viscosity differences among them, suggested the presence of nonmineral

Figure 4-8. High-Temperature Viscosities of Three Australian Bentonites

constituents or additives--possibly polymers. The Trugel Red bentonite appeared to have a high concentration of the nonmineral material. The effect of these constituents was to give the three samples different characteristics at temperatures below 121°C (250°F).

In addition to completing the final report on the drilling fluid/cement studies, planning was underway at the close of FY 1983 for further geothermal drilling fluid development to include (1) study of additives that may improve the high-temperature properties of bentonite-based muds, (2) formulation and test of a high-temperature, bentonite-based mud, and (3) study of the high-temperature properties of saponite. These new investigations were expected to begin early in FY 1984.

5. BOREHOLE MECHANICS

The Borehole Mechanics program emphasizes research concerning borehole stability during drilling, completion, and maintenance. Specific areas of interest include lost circulation, lining and cementing the well, and casing structural failure.

5.1 Lost Circulation Test Facility

Sandia National Laboratories
Technical Consultants: G. Loeppke (505) 846-0301
B. Caskey (505) 844-8835

Project Objective

The first objective of this project was to construct a facility having the capability to test lost circulation materials and techniques under simulated geothermal conditions. The subsequent objective is to use the facility to evaluate materials and techniques for use in solving problems associated with completion and lost circulation in geothermal wells. 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.

Background

A substantial portion of the cost associated with drilling and completing a geothermal well can be attributed to lost circulation problems and poor cement displacement. Lost circulation that occurs during drilling may increase the drilling costs by 15% or more, while incomplete cementing jobs can result in loss of the well. The efforts to establish a test facility and a materials/techniques evaluation program to develop solutions to lost circulation/cementing problems were begun in mid-FY 1980. A survey of industry was conducted to determine whether suitable test facilities were available. Only one facility, a Halliburton test apparatus, was found with capabilities similar to those required for this project. However, the Halliburton facility was scheduled for exclusive long-term use in cement studies by a major oil company. Also, the facility had an operating temperature of less than 121°C (250°F), which is below the temperatures that may be encountered in geothermal wells. Because of the lack of availability and the limited temperature, it was concluded that a new, high-temperature facility that could be devoted to lost circulation material studies was required. The design of the facility was under way by the end of FY 1980.⁶ The detailed design of the test facility was completed during

FY 1981. The fabrication and procurement of components continued throughout FY 1981, and modification of the laboratory building to accommodate the facility was begun.⁷

The modification of the laboratory building was completed in FY 1982, and procurement, fabrication, and assembly of components and subsystems continued throughout the fiscal year. A control and instrumentation system, including the necessary computer software and hardware, was designed, assembled, and installed to provide the required control, monitoring, data gathering, and display of the operation of the test facility. As FY 1982 came to a close, final assembly and connection of all subsystems were under way in preparation for system shakedown tests.¹²

FY 1983 Activities

During this reporting period, the assembly of the Lost Circulation Test Facility was completed, and the facility was successfully proof-tested. In conjunction with the shakedown tests, a series of tests of a lost circulation material (Thermo-Set Seal) was begun and continued throughout the remainder of the fiscal year. A description of the facility and its capabilities and operation was published in Reference 47, and a report of the initial lost circulation material test results was included in Reference 48. The test facility setup is depicted in Figure 5-1.

Facility Description -- The facility has been designed to fulfill the following requirements:

1. Provide a full-scale diameter borehole to allow "cross-flow" evaluation of lost circulation materials.
2. Pump drilling fluids at representative wellbore circulation rates.
3. Handle various circulating fluids and lost circulation material concentrations.
4. Simulate geothermal formation temperatures.
5. Simulate wellbore and formation pressure differentials.
6. Allow the evaluation of various formation types such as permeable, fractured, and vugular.

Figure 5-1. Lost Circulation Test Facility

7. Provide independent control over the several test parameters.
8. Provide instrumentation for near real-time evaluation of a test.

The facility consists of four parts. The heart of the system is the test vessel and its associated accumulators. A mixing system, a heating and pumping system, and a pressurizing system complete the hardware. A simplified schematic of the facility flow system is shown in Figure 5-2.

Figure 5-2. Lost Circulation Test Facility Flow Schematic

A control room houses the computerized data gathering and control system. The facility allows independent control of test parameters such as pumping rate, core/formation pressure and temperature, wellbore pressure, and circulating fluid temperature. The system operational characteristics are listed in Table 5-1.

Table 5-1

**Lost Circulation Test Facility
Operational Characteristics**

Pumping rate	- Variable 0 to 0.02 m ³ /s at 6.9 MPa (0 to 280 gal/min at 1,000 psi)
Circulation fluid temperature	- 163°C (325°F) maximum
Test vessel core temperature	- 204°C (400°F) maximum
Wellbore/formation pressure differential	- 6.9 MPa (1,000 psi) working pressure
Test core size	- 51-cm (20-in.) diameter; 81 cm (32 in.) long
System volume:	
Test vessel and accumulators	- 1.1 m ³ (300 gal)
Heating and pumping	- 1.6 m ³ (420 gal)
Total	- 2.7 m ³ (720 gal)

The test vessel can accommodate a core or simulated wellbore and formation up to 51 cm (20 in.) in diameter and 81 cm (32 in.) long. A conceptual cross section of the test vessel is shown in Figure 5-3. A variety of core designs can be evaluated in the vessel, two of which (permeable and fractured) are depicted in Figure 5-3. The first core used for evaluation in system experiments was designed to hold up to 12 modified API slots so that lost circulation material/plugs could be evaluated in a cross-flow circulation situation and compared to the results obtained in the standard static inline tests conducted earlier.⁴⁹ The steel core is shown in Figure 5-4. The vessel may be heated independently of the circulating fluid by band heaters installed around the waist of the vessel. High-pressure hoses are used to plumb the vessel into the system.

Three accumulators are used to establish and maintain the desired pressure on the wellbore and formation sides of the core. The annulus accumulator controls the wellbore pressure and the pressure of the fluid circulating system. It also is used to contain any increase in system

Figure 5-3. Cross-Sectional Sketch of Test Vessel

Figure 5-4. Steel Core Designed for the Lost Circulation Test Facility Baseline Tests

volume resulting from heating the circulating fluid. The filtrate accumulator controls the pressure on the formation side of the core and receives any fluid/lost circulation material that may pass through the simulated formation fracture. Both accumulators are equipped with pressure regulators and back pressure regulators to maintain the desired pressure for the test. A third "charge" accumulator can be loaded with a slug of fluid/material that can be forced through the test vessel by pressure. Pressurization is accomplished by a nitrogen gas bottle system.

A conventional triplex mud pump, modified for high-temperature service, is used to circulate the test fluid. The desired circulation rate is selected by remotely controlling a hydraulic system used to couple an electric motor to the mud pump.

The circulating fluid is heated in a tube and shell heat exchanger using 0.9 MPa (125 psi) plant steam. The exchanger is rated at 850 kW (2.9×10^6 Btu/h).

A 4.5 m³ (1,200 gal) blender is used to mix and store the circulating fluid used in the tests. Drilling mud is added through a jet mixer. A centrifugal pump is used to circulate the fluid in the mixing loop or to transfer it to the high-pressure test loop.

Two basic test modes are possible with the facility. The slugging mode utilizes the charge accumulator in which the prepared drilling fluid with LCM is loaded and then forced through the core in the test vessel by nitrogen gas pressure. The annulus accumulator catches the fluid that passes out the annulus, and the filtrate accumulator catches the fluid that passes through the simulated formation until an LCM plug is effected.

In the circulating mode, the mud pump is utilized to pump the test fluid in a closed loop through the test vessel, mud tank, heat exchanger, and back to the mud pump. The function of the annulus and filtrate accumulators in this mode is as previously described. These modes can be used in combination such as circulating to establish a filter cake followed by a slug or a slugging test followed by circulation in an attempt to dislodge a plug.

All system functions (i.e., valves, pumps, etc.) are designed to be operated remotely from the control room. This operation can be accomplished by the operator at the control/display board or by the computer. The control/display board provides the operator with a graphic representation of the system piping and components schematic. It is equipped with monitor lights, digital meters, and control switches that allow the operator to monitor the status of motors, valves, pressures, temperatures, accumulator fluid levels, and the fluid circulation rate.

