DRAFT

FY97 Geothermal R & D Program Plan

September 1996

**Sandia National Laboratories
Albuquerque, NM**

FY97 GEOTHERMAL R&D PROGRAM PLAN

**Geothermal Research Department
Sandia National Laboratories
September, 1996**

Abstract

Sandia National Laboratories manages a broad R&D program on geothermal drilling technology for the U.S. Department of Energy. This document describes the program plan for Fiscal Year 1997. Most of the program activities are related to reducing the cost of geothermal drilling, although some are related to other aspects of geothermal energy, such as reservoir technology, production equipment, and geothermal heat pumps. This plan provides a detailed description of each project in the program, including justification for the project, potential cost savings resulting from the project, project participants, required funding, status, statement-of-work, milestones, and deliverables. The projects are arranged according to program area. Current program areas include lost circulation technology, hard-rock drill bit technology, high-temperature instrumentation, acoustic technology, slimhole drilling technology, Geothermal Drilling Organization projects, geothermal heat pump technology, and system studies. The program is heavily oriented toward cooperative work that involves a number of geothermal operators, service companies, consultants, universities, and other national laboratories.

FY97 GEOTHERMAL R&D PROGRAM PLAN

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FY97 GEOTHERMAL R&D PROGRAM PLAN

**Sandia National Laboratories
Geothermal Research Department 6111
September, 1996**

I. Introduction

The purpose of this program plan is to describe the activities in FY97 and beyond that comprise the U.S. Department of Energy (DOE) Geothermal R&D Program at Sandia National Laboratories. The objective for publishing the plan is twofold: 1) to provide a single document where the entire program is described in detail, for use by DOE, industry, and others in understanding our program; and 2) to elicit comments from the geothermal industry on the value of the ongoing and new projects being proposed so that the program can be continually focused on relevant work.

This document is organized according to program areas. Current program areas include lost circulation technology, hard-rock drill bit technology, high-temperature instrumentation, acoustic technology, slimhole drilling technology, Geothermal Drilling Organization projects, geothermal heat pump technology, and system studies. Within each program area are descriptions of the individual projects. Each description includes justification for the project, potential cost savings resulting from the project, project participants, required funding, status, statement-of-work, milestones, and deliverables.

II. Program Overview

a. Justification, Purpose, and Mission

In conducting its Geothermal Research Program, DOE's mission is to sponsor research and development in advanced geothermal energy technology and to work in partnership with U.S. industry and electric utilities to provide a competitive energy option for meeting U.S. and worldwide energy needs. DOE's vision includes: a fully competitive U.S. geothermal industry in domestic energy markets; expanded leadership for the U.S. geothermal industry in world energy markets; and broad recognition of geothermal energy as abundant, reliable, economic, and environmentally beneficial. The program is broad in scope and is designed to assist industry in overcoming near-term barriers by conducting cost-shared research, and to accomplish fundamental research with potentially large commercial payoffs.

Public investment in the program is justified on several grounds. First, the development of reliable, indigenous, and environmentally friendly forms of alternative energy is a national security issue, both strategically and economically. Secondly, geothermal leasing and royalty payments alone already return about two-thirds of the DOE geothermal program budget back to the federal treasury. If further geothermal development occurs as a result of DOE's program, the program could pay for itself in royalty and leasing returns. Thirdly, geothermal energy is "on the edge" in the sense that it is a reliable, developable resource that needs only a small level of public investment to fully compete with less desirable forms of conventional energy production.

An effective way for DOE to provide assistance to the geothermal industry is by developing cost-saving technologies that can be utilized directly. Because of the relatively small geothermal market (as compared to the oil and gas market), the extensive petroleum service industry does not devote much attention or many resources to geothermal-specific problems. Individual geothermal operators cannot afford to develop their own technology because the market (themselves) is even smaller. Because the technology needs of the industry are shared by the entire industry and because it is in the public interest for this industry to thrive, the DOE can justify using the technology development capabilities of its national laboratories to foster the advancements this industry needs. The national laboratories have the capability of concentrating on specific problems in a systematic, long-term manner and bringing broad-based resources to bear in developing new technology or transferring technology from one application to another.

Reduction of geothermal well costs is a major component of DOE's program. Well costs account for roughly one-third to one-half of the total cost of a geothermal power project. Moreover, geothermal drilling costs are accrued very early in a project and, therefore, have a large impact on project economics. For these reasons, the geothermal industry has consistently recommended that reduction of drilling costs be adopted as the top goal of DOE's Geothermal R&D Program.

The purpose of Sandia's Geothermal R&D Program is to help DOE reduce the cost of geothermal energy. Our primary mission is the reduction of geothermal well costs through the development and re-application of advanced drilling technology. Our secondary mission is to assist in other geothermal research areas where our expertise or capabilities are useful. We work closely with industry to identify technical problems and solutions that have the greatest impact, to field test the resulting technology, and to transfer the technology to industry. We strive to *not* compete with private industry but, rather, to fill a niche that private industry does not readily fill, namely advanced technology development for a very limited market. We do not market any technology we develop but strive to transfer it to private industry where it can be commercialized. We also readily serve as facilitators, coordinators, and catalysts to foster the development and commercialization of technologies by private industry.

b. Program Goals

The goal of this program is to reduce geothermal drilling costs in order to reduce the cost of installing geothermal power plants. Based on cost studies we have performed, a well cost reduction goal of 25% is reasonable. Such a reduction in well costs would result in about a 10% reduction in project costs. For a typical \$100 million project, this equates to a \$10 million savings. This is a significant savings that would help geothermal energy improve its competitiveness with conventional energy resources.