All test operations, however, are normally controlled by the computer that is interfaced with all control and monitor systems. The computer positions valves, runs pumps, controls the circulation rate, monitors safe limits for temperature and pressure, starts and stops the test, and gathers data in real time during a test. It is also used for data manipulation and data plotting. Table 5-2 shows the data that can be obtained from a test. The interface of the system parameters to the computer and control/display board is shown in Figure 5-5.

Table 5-2

Data Collection Capabilities

Borehole Circulation Rate

Borehole Pressure

Borehole Temperature

Circulating Fluid Temperature

Formation Pressure

Formation Temperature

Filtrate Flow Rate

Charge Flow Rate

The high-pressure/high-temperature test vessel is also suitable for other uses. Some alternate uses envisioned for the facility include the following:

Figure 5-5. Block Diagram of Lost Circulation Test Facility Control and Instrumentation

1. Mud Rheology -- a study of the effects of aging, temperature, pressure, and shear rate.
2. Formation Damage -- a study of the effects of forward and reverse flow on LCM plugs, proppants, and drilling solids in different formations.
3. Foam Properties -- a study of foam rheology in a borehole/drilling environment. Develop foams suitable for use as LCM media.

Experience during shakedown tests and early test operations with the lost circulation test facility surfaced problems with regulator contamination, pumping capability, flow-rate measurement, and system clean up. The test vessel was also found more suited to qualitative than quantitative analysis. In order to overcome the shortcomings observed during operation of the test facility, consideration was being given to the design of a second generation test vessel as FY 1983 ended. New design features being evaluated included provisions for annular flow with velocities to 1.0 m/s (200 ft/min), elimination of entrance effects, improved data quality, evaluation of gravity effects (pumping direction will include vertical through horizontal), quick slot clean out, quick change of slot size, flow visualization, and capability for other applications such as mud or foam rheology.

Test Activities -- Following successful pressure tests at 6.9 MPa (1,000 psi) of the steel core with all 12 test ports plugged, the first of

a series of tests to determine whether previous in-line slot tester results could be duplicated was conducted. In this initial test, a mixture of 21 lb/bbl bentonite mud and 10 lb/bbl medium Thermo-Set Seal lost circulation material was forced through one 0.1-cm (0.040-in.) slot at a differential pressure of 1.4 MPa (200 psi). The slot plugged in 5 seconds, and the plug held as the pressure was increased to 6.9 MPa (1,000 psi). The initial tests were conducted at room temperature with no flow past the slot(s). Additional test conditions, type of LCM, and the results of the tests are shown in Table 5-3. All slots that plugged subsequently held 6.9 MPa (1,000 psi) differential pressure for 15 minutes. The test results confirmed the plugging performance of Thermo-Set Seal material (ground battery casings) previously recorded during slot tester LCM screening tests.⁴⁹

Some 42 tests were run by the end of FY 1983 using Thermo-Set Seal, the most promising material found in earlier API slot tester evaluations. The tests included coarse and medium grades; differential pressures from 0.7 to 4.2 MPa (100 to 600 psi); cross-flow from 0 to 0.02 m³/s (0 to 230 gal/min); ambient temperature [except one test at 93°C (200°F)]; impermeable core with modified API slot sizes from 0.102 to 1.270 cm (0.040 to 0.500 in.); and concentrations of 5, 10, 20, and 40 lb/bbl in bentonite mud having a viscosity of 30 ± 5 cp. Analysis of the results of these tests was underway as this reporting period ended. Some of the preliminary conclusions indicated that (1) the coarse grade behaved differently than the medium grade, (2) no significant plugging effect was caused by slot orientation, and (3) Thermo-Set Seal will reliably plug slot sizes up to 1.6 times the average particle size of the largest 25% of the particles. As FY 1983 ended, preparations were also underway to test additional types of lost circulation materials.

Lost Circulation Modeling -- Efforts were also begun in FY 1983 to develop an analytic model of the "plugging" mechanisms involved with LCM. An incompressible finite element code, NACHOS, is being used to model the LCM with mud and the annulus/fracture geometry. Variables such as flow velocity and pressure differential across the fracture are included. Initial results are encouraging--calculations show that the viscosity of the

Table 5-3

Lost Circulation Material Test Results

Test Number	Pressure Differential		LCM Type	Concentration (lb/bbl)	Slot Width(s)		Results	Remarks
	MPa	(psi)			cm	(in.)		
1	1.4	(200)	Thermo-Set Medium	10	0.102	(0.040)	plugged	---
2	1.4	(200)	Thermo-Set Medium	20	0.305	(0.120)	no seal	---
3	1.4	(200)	Thermo-Set Coarse	20	0.305	(0.120)	plugged	plug held w/0.01-m ³ /s (200-gal/min) flow past plug
4	3.5	(500)	Thermo-Set Coarse	10	0.305	(0.120)	plugged	---
5	1.4	(200)	Thermo-Set Coarse	5	0.305	(0.120)	plugged	---
6	1.4	(200)	Thermo-Set Coarse	5	0.305	(0.120)	plugged	---
7	4.2	(600)	Thermo-Set Coarse	10	0.305	(0.120), 0.406 (0.160), 0.508 (0.200)	plugged	annulus plugged

mud increases in the vicinity of the fracture. Parametric studies will be performed for a range of LCM concentrations and particle size distributions. Laboratory experiments will be run as required to facilitate and verify the model. Upon completion, the model will aid in designing solutions to specific lost circulation problems.

5.2 Casing Collapse

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

Project Objective

The objective of this project is to investigate the planar radial buckling of commonly used casing employed in a geothermal well environment.

Background

Geothermal well casing is exposed to significant thermal variations as the well is drilled, produced, placed in standby mode, and idled for work-over operations. These variations in wellbore temperature lead to thermally induced stresses that may exceed structural limits and result in failure. This program effort is aimed at analyzing these conditions to determine the proper completion practices required to minimize thermally induced failures.

In an earlier effort, Euler buckling of geothermal well casing was studied, and the results were reported in Reference 50. The report provides preliminary calculations on the buckling phenomenon. Generally, it was found that thermally induced buckling in N80 casing would not be serious if minor adjustments to increase casing stability were made such as applying a tension preload or additional internal pressure while cementing. However, buckling would be detrimental for K55 casing, and full lateral support would be necessary. The effect of wall contact was found to be beneficial for closely confined pipe strings and of no great detriment when hole gaps were large, provided pipe ovalation was unimportant. The weakness in bending of all American Petroleum Institute (API) screw joints appeared to be the structural limitation.

FY 1983 Activities

The study of planar radial buckling of typical well casing under geothermal conditions was completed during FY 1983, and preparation of a

report on the investigation was under way as this reporting period ended. A summary of the study effort follows.

Problem Definition -- In most geothermal well operations a vertical hole is desirable while in some applications directional drilling may be required. The departure from vertical of a drilled hole is influenced by several factors. Among these factors are the type of geologic formation being drilled, drill penetration rate, and bit geometry. The economics of drilling a geothermal well often necessitates that some design compromise be made concerning the aforementioned factors. As an end result, most drilling operations produce holes that deviate from vertical. When the drill casing is lowered into the hole for cementing, the casing may not be concentrically placed within the hole but may be offset to one side. As viscous cement is pumped down the hole to flow around the casing, forces due to drag, pressure, and buoyancy impede the displacement of the vertical drilling mud column, Figure 5-6. These resistive forces may cause a local non-symmetric flow field to develop around the well casing. This nonsymmetric flow of cement can result in the formation of voids and regions of no flow, both of which inhibit a complete and competent cementing job. After the well casing has been set, pressurization within these voids due to geothermal heating of the trapped drilling mud may lead to the collapse failure of the well casing. Geothermal heating of the moist drilling mud has been postulated as the mechanism of pressure generation related to the collapse failure of well casing.^{51,52} However, failures of well casing due to this mechanism are difficult to document since, in general, no post mortems are performed once casing collapse has been detected.

The completed configuration of a downhole well casing is usually determined by the geologic formation and the type of well being drilled. A typical completion configuration is shown in Figure 5-7. Collapse failures resulting from external pressurization of the well casing could occur for the situations shown in Figure 5-8. A plane section of a casing configuration, Figure 5-9, indicates that various amounts of competent cement may surround the casing. For this study, the collapse problem was numerically analyzed using the finite element method. The numerical model consisted of a plane strain symmetric section of the casing. Analyses were performed

Figure 5-6. Forces Acting to Displace and Resist Displacement of a Bypassed Vertical Mud Column During Primary Cementing

Figure 5-7. Typical Well Completion

Figure 5-8. Schematic of Casing with Incomplete Cementing

Figure 5-9. Typical Plane Section of Casing with Less Than Competent Cement

for well casing diameter sizes of 24.5, 34.0, and 50.8 cm (9-5/8, 13-3/8, and 20 in.). The casing was modeled using one 8-node plane strain quadrilateral element through the thickness, although one problem was performed using a more refined mesh for purpose of comparison. Fixed displacement boundary conditions on the casing exterior represented the amount of competent cement. Distributed loads applied to the free exterior boundary of the casing provided the external pressure loading.

Temperature profiles of geothermal well casing strings vary from well to well, and although some analytical work has been done in that area, the profiles are not well characterized. One generalization that can be made about the downhole temperature is that the temperature does not radically change with variations in depth on the order of a casing section. Based upon this observation, it is reasonable to assume that a small section of casing can be considered to be at a constant temperature along its inside diameter. For these reasons, this study was performed incorporating fixed temperature material models. The elastic-plastic material models for K55 and N80 steel were used, and the inelastic isotropic hardening behavior was modeled using piecewise linear segments to fit the uniaxial stress strain curve.

Analysis -- The problem concerning buckling failure of geothermal well casings is essentially a quasi-static collapse problem, and in the following discussion, the two terms, collapse and buckling, are used interchangeably. Buckling is normally thought of as elastic failure mode, but the study included the effects of plasticity. Buckling can be described as the sudden deflection of a structural member that is associated with unstable equilibrium. The phenomena occurs when the structural loading reaches some critical value and often leads to total collapse of the structure. Under a gradual application of load, the structural response near the critical load is characterized by large deformation for small increments of load. Hence, the study of buckling has to do with two different problems: (1) the determination of the critical buckling load and (2) the severity of the resultant deformation, in particular, the postbuckling behavior. This study was concerned with the determination of the critical buckling load.

The numerical techniques used in this study to analyze the problem were incremental loading, eigenvalue buckling prediction, and the newly developed Riks solution algorithm. In order to evaluate the effectiveness of each approach, all three techniques were used to analyze the same problem. The problem was numerically modeled using the general purpose finite element code ABAQUS.⁵³ The model utilized the 8-node biquadratic, plane strain quadrilateral element, CPE8 (9-point integration). Large deformation effects were included by implementation of the nonlinear geometry feature of the ABAQUS code.

Pressure Generation -- Several different mechanisms are capable of generating external pressure around the well casing. External pressure could be generated by the geologic formation itself as a result of creep. Another possible mechanism of external pressure generation is superheated steam. Water from drilling mud or from the geologic formation may become trapped in voids formed by incomplete casing cementation. When the well becomes operable, heat will be transferred through the casing, the cement, and the water into the formation. If the proper ratio of the void volume to trapped water mass, the specific volume, is large enough, it becomes thermodynamically possible for the water to superheat, thereby generating a pressure in the void. The magnitude of these pressures are dependent upon the casing and formation temperatures and upon the specific volume of a system that includes the void and the trapped water.

It becomes apparent that a particular temperature must be chosen to be representative of the actual temperature within the void regions. Admittedly, a great deal of temperature variation can exist within the void, but that distribution represents a complex problem that would detract from the simplicity of this analysis. In addition, conditions at geothermal wells vary greatly and no single geometry can be chosen to address the problem with any generality. For these reasons, no attempt was made to solve the heat transfer problem concerning the diffusion of heat into and away from the well casing. Instead it was assumed that the temperatures within the void regions were the same as those of the well casing inner surface.

Results -- Finite element analyses were performed for 24.5-, 34.0-, and 50.8-cm (9-5/8-, 13-3/8-, and 20-in.) casings for several angles of casing surface fixity. The analyses were performed using fixed elastic-plastic temperature material models for K55 and N80 steels. Casing deflection was monitored at the node corresponding to the point of largest radial deflection. A typical external pressure load versus deflection curve is shown in Figure 5-10. The curve serves only to demonstrate that buckling behavior, large deformation for small increments of pressure loading, is exhibited by the numerical model. Collapse was found to occur when the stresses through the casing thickness exceeded the yield stress, in effect forming a plastic hinge.

Semi-log plots of the collapse pressure (P_{cr}) versus the fixed angle are shown for both steels in Figures 5-11 and 5-12.

Existing well logging technology does not provide a means for determining the amount of casing restraint. Nevertheless, the results of this study can be utilized to bound the problem and to provide some insight into the generalized behavior of the well casing under external pressure loading. The results of the analysis, Figures 5-11 and 5-12, indicate that for angles of fixity less than 120° , the buckling pressure is nearly a linear function of the fixity angle on the semi-log plot. For angles of competent cement greater than 120° , the buckling pressure shows little increase and in some cases even decreases. This is useful in establishing an upper bound upon the external pressure that the casing can be expected to withstand under ideal conditions. The result for unrestrained casing provides a lower bound buckling pressure and can be used to evaluate the possibility of casing collapse due to pressurized steam.

The possibility of pressurized steam as a failure mechanism in the collapse failure of a geothermal well casing can be evaluated systematically using the results of this study and the temperature profile of the well. This possibility is most easily addressed by means of an example. Consider a 50.8-cm (20-in.) diameter casing of K55 steel; according to Figure 5-11 the minimum buckling pressure will be 5.3 MPa (770 psi). By referring to pressure versus specific volume data, the minimum temperature at which that

Figure 5-10. Pressure Load Versus Deflection - 50.8-cm (20-in.) Casing

Figure 5-11. Buckling Pressure Versus Fixed Angle for K55 Steel

Figure 5-12. Buckling Pressure Versus Fixed Angle for N80 Steel

pressure can be achieved is about 260°C (500°F). A typical, but by no means general, well-temperature profile is shown in Figure 5-13. In this application, the shut-in temperature of the 50.8-cm (20-in.) casing will be slightly less than 260°C (500°F). According to the results of this study, the well casing represented by the given profile would probably not experience collapse resulting from pressurized steam. However, this result needs to be examined further.

Maximum temperatures occurring in geothermal wells vary from 260°C (500°F) in dry steam wells to 343°C (650°F) in hot water wells. Superheated steam has the potential of generating external casing pressures up to 48.3 MPa (7,000 psi). This data implies that collapse failures could occur for any of the well casings considered in this study.

The study indicated that collapse failures could occur for the casings studied at very high pressures. These results are not conservative since there are other factors that have not been accounted for in these analyses. As previously mentioned, most drill holes deviate from vertical, with present well drilling technology providing a means for correction through directional drilling. Drilling downhole from an initial deviation can potentially degrade the quality of uphole casing. This occurs because the rotating drill stem could come in contact with and conceivably wear the uphole casing interior. A worn condition could substantially reduce the collapse load of the drill casing.

As FY 1983 ended, consideration was being given to follow-on studies of casing failures. Since this study was based on "perfect" casing, future studies would consider "damaged" casing with reduced thickness from wear due to drilling and/or corrosion. Preliminary scoping calculations on models of worn 24.5- and 34.0-cm (9-5/8- and 13-3/8-in.) casing demonstrated a decrease in collapse load. A comparison of the worn models and the standard models indicated that the estimated radial collapse loads were lowered by 45% to 9.0 and 15.9 MPa (1,300 and 2,300 psi), respectively. Thus, the collapse loads were reduced to the point where collapse might

Figure 5-13. Typical Well Temperature Profile

occur. In future studies, data will be required on worn and collapsed casing from the field, as well as samples of field casing for laboratory testing. These data and casing samples will be needed to inject the necessary realism into the studies.

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. The tools and techniques developed as a part of this effort are basic support devices for the other program elements, yielding definition of the downhole environment for better system definition

6.1 Lost Circulation Zone Mapping Tool

Sandia National Laboratories
Technical Consultant: T. Bauman (505) 844-8885

Project Objective

The objective of this project is to develop a wire line tool capable of locating and defining features of fractures that intersect the borehole.