A 25% reduction in drilling costs will not come about simply with the successful conclusion of any one project described in this plan. Geothermal drilling methods are based on technology that is almost one hundred years old, and many bright people have contributed to the present state of the art, so major advances will not come easily. To succeed, we must employ new materials, techniques, and technologies combined with a systems engineering approach. This approach is used in each project described in this plan. Each project has been chosen because of its potential for reducing costs a measurable amount, so each project should be viewed as potentially "chipping away" at the 25% goal.

Approximately 85% of the projects described in this plan are short- to medium-range in remaining duration, requiring one to three years to complete. This is in accordance with the wishes of the industry, which needs immediate help to reduce costs. The remaining 15% of the projects are long-range, requiring three or more years to complete. The long-range projects, in

addition to developing potentially significant technology, also serve as a focus for each program area, leading to the development of expertise within our staff that provides a technology base for the shorter-range projects.

Thirty-two of the projects described in this document are ongoing, having been under way for 3 months to six years. The other nineteen projects are proposed new projects that have not yet been initiated. Although it may seem desirable to work on fewer projects and accelerate their pace, the research and development process is by far more efficient in the long run with a larger number of projects simultaneously under way. More projects translate to more productive work to be done. When one project reaches a hold point where a staff member must wait for someone else to respond before work can proceed on that project, attention can be transferred to other projects. Furthermore, the likelihood of significant technology advances is improved by considering a larger set of possibilities.

Nevertheless, we have generally structured the program to focus on a few projects for completion in FY97. Other ongoing projects will be continued, but at a slower pace. The proposed new projects will not significantly slow the pace of ongoing projects because additional staff members and contractors will be employed as needed.

We realize that it is not likely that funding will be sufficient to begin all the new projects listed here in FY97. Projects will be prioritized and selected to proceed based on the funding level available. The purpose for including all the new projects in this document is to provide a pool from which new projects can be selected as funding becomes available and to indicate where the program is heading in the future as ongoing projects are completed. This pool of new projects will grow as we continue to evaluate geothermal drilling problems and conceive possible new solutions.

c. Program Management

Sandia's Geothermal R&D Program is managed by the Geothermal Research Department 6111 at Sandia's Albuquerque, NM, facility. The department consists of approximately 20 staff members, including contract employees. The department is one of nine departments in the Geoscience and Geotechnology Center of the Energy and Environment Division at Sandia.

The program is managed for the DOE Office of Geothermal Technologies, which provides overall program direction, promotes transfer of the developed technology to industry, and provides primary program funding. The Sandia role in DOE's program is described in a program management plan developed by DOE. We have also obtained funding for FY97 work from the DOE Office of Fossil Energy, the NADET Institute, and the Department of Defense for several of the geothermal-related projects described in this document.

The Manager of Department 6111 oversees the multiple program areas, each of which has a program area leader. Each program area is comprised of individual projects, which are described in this document. Projects are headed by a project leader and may include staff members within Department 6111, other staff members within Sandia, and contract employees. The department extensively uses both on-site and off-site contractors to augment our geothermal staff. Project leadership is often shared with industry, university, or national lab partners. The names, phone numbers, and addresses of the various project and program leaders are provided in each project plan in this document.

The work performed under this program is documented in various forms. Conference papers and journal articles are often published as work on a project proceeds. At the conclusion of a project, a Sandia Report is generally written that documents the development effort and final

status of the technology. The last section of this plan contains a partial bibliography of documents published on projects conducted under this program over the past 20+ years. During the next year, we plan to complete this bibliography and publish it together with the abstract of each document.

A mailing list is maintained of persons interested in the program who receive copies of our technical publications. Over the next year, we plan to refine the mailing list with the publication of a quarterly newsletter on program status. The goal is to increase awareness of our program within the geothermal industry and to improve technology transfer from our projects.

d. Program Participation

Sandia's program is broad and involves a large number of people affiliated with Sandia and with our industry, university, and national lab partners.

Sandia Participants: The following individuals include Sandians and on-site contractors in the Geothermal Research Department, in the Geoscience and Geotechnology Center, and in other parts of the lab.

Dan Arvisu	Doug Drumheller	John Finger	John Gabaldon
Dave Glowka	Pat Gronewald	Virginia Grossman	Charles Hickox
Martin Heinstein	Joe Henfling	Ron Jacobson	Paul Klimas
Steve Knudsen	Steve Lambert	Dick Lynch	Chip Mansure
Randy Normann	Ken Pierce	Jeana Pineau	David Raymond
Dee Remenar	Allan Sattler	George Staller	Mike Stone
Bill Sullivan	Mazzan Tabbara	Jim Uhl	Steve Yrene
John Waggoner	Jim Westmoreland	Gary Whitlow	Jack Wise
Elton Wright	Ernie Zamora	Dave Zeuch	

Industry, Universities, and National Laboratories: The following list includes other participants, such as contractors, collaborators, and partners.