Background

Under a project completed in FY 1982, the Acoustic Borehole Televiwer (ABT) was successfully upgraded for operation at high temperatures and pressures, and the capability of the instrument to operate at temperatures up to 280°C (536°F) and at pressures up to 31 MPa (4,500 psi) for seven hours was demonstrated in full-scale laboratory and field tests. The field tests of the upgraded ABT proved the tool was valuable for casing inspection as well as for fracture characterization in geothermal wells. The technology developed was transferred to industry (Simplec Manufacturing Company) for use in the design of new commercial televiwers. The results of the project were reported in References 54 and 12. A schematic of the acoustic borehole televiwer system is shown in Figure 6-1.

FY 1983 Activities

In view of the high-resolution data and superior performance experienced with the upgraded Acoustic Borehole Televiwer, a decision was made in FY 1983 to initiate an effort to modify the tool for mapping of lost circulation zones. The design modifications included the addition of a temperature sensor to aid in lost circulation zone location and of a second frequency (400 kHz) sensor to allow a few inches of penetration into the formation. In addition to the design modification work, further field testing with the ABT was planned to obtain additional operating data on the tool under high temperatures and pressures and to determine any additional tool modifications required for use in the fracture mapping role.

Figure 6-1. Schematic of Acoustic Borehole TelevIEWer

A field test was attempted with the ABT in an effort to map a loss zone in a Union Oil Company geothermal well located in the Salton Sea area. Initial photographs of two different sizes of casing were found to be consistent with the estimated condition of the two casing strings. However, when the tool was positioned below the loss zone in preparation for logging back to the fracture/loss zone, the signal was lost within two minutes after passing into the high-temperature fluid below 625 m (2,050 ft). After pulling and cooling the tool, disassembly of the cablehead showed that insulation on the conductors had melted, allowing wires to short together. Subsequent attempts at a field fix of the cablehead/cable connectors failed, and operations were suspended, pending availability of a suitable high-temperature cable and cablehead.

The electrical and mechanical design modification work was continuing as FY 1983 ended, and planning for a field test in Los Alamos National Laboratory's EE-3 hot dry rock well to characterize previously identified open-hole fractures was under way. In addition, a search for a suitable high-temperature wire line for use in field tests of the Acoustic Borehole Televiewer was being made.

6.2 Acoustic Cement Bond Diagnostics

Sandia National Laboratories

Technical Consultants: Hsi-Tien Chang (505) 844-7588

Fred Wolfenbarger (505) 844-7306

Project Objective

The objective of this project is to develop high-temperature technologies for use in the design and fabrication of an acoustic cement bond logging instrument for operation at temperatures up to 250°C (482°F).

Background

There are currently no commercially available high-temperature cement bond and casing integrity logging systems for geothermal wells with maximum temperatures in excess of 250°C (482°F). Most commercial logging tools, developed for the oil and gas industry, become unreliable above 150°C (302°F) in actual field tests. As a consequence, geothermal well operators must cool the well in order to run surveys. The thermal shock from cooling could cause well damage to both casing and cement. Also, loss in production time due to cooling prior to logging is expensive. Hence, a distinct need exists for development of high-temperature logging capabilities to support the timely growth of geothermal energy. In response to this need, Sandia began an upgrade research program in late FY 1980, focusing on improvement of the temperature capabilities of the acoustic cement bond logging tool. The program description and development approach were described in Reference 55.

Work to develop high-temperature circuits suitable for use in the design of an upgraded, geothermal acoustic cement bond logging instrument continued during FY 1981 and was reported in References 56 and 7. The FY 1981 efforts included successful operation for approximately 150,000 cycles at 10 pps of a redesigned Spryton tube. The tube used bismuth for the anode and cathode in a new trigger circuit design. Evaluations of various commercial electronic components to determine maximum operating temperatures were also conducted. The design of a 1:15 pulse transformer using Sillectron and magnet wire was completed by the end of FY 1981.

Design efforts on the acoustic cement bond logging instrument continued throughout FY 1982. Improved circuit design and component selection resulted in the temperature-caused variation in the output voltage and current of the transmitter system being reduced from 30% to 10%. The receiver circuit design was completed by January 1982 and included a Harris Semiconductor 2600-1 operational amplifier that worked satisfactorily at temperatures up to 250°C (482°F). Transmitter/receiver breadboard circuits were successfully tested in an oven at temperatures up to 250°C (482°F) for 2 hours. Subsequently, the layout for a printed circuit board design was completed. The design of the transmitter and receiver transducers, acoustic isolator system, and mechanical housing for the tool was also begun in FY 1982 and was continuing at the close of the fiscal year.¹²

FY 1983 Activities

The design of the transmitter and receiver, the acoustic isolator system, and the mechanical housing was completed, and fabrication of the prototype cement bond logging tool was under way as this reporting period ended. The basic elements of the acoustic system are illustrated in Figure 6-2. The cablehead connects the instrument to the cable from a logging truck. Transmitter electronics provide the electric energy to the transducer, which converts electric energy into acoustic energy. The transmitter circuit also determines the pulse repetition rate of the system. Receiver electronics amplify the signal received so that it can be transmitted through thousands of feet of cable to the surface for analysis. Transducer fluid couples the acoustic energy from the transducer to the wellbore and formation. The bellows makes room for transducer fluid to expand as the temperature increases. The acoustic isolator eliminates the direct signal path from the transmitter to the receiver through the instrument, thus allowing the receiver to detect a weak return from the formation. A summary of the tool design efforts was reported in Reference 57.

Laboratory experiments identified a magnetostrictive transmitter and a piezoelectric receiver as the best approach for an acoustic cement bond tool capable of operating at high temperature. By using a parallel inductance in the receiver's electronics, the acoustic output of the

Figure 6-2. Basic Elements of the Acoustic Cement Bond Logging Tool

transmitter/receiver pair is reduced less than 2 db over a temperature range from ambient (room temperature) to 250°C (482°F).

Transmitter -- A magnetostrictive transducer is used as a transmitter because it can generate more acoustic energy than most piezoelectric materials at 10 to 40 kHz. The material selected is a 2-V Permendur which has high Curie temperature and stable electrical characteristics up to 250°C (482°F). The magnetostrictive transducer is excited by a circuit that includes a Sprytron tube. The initial input voltage is about 100 V, which will be ringing up to 350 V through a 1-H inductance. This energy is stored in a 1-μf capacitor. When the Sprytron is triggered, the energy is transferred from the capacitor to the transducer, resulting in a strong magnetic field in the core. After the core's magnetic field reaches saturation, it resembles a short circuit since the flux cannot continue to increase. A surge current of 100-amp peak will pass through the core and charge the capacitor into a reverse voltage. This negative voltage also appears at the Sprytron's terminals and effectively cuts off the tube, completing a cycle. The input will recharge the capacitor again, and the Sprytron is waiting for the next trigger signal to repeat the cycle. During such a cycle, the magnetic flux in the core increases from a small value to saturation and then reduces to a small value as the Sprytron is cut off. Such changes of flux will cause the dimension of the core to change and thus generate an acoustic output.

Since eddy currents reduce the output, a tape core, rather than a solid core, was used. Unfortunately, a tape core created one difficult problem that was not anticipated. During tests, the acoustic output of a tape core dropped significantly above 100°C (212°F). Since 2-V Permendur has a curie point at 940°C (1,724°F), it was not obvious what might be the reason for such a behavior. In order to search for the cause, four transducers were tested in an oven at 450°C (842°F). The cores were deformed, and the tapes were delaminated. This experiment suggested that the adhesive used to bind the tape cannot withstand the temperature. Attempts to impregnate the core with high-temperature resin failed because the resin used has high viscosity and could not flow through the whole surface of the tape when impregnated in a vacuum. Various techniques to impregnate the

cores with high-temperature adhesives were explored. These tests showed that the cores lost their magnetostrictive properties when impregnated with high-temperature resin or when painted with high-temperature adhesives. Because of these problems, the testing of bare cores without adhesives was attempted. This approach led to the identification of cores capable of generating continuous acoustic output at temperatures as high as 250°C (482°F). Although the acoustic output of the bare cores was reduced by a factor of eight over a temperature range from ambient to 250°C (482°F), compensation for the reduction can be achieved by an electronic circuit or by a calibration technique.

Receiver -- Piezoelectric transducers in general have high sensitivity and therefore are ideal as receivers. Materials with low Curie temperature, such as barium titanate, was not considered appropriate for the cement bond logging tool. Some crystals, such as lithium niobate, have a very high Curie point but require a special cut and cannot be molded into desired shapes. Among the ceramic materials, a lead titanate-lead zirconate performs well in a hot environment. Two transducers made of such a material were designed to operate at about 35 kHz when separated by 4.1 cm (1.6 in.) in an oil bath. One was used as the transmitter, and the other was used as the receiver. The first few cycles received by the receiver are the direct ray from the transmitter, while the latter cycles contain reflections from the test chamber and therefore are not the direct response of the transducer. Test results, as shown in Figure 6-3, indicate little change in the acoustic amplitude in the first few cycles from room temperature to 240°C (464°F).

Previous tests of disk transducers at MHz frequency range suggested that a K-95 material (modified lead titanate) was usable for a high-temperature piezoelectric receiver. However, when this material was molded into a tubular shape, the transducers could not be polarized. Hence, tests were conducted using tubular transducers fabricated from PZT-5 (lead titanate-lead zirconate) and from K-81 (lead metaniobate). These materials showed better reception characteristics, but as the temperature increased, the capacitance between the electrodes increased, reducing the acoustic output. This effect was reduced by using a capacitance with a negative temperature

Figure 6-3. Oscilloscope Tracer of a Lead Titanate-Lead Zirconate Transducer at Various Temperatures

coefficient in parallel with the electrodes. A second technique to prevent reduction of the acoustic output was connection of a parallel inductance such that the output impedance was the highest at 250°C. The latter approach appeared to yield the more desirable results in maintaining the acoustic output.

In piezoelectric transducer measurements, care should be taken with any associated measurement circuit. The capacitance and leakage resistance

between the electrodes of some transducers can change drastically. A decrease of the leakage resistance will reduce the output. However, any change of capacitance at different temperatures can also affect the output, but this may not be a direct indication of degradation of the transducer. Particularly, LC resonance in the measurement circuit should be avoided.

A cylindrical transducer can receive acoustic input from all directions and is commonly used in logging tools. A cylindrical transducer will respond to the acoustic waves in three different polarizations; namely, the radial, longitudinal, and tangential polarizations. The sensitivity of different polarizations depends on the dimension of the cylinder. To avoid mode interference, the resonant frequencies of various polarizations should not be too close. Otherwise, data will be hard to interpret. If the length of the transducer to the mean diameter ratio is between 1 to 2.5, the resonant frequency of the longitudinal mode will be very close to that of the radial mode; these dimensions should be avoided in the design. In addition, many transducer materials have low radial coupling coefficient when the thickness to the diameter ratio is between 0.2 to 0.4. This region should be avoided also if the radial polarization is of interest.

A striped configuration is another way to reduce mode interference. The stripe is a conductor that shorts the transducer's responses in radial and longitudinal directions. The electrical output is obtained from adjacent stripes. In theory, the sensitivity should increase as the stripes are moved further apart, but there is a practical limitation of about 1.9-cm (0.75-in.) separation for an effective polarization. For example, a 2.5-cm (1-in.) ID lead titanate-lead zirconate transducer requires four stripes.

Acoustic Isolator and Mechanical Housing -- If the acoustic signal travels directly from the transmitter to the receiver through the body of the instrument, it will interfere with the receiver's reading. Unfortunately, a downhole instrument requires a strong solid housing to withstand formation fluid pressure. Such a housing is usually made of steel, which has a high acoustic velocity. Consequently, the acoustic signal coming through the instrument could reach the receiver before the formation

return. In addition, a high Q material may be used for the receiver in order to increase its sensitivity. Under such a circumstance, the acoustic signal from the instrument may still be ringing as the formation signals arrive. This situation makes the data analysis extremely difficult. Some instruments used in the industry today have many elongated slots on the housing between the transmitter and the receiver. The acoustic signals have to travel in a zig-zag pattern to reach the receiver. Hopefully, there will be enough time delay so that the direct instrument signal will arrive after the formation return. This approach is meaningful only if the structures to be sensed are not too far away from the borehole. Therefore, its application is limited. In the tool design, an acoustic isolator is located between the transmitter and the receiver. This isolator is made of sections of steel pipe with cross sections designed to induce acoustic discontinuities, thus reducing the acoustic transmission along the instrument.

Mobil jet oil is used as the coupling fluid inside the transducer housing. It has a high boiling point, although its volume increases 20% from room temperature to 250°C (482°F). To provide room for this expansion, an air space is left or a mechanical bellows can be installed inside the transducer housing. Seven-pin connectors from Gearhart Industries have survived temperatures up to 250°C (482°F). Y267 EPDM is an effective elastomer at high temperature,⁵⁸ and many companies have started to manufacture O-rings using this compound. If the instrument is not exposed to high temperature for long periods of time (a few hours), Viton O-rings can be used.

Fabrication of the cement bond logging tool prototype is expected to be completed by mid-FY 1984. Laboratory testing will begin at that time.

6.3 Geopressured-Geothermal Reservoir Diagnostics

Sandia National Laboratories

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

Project Objective

The objective of this project was to develop a high-resolution pressure transducer, 103 to 138 MPa (15,000 to 20,000 psi), together with associated high-temperature circuitry, 200° to 225°C (392° to 437°F), for use in geopressured-geothermal reservoirs.

Background

High-temperature and high-pressure reservoir diagnostics techniques are needed to assess geopressured resources of methane and hot water. Because of the lack of instruments with high temperature/pressure ratings, the accuracy of resource estimates of a geopressured-geothermal reservoir using various currently available techniques can vary by a factor of up to 10. For this reason, a project was begun in mid-FY 1980 to investigate circuit modifications that could be readily implemented into the high-pressure gauge of existing equipment to extend the temperature capability.

Early efforts included the use of W. P. C. Worth temperature tools in tandem with a Hewlett Packard pressure gauge in laboratory experiments with circuits redesigned for 200°C (392°F) operation. This work continued into FY 1981 with a new selection circuit (a circuit that selects between temperature and pressure signals) surviving 200°C (392°F) oven tests. However, both the pressure tool and the temperature-sensing circuitry failed since the oven tests were above their specified operating temperatures.

The Worth temperature tool was further modified for high-temperature use and tested at 200°C (392°F). The Worth tool qualified at this temperature in the laboratory, but it failed to function in an attempted field test in a well near Zapata, Texas. A new chopper-stabilized amplifier for use with a strain gauge transducer was designed and successfully tested in

the laboratory. Before these efforts could be completed, work was suspended pending redirection of the project in response to forecast reductions in FY 1982 funding.

The project was redirected in FY 1982, focusing on long-term, high-risk development at a lower level of effort. Project activities were concentrated on the designing of a bottomhole pressure gauge transducer, having a pressure rating between 103 and 138 MPa (15,000 and 20,000 psi) and a temperature rating between 200° and 225°C (392° and 437°F). Bottomhole pressure gauges currently available and under development were evaluated for geopressure application. The most promising devices appeared to be the strain-gauge transducer and the eddy-current transducer. Initial investigations identified four transducers capable of geopressure application. Preparations for comparison testing of these transducers were under way at the close of FY 1982.¹²

FY 1983 Activities

Comparison testing of candidate high-resolution pressure transducers for use in geopressured-geothermal reservoirs was completed in FY 1983.⁵⁹ In earlier work on the evaluation of bottomhole pressure gauges currently available, transducers manufactured by Bell and Howell, Kaman, Kulite, and Sensotec were identified for laboratory comparison tests. Subsequently, the price of the Kaman transducers was determined to be in excess of the program funds budgeted for their purchase. Therefore, transducers from Precise Sensors, Dynisco/BLH, Paine, and Teledyne-Taber were evaluated as replacements for the Kaman. The Precise transducer was found to have a high-temperature rating, but it was not considered appropriate for geothermal application since it is water cooled. Dynisco produces transducers rated at 207 MPa (30,000 psi) with a compensated temperature range to 218°C (425°F). However, this type of transducer is a 1 mV/V, 120 Ω bridge using 6V excitation. The low output was not considered adequate for deep well measurement. Temperature and pressure ratings of the Paine transducer appeared suitable, but the quoted 50-week delivery time exceeded project requirements. The Teledyne-Taber met cost and delivery time and was selected to replace the Kaman. The ratings of the four transducers used for the laboratory comparison tests are shown in Table 6-1.