Amoco Production Research	Baker Hughes Inteq	Baker Oil Tools
Ballew Tools Co.	Bertram Drilling	Brookhaven Nat'l Laboratory
CalEnergy	Colorado School of Mines	Dennis Tool Co.
Drill-Cool Systems	Dynaflo, Inc.	Earth Science Research Inst.
Epoch Well Logging	Ewbank and Associates	Fischer-Rosemont
FlowDril Corporation	Geo-Centers, Inc.	Geo Hills Associates
Geothermal Management Co.	Halliburton Services	Hughes Christensen Co.
International Logging Japan	Jet Propulsion Laboratory	Johnston Pumps
Ktech Corporation	Lawrence Berkeley Nat'l Lab	Livesay Consultants, Inc.
Loop Tech International	Maurer Engineering, Inc.	Maxwell Technologies
Mill Pond, Inc.	Nat'l Renewable Energy Lab	New Mexico Tech
Novatek, Inc.	Panametrics, Inc.	Peek Measurements
RE/SPEC, Inc.	Security DBS	SlimDril International
Smith International	South Dakota State University	Southern Methodist Univ.
Stanford University	Stokes and Spiehler	Technology International, Inc.
Tecton Geologic, Inc.	Terra Tek, Inc.	Thermochem
Tonto Drilling Services	Tracor, Inc.	U.S. Army, Fort Bliss
U.S. Geologic Survey	University of SW Louisiana	Unocal
Viera Artesian Wells	Winslow Pump and Well, Inc.	

III. Lost Circulation Technology

a. Background

Lost circulation is the loss of drilling fluid to the rock formation surrounding the borehole. This can cause significant problems during drilling because it does not allow the drilling fluid to perform some of its vital functions, namely removing rock chips, stabilizing the borehole walls, and lubricating the drill pipe in the hole.

With inadequate hole cleaning, rock chips can build up in the wellbore or pack away in the loss-zone fractures. When the mud pumps are stopped to make a connection, the chips can settle into the bottom of the hole and stick the drillstring, sometimes leading to a twist-off. Without a full borehole and the hydrostatic pressure necessary to stabilize the borehole wall, the downhole rock formation more easily fractures and/or sloughs into the wellbore, which can also stick the drillstring. In wireline core drilling, where the clearance between the drillstring and the wellbore wall is small, a total loss of circulation means a loss of lubrication between the drillstring and the wall above the wellbore fluid level. This often leads to severe excess torque conditions while drilling. Even a small fluid loss can be an expensive annoyance because drilling fluids are costly, at least several dollars per barrel.

If the loss of circulation is not corrected while drilling, the problem can become very severe and even more costly when it is time to case the well. It is necessary in geothermal wells that the casing be cemented to the rock formation along its entire length; otherwise, buckling of the casing may result when it undergoes thermal expansion as the well is produced. This has led to the total loss of more than one well. Yet it is difficult to obtain a good cement job in the presence of an unplugged loss zone because the cement simply flows into the loss zone and does not return up the annulus to the surface. It is expensive to remedy this situation after it has occurred, so it is far better to plug each lost circulation zone shortly after it is penetrated during drilling.

Lost circulation treatments commonly used in geothermal drilling include adding lost circulation materials (LCMs) to the drilling fluid and pumping Portland cement through open-end drill pipe into the wellbore near the loss zone. LCMs usually consist of scrap material that contains particles, flakes, and fibers capable of bridging and sealing relatively small fractures. Examples include cottonseed hulls, ground walnut shells, wood chips, scrap paper, and mica. Under severe lost circulation conditions, LCMs are limited in their effectiveness for two reasons: particles small enough to pass through a drill bit nozzle are too small to bridge fractures that have an aperture larger than the nozzle diameter; and most scrap materials that would be economical LCMs do not have high-temperature stability or the strength required to bridge a fracture. Nevertheless, LCMs are routinely used in geothermal drilling because of their ability to prevent fluid losses through pores or small fractures along the wellbore wall.

Cementing is the favored lost circulation treatment for large fractures because it usually works if a large enough cement volume is pumped. The cost of treating a single lost circulation zone, however, is typically \$10,000-20,000 because of the large cement volumes often required and the time lost waiting for the cement to harden before drilling can resume. The nature of the cement treatment depends on the location of the loss zone relative to the bottom of the hole.

If the loss zone occurs on bottom, as when a permeable zone is first penetrated, the first requirement is to fully drill through the zone before trying to seal it. A zone often consists of multiple fractures or highly permeable strata that may be several feet thick. After drilling through the zone, the drill pipe is tripped, the bit removed, and the pipe reinserted as open-end drill pipe, with the lower end situated near the loss zone. A cement plug of some pre-determined

quantity, typically 300 ft³, is pumped downhole, then the pipe is pulled above the loss zone while waiting on the cement to harden enough to test. After a pre-determined time period, typically 4-6 hours, wellbore circulation is attempted by pumping drilling fluid through the open-end drill pipe. If full circulation is regained, the drill pipe is pulled out of the hole to re-attach the drill bit, and drilling resumes when the bit is back on bottom, assuming the full 8-12 hour set time of the cement has since passed. If the wellbore is still losing fluid, more cement will be pumped, and the waiting and testing process will be repeated. Some loss zones require multiple treatments.