Table 6-1

Test Transducer Ratings

Manufacturer	Pressure Range		Upper Boundary, Compensated Temperature Range	
	Pa	Psi	°C	°F
CEC (ell and Howell)	138	(20,000)	235	(455)
Teledyne-Taber	138	(20,000)	235	(455)
Kulite	138	(20,000)	235	(455)
Sensotec	103	(15,000)	315	(599)

Since transducers were not available to permit testing at the originally planned 138 MPa/300°C (20,000 psi/572°F) levels, the test plan was modified to test the transducers listed in Table 6-1 initially at 103 MPa (15,000 psi) and 200°C (392°F). Then, the test temperature was increased incrementally up to 235°C (455°F). If the 235°C (455°F) temperature level was met, the test pressure was increased to 138 MPa (20,000 psi), the anticipated upper limit for these comparison tests.

In general, all the transducers performed within the manufacturer's specifications during short-term tests, meeting specifications such as combined linearity and hysteresis, but the percent variations produced large absolute fluctuations. The range of performance could not be extended beyond the manufacturer's specified values since some of the transducers did not survive to the rated pressures and temperatures. All of the devices showed a lack of repeatability when cycled from low to high temperature and from low to high pressure and back. Although the variations were within the manufacturer's overall error percent of full-scale specifications, these inaccuracies constituted relatively large absolute values for the full-scale ranges 103 to 138 MPa (15,000 to 20,000 psi). The response time of all transducers to a step change in pressure was faster than 2 seconds, the minimum test equipment readout time.

One of the Sensotec transducers failed above 110 MPa (16,000 psi) during the high-pressure portion of the initial burn-in and high-pressure cycling. Another of the Sensotec and both of the Teledyne-Taber transducers failed during long-term testing but only at pressures exceeding about 83 MPa (12,000 psi). At lower pressures, they continued to operate. The failure mode appeared to be some type of internal pressure leak. Only one transducer, a Bell and Howell model, showed exceptional stable behavior during long-term, high-temperature testing. All other devices showed various degrees of drift or fluctuation with time under comparable conditions.

Conclusions -- The test results of the comparison study of commercial strain-gauge pressure transducers for use in the harsh, downhole geopressured, geothermal, and deep oil and gas well environments were analyzed, and the major conclusions were

1. The output ratio of the transducers fit a linear function. However, the zero-shifts of these linear functions were highly nonlinear with respect to temperature, and some could not be adequately approximated by a low-order polynomial.
2. An obvious hysteresis was present in all transducers and was, in general, nonlinear and could not be adequately approximated by a low-order polynomial.
3. The long-term stability of the different transducers did not show any definite trends. The drifts were monotonic and could be compensated for with a calibration curve or additional electronics in most cases.
4. In the comparison tests, constant output with time was not apparent.
5. The long-term tests showed a drift in all but one of the transducers. Long-term stability was the most critical problem identified from the standpoint of applicability to long-duration, transient well testing.
6. The lack of standardization of the transducers' mechanical and electrical connectors was also considered a serious problem.
7. Overall, the test results indicated that currently available commercial transducers have a temperature/pressure limitation in the range of 138 MPa/235°C (20,000 psi/455°F) for geopressured/geothermal use. In

order to achieve acceptable performance above this pressure/temperature range, additional research and development will be required.

Although additional work is required to develop a suitable high-resolution pressure transducer for use in geopressured-geothermal reservoirs, resource limitations and higher priority projects preclude continuation of this research and development effort at this time.

6.4 Radar Fracture Mapping

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

Project Objective

The objective of this project is to develop a high-frequency technique for the location of fractures in the vicinity of boreholes from downhole measurements in a single wellbore.

Background

A survey of the technical literature indicated that various previous experiments reported findings that some hard rocks act as a low-loss dielectric at 30 to 300 MHz, the VHF frequency. This low-loss dielectric characteristic suggested that electromagnetic waves might propagate tens of meters through some rocks and provide detectable radar returns from brine-filled fractures.

Drilling in the Valles Caldera, New Mexico geothermal resource area resulted in dry holes not far from producing wells. While a fracture system apparently existed in the area, failure to locate and intercept the fractures from dry holes led, in part, to abandonment of the efforts to exploit commercially the geothermal resources in the region. Since the capability to characterize fractures in the vicinity of boreholes (but not intersecting the boreholes) offers the potential to convert a dry hole to a producing well or to increase production from geothermal wells, a decision was made in FY 1983 to start a research effort aimed at adapting high-frequency technology to fracture location from a single borehole.

FY 1983 Activities

Project work was begun in mid-FY 1983 with a simple field experiment at a granite quarry in Marble Falls, Texas to confirm the radar fracture detection concept. A section of granite was selected that had an existing flame-cut slot, and the slot was filled with salt water to simulate a

brine-filled fracture. A transmitter consisting of two dipole antennas arranged to provide a directional signal toward the fracture was installed in a borehole opposite the fracture. A receiver was also located in the same borehole. The radar returns from the simulated fracture were detectable in boreholes located at distances of up to 12 m (39 ft) from the fracture. These results indicated for the first time the feasibility of developing a downhole VHF radar for use in a single borehole for detection of fractures located away from the borehole.

The experimental electromagnetic measurements in the feasibility tests produced useful data sufficient to meet the project's initial test objectives. The acoustic measurements were less conclusive and productive for several reasons related to the experimental test configurations used in the field and the manner of field data acquisition. Because of these limitations, additional field experiments were considered necessary.

Analysis of the acoustic data provided accurate measurements of the shear and compressional wave propagation velocities in the granite. These data also revealed a significant sensitivity in the received signal to the rotational position of both the acoustic source and the receiver. Further, there appeared to be at least a modest influence on the received signals by the centering of the probes in the borehole.

Computer print-outs of the acoustic data also revealed significant reverberations contributed by various wave modes in the borehole. Masking effects of these oscillations can be significantly reduced by computer processing if special data acquisition procedures are employed during data recording.

Based upon the results of the field feasibility tests, modifications to the test apparatus and additional field testing were planned. The test apparatus modifications were to include:

1. Attachment of rigid lightweight tubes on the transmitter and receiver probes to permit rotation of the probes to known positions with respect to each other and the target when implaced in the boreholes.

2. Modification of the probe centralizers to permit accurate centering of the probes in the boreholes.

3. Modification of digital field data acquisition software to permit onsite evaluation of the recorded data.

The additional field tests were scheduled for early FY 1984 at the Texas Pearl Quarry in Marble Falls, Texas to acquire high-resolution controlled acoustic reflection data. The planned experiments will include (a) common-depth scans of the probes in adjacent boreholes with data stations at 20.0-cm (7.9-in.) intervals and (b) offset scans of the boreholes with one probe held fixed while the other probe is positioned at 20.0-cm (7.9-in.) spaced intervals up the borehole. Data waveforms acquired in the latter mode will provide a move-out pattern in the reflection signals different from the direct signals recorded in (a) to permit differentiation between direct and reflection signals. Experiments will also be performed to correlate first-motion polarity in the received signal with transmitter transducer direction orientation in the borehole. Data from these tests will be computer processed to remove stationary nonreflection signals to the greatest extent possible. The final data printouts shall be analyzed to evaluate the potential of acoustic probing for fracture detection.

Planning was also begun during this reporting period to design and construct an experimental apparatus for a laboratory test facility. The facility will be used to perform electric field pattern measurements for a simulated borehole EM directional antenna for remote detection of fracture zones and evaluate the projected performance of at least one multi-element array in detecting a brine-filled fracture. The apparatus will include a container for simulating a water-filled borehole about 15.0 cm (5.9 in.) in diameter surrounded with granite having various electrical parameters ($\epsilon_r \sim 3$ to 10, $\sigma \sim 10^{-3}$ to 10^{-1} si/m). In addition, special test jigs and equipment will be fabricated for making time domain electric field measurements for a single-element antenna (resonant in the VHF band) positioned at all reasonable locations on the radius of the simulated borehole. Experiments will include time domain electric field measurements on a single-element antenna immersed in water within the simulated vertical borehole for at

least 5 radial positions for every 22.5° in the horizontal plane and for at least three moisture/conductivity conditions of the surrounding sand (simulated granite). From measured data, predictions will be made of horizontal plane field patterns for at least three multi-element array configurations (i.e., 2-element, 4-element, 16-element circular array). Also, time domain electric field measurements will be conducted under such array configurations to determine the maximum detectable range for a given antenna input power.