When a seal of the loss zone is finally achieved and drilling resumes, the cement in the wellbore is first drilled out. When the bit reaches the loss zone, it is not uncommon for the plug to begin leaking or totally fail as the hole is re-opened. This is probably due to inadequate penetration of the cement into the loss zone. This is a confusing situation, where the drilling fluid will readily flow into the loss zone but the cement will not. It is caused by unintended bridging or premature cement setting at the fracture aperture along the wellbore wall. Its occurrence requires that the entire cement treatment be repeated. The time and material cost of this process is significant.

If a new loss zone develops uphole, or a previously sealed loss zone begins to leak uphole, the cementing process can be even more difficult. In such cases, which are fairly common, the open-end drill pipe is situated near the estimated depth of the loss zone, and a given volume of cement is pumped. The theory behind this practice is that the cement will flow out of the drillpipe, into the wellbore, then into the loss zone; that while in the wellbore, the cement remains intact as a plug because of its viscosity and because of the support of the wellbore walls and the confined fluid below the loss zone. In large-diameter wellbores, however, what often happens is that the cement does not remain intact but responds to gravity and channels through the lower-density drilling fluid beneath it, sinking to the bottom of the wellbore. In such cases, enough cement must be pumped to fill the entire wellbore beneath the loss zone, plus enough to plug the zone itself. In addition to the wasted time drilling through long intervals of cement in the wellbore, large volumes of cement fines require additional mud conditioning to maintain proper drilling mud properties.

It is not uncommon for over thirty cement plugs to be required for a single geothermal well. With each plug costing \$10,000-20,000 in time and materials, it is evident that lost circulation is an expensive problem in geothermal drilling.

b. Justification for Technology Development Effort

Because of the fractured and vugular nature of volcanic rock, where geothermal resources are often found, lost circulation is a more pervasive problem in geothermal than in oil and gas drilling. In fact, lost circulation accounts for about 10-20% of the total cost of drilling a typical geothermal well. Based on the technologies we are currently developing, a 30-50% cost-reduction goal for lost circulation-related costs is reasonable. This would reduce geothermal well costs by about 3-10% and overall project costs by about 1-5%.

c. Lost Circulation Projects

Eight projects are planned in the lost circulation technology program area. Four of these projects address the need for better characterization of lost circulation zones and better diagnosis of related problems. Four projects pertain to the development of downhole tools or materials for sealing lost circulation zones. Six of the eight projects are ongoing; two are proposed new projects. The projects are described in the following pages.

Rolling Float Meter for Outflow Rate Measurement

Program Area: Lost Circulation Technology

Project Leader: George Staller, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-9328, Fax 844-3952
Program Area Leader: George Staller, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-9328, Fax 844-3952
Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Measuring the outflow rate of drilling fluid from a well is important for several reasons. If the outflow rate differs from the inflow rate, then the wellbore is either producing or losing fluid. If it is producing fluid, a gas or steam kick may be coming and special drilling precautions should be taken.

If the wellbore is losing fluid, an accurate measure of the loss rate would help diagnose and treat the loss zone. For example, the fluid loss rate may be small, indicating that the fluid is leaking through either small fractures or pores in the wellbore wall. This type of zone might be sealed with an LCM added to the drilling fluid. A larger loss rate would indicate fractures that may be too large to be plugged with LCM.

Tracking the loss rate over time is useful in a variety of ways. Field tests have shown that when a loss zone is intercepted, it immediately shows itself at the surface as a reduction in flow rate. Multiple small loss zones can then be identified and tracked by a driller if the data are displayed as a time history plot. Such a plot is also sometimes useful in determining when a loss zone has been fully penetrated so that treatment of the zone can be undertaken. In this case, the fluid loss rate generally increases as the borehole penetrates through the zone, then it stabilizes at a constant rate when the zone has been fully penetrated.

Accurate outflow rate measurement also permits the effectiveness of a lost circulation treatment to be accurately assessed. It is important to completely seal a loss zone before drilling ahead because it is difficult to identify and treat a leaking loss zone that is not on bottom. Accurately comparing the inflow with the outflow rate is the only way to know that a loss zone has been sealed completely before resuming drilling.

None of the measurements described above are currently feasible with commercially available flow meters. The industry standard outflow meter, the paddle meter, is notoriously inaccurate but is often used because it at least gives a qualitative measure of the flow status in the mud return line. It is not capable, however, of providing accurate, quantitative data that can be used for diagnosis as discussed above. Measurement of the fluid flow rate in a partially-filled pipe with an abrasive, particle-laden fluid is not an easy task. Any device used must be capable of withstanding the erosive environment and any gas or steam kicks that might blow down the mud line; must not cause rock chips to fall out of the flow; must accurately extract information from the turbulent, wave-dominated surface stream in the mud line; and must be easily installed on any rig.

Under this project, a new type of outflow meter that fits these requirements is being developed and commercialized. The rolling float meter consists of a rolling float that rides on the surface of the mud flowing down the inclined, partially-filled mud return line. As the outflow rate increases, the level of the fluid in the mud line increases, and the float rides higher in the mud

line. The float spins on a pivot arm that changes angle as the float rides higher or lower in the line. This angle is measured with a potentiometer. Thus a constant DC voltage applied to the meter results in an output voltage from the meter that is proportional to the angle of the pivot arm and can be calibrated with the outflow rate in the mud line. The meter has been shown in laboratory and field tests to provide highly accurate and reliable data, as described in more detail below.