On the 1st of January 1901 the
first of the new year was
celebrated with a grand
fireworks display in the
park. The weather was
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7. PERMEABILITY ENHANCEMENT

The goal of permeability enhancement is to develop the technology and methodology required to increase the production rates or injection rates of geothermal wells. Work under this program will include definition and evaluation of existing reservoir production/injection zones to determine the nature of the formation permeability, quantification of the geometry of fractures intersecting the wellbore as well as their extent, definition of performance requirements and identification of research needs for enhancing the permeability of geothermal wells, and development of the specific technology to meet these performance requirements and needs.

7.1 Surface Electric Potential Fracture Mapping

Sandia National Laboratories

Technical Consultants: C. M. Hart (505) 844-4344
H. E. Morris (505) 846-4732
D. Engi (505) 844-4831

Project Objective

The objective of the surface electrical potential fracture mapping project is to develop a surface technique for mapping fractures that intersect the wellbore.

Background

The surface electrical potential system (SEPS) measures variations in resistivity contrasts resulting from the flow of a conductive fluid into the earth. This system, essentially a "mise a la masse" technique,⁶¹ utilizes the stimulation well as a current source electrode and an outlying well as the current sink. Hole-to-surface resistivity measurements are made by injecting bipolar pulses of current into the stimulation well and measuring the resultant distribution of electrical potential on the earth's surface. A rigorous analysis of potential distributions resulting from a penetrating electrode has been presented by Muskat.⁶²

The surface distribution of equipotential lines surrounding the pole source buried in a laterally isotropic earth (a homogeneous halfspace) is in the form of concentric circles with the stimulation well as their center, Figure 7-1. During stimulation, the well casing, along with the associated reservoir matrix, when filled with a conducting fluid, acts as a changing current injection electrode. As the stimulation treatment progresses, the electrode geometry changes and the electrical potentials measured at the surface reflect this changing shape.

The SEPS data are taken by periodically recording the induced potential differences at the earth's surface between an infinite reference probe and the data probes placed every 15° circumferentially around the

Figure 7-1. Surface Electrical Potential Distribution

stimulation well. Background data are taken to establish the induced potential levels around the well prior to the stimulation treatment. These data then become the reference data for detecting the changes produced when the conductive fluid alters the electrical geometry. If the electrical potentials before, during, and after the stimulation are compared, diagnostic information about the directional nature of the treatment is obtained.

This technique has been used in the evaluation of hydraulic stimulation treatments in oil and gas reservoirs but had not been applied in a geothermal well or during an acid stimulation.

FY 1983 Activities

During the latter part of this reporting period, Sandia's surface electrical potential system was fielded during the chemical stimulation treatment of the Rossi 21-19 well in the Beowawe Geothermal Field. The objectives of the experiment at the Beowawe site were (1) to determine whether or not the technology is sensitive to chemical treatments of geothermal wells and, (2) if so, to map the directional nature of the treated zone.

Chevron has drilled a total of five deep wells in the Beowawe Geothermal Field in north-central Nevada. One of these wells, Rossi 21-19, has been subcommercial, even though it does intersect a high-temperature zone. Pressure interference tests have shown that all of the Chevron wells are hydraulically connected. Thus, it has been assumed that Rossi 21-19 was completed in a limited zone of restricted permeability and/or was damaged during drilling.^{63,64} As a part of DOE's comprehensive 8-well geothermal reservoir well stimulation program, Republic Geothermal, Inc. and its contractors performed a 227-m³ (60,000-gal) two-stage chemical stimulation treatment intended to remove the near-wellbore restriction suspected to exist in Rossi 21-19.

The Beowawe Geothermal Field is located on an ENE striking Basin and Range normal fault that marks the southwest boundary of Whirlwind Valley, a few miles southwest of the town of Beowawe in north-central Nevada. The complicated geology of this field has been the subject of many geologic studies, and the reservoir is thought to be in the lower Paleozoic carbonates at depths approaching 6,096 to 9,144 m (20,000 to 30,000 ft). The low salinity brine of the reservoir (1200 ppm TDS) flows upward from the carbonates by way of a complicated series of faults. The east-northeast trending Malpais fault system is one of two major fault sets in the area. Rossi 21-19 lies along the Malpais fault zone at the base of the Malpais rim.

The stimulation well, Rossi 21-19, was drilled by Chevron Resources Company in 1979 to a depth of 2,198 m (7,212 ft). A slotted liner is hung at the producing zone, ranging from 1,274 to 2,199 m (4,178 to 7,213 ft). The actual production interval(s) in the well may lie anywhere in a range between 40 and 305 m (130 and 1,000 ft). Interpretations of electric log data suggest possible productive intervals at 1,341 to 1,402 m, 1,524 m, and near 1,859 m (4,400 to 4,600 ft, 5,000 ft and near 6,100 ft). Downhole static temperature is near 197°C (386°F) at 1,555 m (5,100 ft).

In the experiment, Sandia's SEPS was set up, and the surface electrical potential data were taken by measuring potentials at 65 probe locations placed circumferentially around Rossi 21-19 at distances of 229, 610, and

1,220 m (750, 2,000 and 4,000 ft). A schematic of the probe array is presented in Figure 7-2. The probes were stainless steel rods measuring 46 cm (18 in.) in length and 1.3 cm (0.5 in.) in diameter and were driven approximately 15 cm (6 in.) into the ground. A wire from each probe was fed to an associated potential measurement box (PMB) located adjacent to the inner potential probe. The output from the PMBs was frequency multiplexed into cables that carried power from an instrumentation van to the PMBs and transmitted data from each PMB to the instrumentation van.

Figure 7-2. Surface Electrical Potential Array for Rossi 21-19 Acid Stimulation

The potential field was created by injecting electrical current flow into Rossi 21-19. Bipolar current pulses from a series of solid gel batteries was injected at the Rossi 21-19 wellhead, and the current was returned via two current return (sink) wells. The first sink well, the Batz well, was approximately 3.2 km (2 mi) NE of Rossi 21-19. Interference

tests had previously suggested that Batz was hydrologically coupled to Rossi 21-19. Thus, this current return path was a part of the current injection electrode. The second current return well was a windmill that was located approximately 4.8 km (3 mi) SW of the injection well. This well was drilled to a shallow fresh water reservoir and had no hydraulic communication with Rossi 21-19.

The directional reversal of the injected current during each measurement was necessary to prevent polarization effects. The potential for each probe location was taken as the difference between the sampled positive and negative pulse referenced to infinity and normalized with respect to the current used to induce the field. The injected current and the data collection were controlled from the instrumentation van by a PDP 11/34 mini-computer.

The stimulation design for Rossi 21-19 was a two-stage chemical treatment confined to the slotted liner interval below 1,332 m (4,369 ft). An abbreviated test schedule is given in Table 7-1.

Table 7-1
Test Schedule

<u>Date</u>	<u>Activity</u>	<u>Fluid Pumped</u>
8/16-8/17	SEPS Background Data	one
8/20	Injectivity Test	Water
8/21	Acid Injection 1, Injectivity Test	Water and HCl Water
8/22	Acid Injection 2, Injectivity Test	Water, HCl, HF Water
8/23	SEPS Posttest Data	None

The first acid treatment included 80 m³ (500 bbl) of 14.5% hydrochloric acid (HCl) displaced by 382 m³ (2,400 bbl) of water, and the second treatment consisted of 156 m³ (982 bbl) of 12% HCl and 3% hydro-fluoryl (HF) acid solution followed by 636 m³ (4,000 bbl) of water. Injectivity tests

performed before and after stimulation indicated a 2.3 fold increase in injectivity by the end of the second treatment.