Estimating a potential cost savings resulting from the use of a rolling float meter is difficult, but we can make some reasonable assumptions. If a well requires 24 lost circulation cement plugs and the meter reduces the amount of time required to assess each loss zone by one hour, then one day of drilling time is saved, or \$5-10k at current rig rates. It can be further assumed that the ability to determine when the loss zone has been fully penetrated would prevent at least one of the loss zones from being treated prematurely, saving one cement plug and another \$10-20k. Another reasonable assumption is that the ability to determine when a loss zone has been completely sealed before drilling ahead would prevent at least one of the loss zones from becoming an off-bottom loss zone in the future, where at least one additional cement plug would be required. This would save another \$10-20k. Using these very conservative assumptions, the rolling float meter could therefore save \$25-50k per well, or about 1% of the cost of a typical geothermal well.

Project Participants:

- Sandia National Laboratories: Lead development effort; design, fabricate, laboratory test, and field test; coordinate industry field testing effort; work with industry to commercialize meter; document and publish results.
- Tecton Geologic: Participate in industry field testing effort.
- Int'l Logging Japan: Participate in industry field testing effort.
- Epoch Well Logging: Participate in industry field testing effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$155k	Sandia salary, hardware, travel, field expenses

Industry participants will provide funding to cover their own expenses on this project. In some cases, their services are worth several thousand dollars per field test.

Status: This is an ongoing project that has been under way at a low level of effort since 1990. The meter was designed and lab tested in 1990. It was shown that the concept of using a counterbalanced, rolling float to measure the flow rate in an inclined, partially-filled pipe was sound. An unanticipated effect was also discovered that made the concept work. The flow path of the fluid beneath the rolling wheel creates a Bernoulli-effect suction that holds the rolling float on the surface of the fluid. This very pronounced effect is what prevents the float from skipping off the moving fluid surface.

The design was optimized in a series of lab tests that investigated the effects of wheel shape and size, pivot-arm length, mud weight, mud viscosity, rock chip concentration, and mud line inclination angle. A field prototype was built based on the optimal design, and it was field tested

at the Long Valley Exploratory Well in 1991. A comprehensive field test was conducted, where outflow rates were measured with the rolling float meter, a paddle meter, and an acoustic level meter. Inflow rates were measured with pump stroke counters, rotary speed transducers, magnetic flow meters, and an acoustic Doppler flow meter. The data were recorded for six weeks, during which time the rolling float meter was shown to be accurate within 2%. This was much better than the 15% inaccuracy found for the paddle meter and the 5-10% inaccuracy found for the acoustic level meter.

Deficiencies in the rolling float meter's long-term field survivability were noted, however, which required further development work. The largest problems were: warpage of the vinyl float when the outflow mud temperature reached about 145°F; and corrosion and siezing of the float's bearings. The meter was further refined by developing a cast polyurethane foam wheel and new bearing splash guards. Both designs were tested in the lab and shown to survive spinning for more than 28 days in mud heated to 190°F.

After publication of two conference papers (Schafer *et al.*, 1992 and Glowka *et al.*, 1992b) and a Sandia Report (Loeppke *et al.*, 1992) on the rolling float meter, significant industry interest was evident. As a result, an industry field test program was initiated in which rolling float meters were loaned to eight different service companies for field evaluation. Experience with the meter was mixed. In some cases, the companies never actually tested the meters in the field, and they were returned to us. In other cases, the meters were damaged before they were tested. In cases where they were actually tested, some of them were installed, calibrated, and operated improperly. A few meters were properly installed and operated, and these were found to be reliable, accurate, and of significant interest to those testing them. Some of the industry participants commented that they would be interested in obtaining a rolling float meter commercially.

The advent of field testing related to other projects allowed Sandia to conduct more extensive field testing of the rolling float meter in 1994-95. It was again demonstrated that when properly installed and calibrated, the rolling float meter provides excellent results. Very small fluid losses were shown to be detectable much quicker than with the conventional technique of monitoring the mud pit levels. No bearing problems were encountered, but it was discovered that after more than one month of operation in hot drilling mud, the polyurethane foam float did start to show signs of wear. Also, measurement problems were encountered when the mud line inclination angle was outside the 5-12° range tested in the lab. These tests convinced us of two things: 1) the rolling float meter is a useful instrument that can reduce drilling costs if the final problems are eliminated; and 2) we need to work more closely with industry in demonstrating the proper installation, calibration, and use of the meter in order for it to gain acceptance, generate demand, and become commercially viable.

A second-generation rolling float meter has, therefore, been designed and is scheduled for fabrication in September, 1996. New features include: a stainless steel, finned float to replace the polyurethane float for improved life; a conventional rotary potentiometer to replace the pendulum potentiometer to reduce cost; a miniature gear transmission to increase the sensitivity of the potentiometer output to flow rate; a rotary speed sensor to detect rotation of the float as a diagnostic signal for float operation; and a more rugged pivot arm and housing.

Statement of Work: The first prototype of the second-generation rolling float meter will be fabricated and assembled by the beginning of FY97. The meter will then be tested in Sandia's Wellbore Hydraulic Flow Facility, which is a flow loop with a full-scale, simulated mud return line that was used to develop the first-generation meter. The operation and accuracy of the meter will be confirmed under a variety of mud viscosities and mud-line inclination angles.

The meter will then be tested in the field in cooperation with Epoch Well Logging. Sandia will assist Epoch in installing, calibrating, and using the meter and will work with Epoch in interpreting the resulting data. This test will be conducted in conjunction with a test of a Doppler flow meter being evaluated under another project. The Doppler meter will be used on the inflow line and will provide data that can be compared with data from the rolling float meter to detect possible kicks or lost circulation. The objectives of the test will be to: 1) demonstrate the proper use of the meter to Epoch personnel; and 2) demonstrate the usefulness of the data that results from accurate inflow and outflow measurements.

Any final design changes will be identified during this field test. This includes any changes to improve manufacturability or to reduce fabrication costs. A second prototype unit will be fabricated based on the final design and will then be laboratory and field tested like the first unit. If Epoch decides to build their own rolling float meters, Sandia will provide technical assistance if necessary.

Sandia will also continue to work with the other participating service companies, Tecton Geologic and Int'l Logging Japan, in evaluating rolling float meters in the field. These companies currently have first generation meters and are interested in further field tests with them. If their interest continues, we will offer them an opportunity to test a second-generation design.

Meanwhile, we will continue to pursue commercialization of the meter. As field evidence of the utility of the rolling float meter continues to accumulate, we believe interest will grow in both the geothermal and oil and gas drilling industries. This will create a market that someone will undoubtedly supply with rolling float meters if it becomes large enough. The meter is a very simple device that can be readily fabricated and assembled for very little cost. We will work with and provide assistance to companies interested in manufacturing and marketing the meter to the drilling industry. Even if a company cannot be found to market the meter, we will release complete drawings that will allow any operator, driller, or service company to fabricate the meter using standard machining techniques.

We plan to complete this project in FY97. Additional technology transfer work will undoubtedly continue in future years in the form of technical assistance, but most of our fabrication and sponsorship of field testing should be completed within a year.

Milestones: The following milestones have been adopted for this project:

- *Present paper on rolling float meter testing at GRC conference (10/96).*
- *Complete initial laboratory testing of second-generation rolling float meter (10/96).*
- *Complete first field test of second-generation rolling float meter in cooperation with Epoch Well Logging (12/96).*
- *Identify any final design changes to improve performance and manufacturability (12/96).*
- *Complete final rolling float meter design changes (2/97).*
- *Complete laboratory testing of modified second-generation rolling float meter (3/97).*
- *Complete second field test of second-generation rolling float meter in cooperation with Epoch Well Logging (4/97).*

- *Identify a manufacturer for the rolling float meter (8/97).*
- *Complete final Sandia Report on rolling float meter (9/97).*

Deliverables: This project will result in the following deliverables:

- *Drawings for an accurate, reliable rolling float meter design that can be fabricated by a geothermal operator, service company, or manufacturer.*
- *Possible commercial availability of the rolling float meter.*
- *Conference papers and a final report on the design, testing, and operation of the rolling float meter.*

Doppler Flow Meter for Inflow Rate Measurement

Program Area: Lost Circulation Technology

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Justification: The inflow rate transducer is one half of the hardware system needed to detect and characterize lost circulation zones, the other half being the outflow rate transducer. All of the uses listed under the rolling float meter project for a good outflow measurement system, therefore, also apply to the inflow rate measurement technique. Measuring the inflow rate to the well is even more important than measuring the outflow rate, however, because the inflow rate controls other parameters, such as bit hydraulics, bit cleaning and cooling, and hole cleaning. Inflow rate is, therefore, almost always measured in geothermal drilling operations, but not very accurately. The industry standard here is the mud pump stroke counter, which gives the theoretical volumetric pumping rate if the efficiency of the pump is accurately known. The problem is that the pump efficiency changes constantly, so flow rates based on the pump stroke counters are never very accurate. Some pump efficiency changes, in fact, are indications of pump problems, which occur frequently and are completely undetectable with a pump stroke counter. This is because the counter indicates what the pump should be delivering, not what it is actually delivering.

Measurement of the flow rate in a drill rig inflow line is challenging because of the abrasiveness of the drilling fluid. Any intrusive device will eventually erode away and could be pumped downhole and lodged in a bit nozzle. The high-pressure requirement downstream of the mud pump eliminates one of the best types of non-intrusive flow meters for that location from consideration, namely the magnetic flow meter. Magnetic flow meters do work well on drill rigs if they can be placed on the suction side of the mud pump, but this is not always possible because of space limitations. Furthermore, the cost of magnetic flow meters, roughly \$1000 per inch of pipe diameter, is prohibitive in most cases for this application.

A Doppler flow meter, on the other hand, has all the desirable characteristics for a drill rig inflow measurement device. It is non-intrusive, relatively low-cost, can be easily and quickly installed on the drill rig standpipe, and can be easily moved from rig to rig. In operation, an acoustic signal is directed from the transmitter through the pipe wall and into the fluid, where it reflects off particles in the fluid and is picked up at the receiver. The Doppler shift in the received signal is proportional to the velocity of the particle and, hence, the fluid. Averaging the various Doppler shifts received from particles across the pipe results in an average fluid velocity that, when multiplied by the flow area, yields the volumetric flow rate.

Under this project, a new type of commercial Doppler flow meter that shows considerable potential is being evaluated in the laboratory and the field as a potential substitute for the pump stroke counter. Peek Measurements markets its Polysonics flow meters that use the Doppler technique plus advanced noise rejection algorithms to measure the flow in pipes under high ambient-noise conditions. We have conducted numerous tests to date that indicate that the meter shows considerable promise for drill rig applications.