Since the success of this diagnostic technique relies on changes in resistivity resulting from the flow of a conductive fluid into the formation, quantitative estimates of expected resistivity contrasts were made before the SEPS was fielded. Resistivity of the in situ brine was measured at 80 ohm-m. The effect of adding various concentrations of HCl to the sampled in situ water is shown in Figure 7-3. The reduction in resistivity by an order of magnitude is due almost entirely to the HCl. The addition of HF to the solutions had an insignificant effect due to the high acidity of HCl and the low ionization constant for HF. Thus, it was concluded that SEPS should easily detect the presence of HCl at the levels to be injected.

Figure 7-3. Resistivity Versus Hydrochloric Acid

SEPS data from both current return wells were collected during all of the experimental stages outlined in Table 7-1. A different set of data was acquired approximately every five minutes. The data was displayed in the field during real time, so some indication of the directional nature of the treatment zone was available on site. Subsequently, data from discrete times that were representative of the various experimental stages (background, injectivity tests, acid injections, and posttest) were more thoroughly examined. Analysis of these "snapshots" along with the real-time observations provided preliminary interpretation of the subsurface activity during the chemical stimulation.

Test Results -- Polar plots of the background data collected around Rossi 21-19, using the Batz well for current return, are shown in Figure 7-4. The windmill current return data provided similar plots. These data remained stable over a two-day period. Because of the resistivity contrast between the in situ brine and the surrounding earth, the Malpais fault ($60^{\circ}/255^{\circ}$ orientation) was seen in the background data from all three radii. Also apparent in the data were a near-surface conductive body at the 195° , 229-m (750-ft) probe and a near-surface anomaly at the 1,219-m (4,000-ft) radius in the vicinity of the 0° and 345° probes. A neighboring well, Ginn 1-13, was depicted by a protrusion in the 610-m (2,000-ft) radius, 315° probe. This probe location was within 31 m (100 ft) of the 2,745+ m (9,000+ ft) well. (Note that the magnitude of the potential measurement decreased because the current was sinking in this deep well.)

No observations were made during the injectivity tests. This was not surprising because the water was being pumped from and reinjected to the same reservoir, thereby creating no resistivity contrast.

Some activity was observed along the known predominant fracture direction and toward the Ginn well during the hydrochloric acid stage, but the data did not indicate any significant movement during this stage. The HCl was not expected to produce any measurable stimulation effect but was necessary to prevent formation of insoluble calcium fluoride precipitate in the formation during the second stage.

Figure 7-4. Polar Plot of Pre-Stimulation Potentials (mV/A)

Data from the second acid injection portrayed definite acid flow patterns as exemplified in Figure 7-5. Major acid flow paths were along the Malpais fault line ($60^{\circ}/255^{\circ}$ orientation) and along a $15^{\circ}/195^{\circ}$ path. Although not obvious from the "snapshot" displayed in Figure 7-5, some movement of the treatment fluids was seen along an east-west path approximately 610 m (2,000 ft) north of Rossi 21-19 with activity centered at Ginn 1-13. The conductive paths observed during the HCl/HF treatment are illustrated in Figure 7-6.

Post-stimulation data (Figure 7-7), when compared to the background data of Figure 7-4, indicated that the chemical treatments altered the in situ flow patterns. The predominant $60^{\circ}/255^{\circ}$ fracture was still present, but the flow appeared to be enhanced along the 60° azimuth. This was most obvious in Figure 7-7 from the 1,219-m (4,000-ft) radius data. The stimulation also appeared to have increased permeability between Rossi 21-19 and

Figure 7-5. Polar Plot of Acid Injection 2 Potentials (mV/A)

Figure 7-6. Plan View of Conductive Paths During Acid Injection 2

Figure 7-7. Polar Plot of Post-Stimulation Potentials (mV/A)

Ginn 1-13. Data from the windmill sink indicated the response was consistent with that of the Batz well.

Conclusions -- Based on a preliminary analysis of the field test data, the following are the major conclusions resulting from the experiments with the surface electrical potential system in the Beowawe Geothermal Field:

1. The feasibility of using the surface electrical potential technique to map fractures intersecting boreholes was demonstrated.
2. Analysis of posttest data indicated that the stimulation indeed altered flow patterns. Moreover, the SEPS was, in fact, sensitive to the chemical treatment, and there appeared to be substantive data relative to the directionality of the treatment.

3. Because of the high conductivity of the in situ fluid, the system was able to detect a major conductive path extending along azimuths ENE and WSW from Rossi 21-19 before any acid injection. This path of flow was enhanced during the stimulation treatment, and a second major flow path appeared to the NNE. Some activity was also evident in the vicinity of an adjacent well (Ginn 1-13).

As FY 1983 ended, analysis of the data from the Beowawe Geothermal Field experiments was continuing, and preparation of a final report on the tests was under way. Consideration was also being given to additional efforts to understand and quantify data produced by the surface electrical potential technique to include a modeling effort. Construction of a laboratory facility to generate experimental data in support of the model development was being evaluated along with the need for additional field testing of the surface electrical potential system.

7.2 Geothermal Well Fracture Permeability Studies

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

Project Objective

The objective of this project is to determine the fracture characteristics required to impart a desired productivity to a given geothermal well.

Background

Production or injection rates of existing wells can usually be increased by enhancing the permeability of the production/injection zone. In the case of oil and gas wells, this enhancement is accomplished by increasing the near-wellbore permeability, using such techniques as hydraulic fracturing, gas or foam fracturing, and explosive fracturing. However, in geothermal wells, much higher production/injection rates require that this increase come from establishing fractures that connect the wellbore to existing reservoir fracture systems. The differences between geothermal reservoirs and oil and gas reservoirs preclude the use of much of the technology developed for the oil and gas industry, and due to the small size of the geothermal industry (0.1% of energy production), there are currently no economic incentives for industry involvement in the necessary research.

In the case of production, the need for enhanced permeability has been recently evidenced by the experience in the Valles Caldera in New Mexico. Several commercially productive wells were drilled adjacent to several "dry holes." Apparently, the nonproductive "dry holes" do not intersect the existing reservoir fracture systems, and previous attempts have not been successful in creating connecting fractures. In order for geothermal areas like the Valles to be viable energy resources, a reliable technique for enhancing permeability is needed. The mechanics of fractured production are not adequately understood in order to design the enhancement methodology for geothermal wells with any confidence of success.

Enhancement techniques will also be needed in injection wells in order to allow for disposal of the geothermal brine once the heat energy has been removed. ReInjection is needed to assure that the reservoirs are not depleted of fluids by the production process, to prevent subsidence of the surrounding terrain, and to avoid surface environmental damage from the produced fluids. Since reinjection wells must accept comparable or larger flow rates than production wells, they must also intersect existing reservoir fracture systems.

Previous efforts at well stimulation have generally been unsatisfactory, producing minimal or no increase in flow rate. Thus, there is an apparent need for additional research aimed at understanding the previous tests and developing the technology required to successfully enhance the permeability of geothermal wells. An integral part of such a research program will be the development of analytical techniques to provide tools for the evaluation of potential new technologies for permeability enhancement and to characterize formation fracture systems for optimum production/injection.

FY 1983 Activities

Near the end of this reporting period, planning of a study to determine the fracture characteristics required to increase the productivity of a given geothermal well was begun. Two major tasks will be pursued simultaneously. The first task is to determine the fracture characteristics attainable with both hydraulic fracturing, which produces planar fractures, and high-energy gas fracturing (HEGF), which produces radial fractures. Hydraulic fracturing has been studied for more than 30 years and, although the process is still not completely understood, this study will make use of existing data on planar fractures rather than attempting to make new discoveries. In the case of HEGF, fracture characteristics have not been studied in any detail. A need exists to determine the number, length, and conductivities of such fractures, anisotropic effects due to confining pressures, effects of existing fracture systems, and the utility of using erosive fluids or acids to increase conductivities. An experimental program is being contemplated to answer these questions.

The second task is to determine the fracture characteristics required to impart a given productivity to a geothermal well. A numerical model is being developed to determine the flow/pressure behavior of a wellbore with an induced fracture system. The effects of existing fracture systems, the created fracture pattern and conductivity, flashing in the formation and fractures, and reservoir management will be studied. Both planar and radial fractures will be included in order to determine the conditions under which either hydraulic fracturing or HEGF techniques result in higher well productivity. The studies are expected to begin early in FY 1984.

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