Estimated cost savings resulting from the use of the Doppler flow meter are as follows. First, it is recognized that an accurate inflow meter would share in the 1% drilling cost savings estimated for the rolling float meter project. Beyond that, additional improvements and savings that might result from accurate inflow measurements include: early detection of pumping problems that may prevent costly breakdowns or permit pump maintenance to be more cost-effectively scheduled; proper bit hydraulics, resulting in longer bit life and faster rock penetration; proper hole cleaning that might prevent stuck drill pipe or slow down the rate of rock penetration; and the ability to accurately spot lubricating fluids at a stuck pipe location to free it. Each day of time the inflow meter saves over the life of the well represents about 1/2% of the total well cost.

Project Participants:

- Sandia National Laboratories: Lead laboratory and field evaluation; work with industry to evaluate the meter; document and publish results.
- Peek Measurements, Inc.: Cooperate with meter evaluation effort; provide field application support.
- Epoch Well Logging: Participate in field evaluation effort.
- Tecton Geologic: Participate in field evaluation effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$80k	Sandia salary, hardware, travel, field expenses

Industry participants will provide funding to cover their own expenses on this project. In some cases, their services are worth several thousand dollars per field test.

Status: This is an ongoing project. It has been under way at a very low level of effort since 1988, when we attempted to use an early 1980s-model Doppler flow meter from our laboratory to measure inflow rates on a wireline core rig. The meter did not function properly in that environment because rig noise overwhelmed the meter's acoustic signal, causing the indicated rate to drift.

Another attempt was made in 1991 to use a state-of-the-art Doppler flow meter on the rig used to drill the Long Valley Exploratory Well. Improvements in the technology during the previous ten years resulted in higher signal strength and a hope for better performance; however, the meter did not function well, presumably again because of drill rig noise (Schafer *et al.*, 1992). Another attempt was made in 1993 on a wireline coring rig at Steamboat Hills, NV. Both magnetic flow meters and Doppler flow meters were installed on the inflow and outflow lines of the rig. The magnetic flow meters functioned well, but the Doppler meters again experienced difficulties with changing rig noise, as confirmed by recorded noise measurements.

We were conducting preliminary lab tests in 1994 to determine if there was a way to overcome the rig noise problem when Peek Measurements, Inc., introduced a new-generation Doppler flow meter. Their DDF Doppler meter performs a fast Fourier transform (FFT) on the Doppler signal and displays the signal strength as a function of frequency. Rig noise is readily apparent in this display and can be filtered out of the signal if it falls within the Doppler frequency band. We acquired a meter from Peek and tested it on a geothermal drill rig. Despite a few problems with

the initial software, the flow meter demonstrated reliable and accurate inflow measurement capabilities. We also purchased a later model of the meter that has higher signal strength and have successfully tested that meter in the field as well. Altogether, we have tested the two meters on two large drill rigs, two wireline core rigs, and a producing slimhole. In all applications, the meters have performed well, particularly the model with increased signal strength (Whitlow *et al.*, 1996).

Statement of Work: We have completed sufficient laboratory and field testing of Peek's DDF Doppler flow meter to conclude that it can be used to provide accurate and reliable inflow data on a drill rig. It will take more than our recommendation, however, to get the flow meter accepted and used for this application. We will work with industry participants to demonstrate the meter's proper use and the utility of its data. We will assist Epoch Well Logging in installing and using the meter and interpreting the resulting data. This test will be conducted in conjunction with a test of a rolling float meter being evaluated under another project. The rolling float meter will be used on the outflow line and will provide data that can be compared with data from the Doppler flow meter to detect possible kicks or lost circulation. The objectives of the test will be to: 1) demonstrate the proper use of the meter to Epoch personnel; and 2) demonstrate the usefulness of the data that results from accurate inflow and outflow measurements. Sandia extends an invitation to any operator or service company interested in a similar demonstration of the meter at their field site, because we always welcome additional field test opportunities.

In addition to conducting field demonstrations of the meter's use, we plan to publish the laboratory and field test results and present them at pertinent conferences. This should encourage others to evaluate the meters in their drilling operations and thus create demand that could result in their widespread use.

We plan to complete this project in FY97. Additional technology transfer work will undoubtedly continue in future years in the form of endorsement of the meter and assistance in its operation on drill rigs, but most of our sponsorship of field testing should be finished within a year.

Milestones: The following milestones have been adopted for this project:

- *Present paper on Doppler flow meter testing at GRC conference (10/96).*
- *Complete first field test of Doppler flow meter in cooperation with Epoch Well Logging (11/96).*
- *Complete second field test of Doppler flow meter in cooperation with Epoch Well Logging (4/97).*
- *Complete final Sandia Report on field evaluation of the Doppler flow meter (9/97).*

Deliverables: This project will result in the following deliverables:

- *Conference papers and a final report on the laboratory and field evaluations of the Doppler flow meter.*
- *Possible use of the Doppler flow meter by the geothermal and oil and gas drilling industries.*

Expert System for Lost Circulation Control

Program Area: Lost Circulation Technology

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The rolling float meter and Doppler flow meter projects will provide readily available and accurate inflow and outflow measurements for the drilling industry. The raw data provided by these instruments must be interpreted. With practice and experience, it should be possible for a good driller or drilling engineer to use this data to detect and diagnose drilling hydraulic problems, such as lost circulation and gas or steam kicks. The adeptness with which the driller or drilling engineer uses this information, however, will depend on the individual and his or her familiarity with the drilling conditions present in the field. Both need accurate raw data and, when possible, interpreted data to help them make good decisions.

To assist the driller and drilling engineer in interpreting the drilling hydraulic data, it is possible to develop expert system software that monitors the inflow and outflow rates along with other rig parameters (such as weight-on-bit, drilling torque, rotary speed, penetration rate, pump speed, and standpipe pressure) and interprets the data to identify anomalies that may occur during drilling. All of this data is presently recorded during most geothermal drilling operations. Any anomalies that occur could be brought to the attention of the driller and/or drilling engineer. Standard and company-specific instructions could be recorded for handling particular problems. Even if the driller or drilling engineer is not required to follow the instructions suggested by the software, a logical analysis of the present situation would be welcomed by anyone who must make important decisions at any hour of the day or night.

Such an expert system is being developed via this project. Under contract to Sandia, Tracor Inc. is modifying its existing expert system developed for detecting and controlling gas kicks in petroleum wells. The system will monitor all necessary parameters and analyze any fluid losses or gas/steam kicks detected. Expert advice on how to deal with the lost circulation or kick situation will ultimately be incorporated into the system. The system may also be extended to detect and analyze a wide variety of potential rig problems that are discernable in data that is routinely collected in most geothermal drilling operations.

Estimated cost savings resulting from the use of the expert system are as follows. First, it is recognized that the expert system would share in the 1% drilling cost savings estimated for the rolling float meter project. Beyond that, additional improvements and savings that might result from an expert system that monitors a wide variety of rig functions include: prevention of drillstring twist-offs caused by abnormal drilling torque; monitoring of weight-on-bit and rotary speeds to ensure proper bit operation and to maximize bit life and penetration rates; and detection of excessive speed by the driller in moving the drill pipe, which can lead to induced lost circulation. Each day of time the expert system saves over the life of the well represents about 1/2% of the total well cost.

Note that this project is a Geothermal Drilling Organization (GDO) project. It is described here rather than in the GDO section of this document because Sandia initiated the project as part of its lost circulation program.

Project Participants:

- Sandia National Laboratories: Coordinate work between Tracor and CalEnergy; conduct laboratory testing and assist in field evaluations; document and publish results.
- Tracor Inc.: Modify existing software to develop geothermal-specific expert system; participate in lab and field testing.
- CalEnergy: Provide data from one of its drilling operations to use in software development; provide access to drilling operations to test prototypes of the system developed.
- Other Service Company (to be determined): Participate in field evaluation effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$55k	Sandia salary, hardware, travel, field expenses; Tracor contract for \$50k (\$27k remaining to be spent in FY97).
DOE Geothermal - Drilling Tech.	FY98	\$200k	Tracor contract for \$200k.
DOE Geothermal - Drilling Tech.	FY99	\$200k	Sandia salary, hardware, travel, field expenses; Tracor contract for \$150k.

Tracor is currently under a cost-shared contract with Sandia for Phase 1 this work. The funding level shown above for Phase 1 includes \$27k that Tracor will invoice from the Sandia contract in FY97. Tracor has contributed \$25k of their own funding to the Phase 1 effort. In addition, CalEnergy has contributed data worth approximately \$25k to the Phase 1 effort; these data are being used by Tracor in the model development. If Phase 1 is successful, the second phase will be conducted in FY98, and the third phase in FY99.

Status: This is an ongoing project. It has been under way since the middle of FY96, when it was approved and initiated as a Geothermal Drilling Organization project. The project was developed by Sandia when it was recognized that Tracor's expert system for gas-kick detection in petroleum wells had most of the characteristics needed by a lost circulation expert system for geothermal drilling. Some type of software system was needed to help interpret the inflow and outflow data in real time, and, in fact, Sandia had studied the use of an expert system for lost circulation control as far back as the early 1980s (Christiansen, 1987).

A GDO proposal was written that divides the project into three phases. Phase 1 is Proof of Concept, where Tracor will make minor modifications to their gas-kick expert system to make it functional for lost circulation conditions in geothermal drilling. They will apply existing field data that contains inflow and outflow rates as well as other rig parameters like weight-on-bit, rotary speed, and drilling torque. They will then assess the expert system's capability of using the data to accurately diagnose the lost circulation conditions associated with the various loss zones covered by the data.

Following presentation of the proposal to the GDO membership, CalEnergy volunteered to make their field data available for Phase 1, an estimated \$25k contribution. Tracor volunteered to contribute \$25k of their internal R&D money to the effort. With the industry cost-share requirement met, the GDO membership then voted to allocate \$50k of DOE funds to the project. A Sandia contract was placed with Tracor in May, 1996, and the CalEnergy data were transferred to Tracor. Phase 1 is scheduled to be completed in FY97.

If Phase 1 is successful in demonstrating the utility of the expert system in detecting and diagnosing loss zones, the GDO will then consider endorsing Phase 2 of the project, System Development. Here Tracor will fully develop the system to use as many data channels as possible and to monitor rig operations for a variety of possible problems, including lost circulation and other parameters of interest to GDO members. In Phase 3, Testing and Implementation, laboratory and field tests will be conducted to evaluate and fine-tune the performance of the expert system in the field. The deliverable will be a working software system that will be given to participating GDO members and will be otherwise commercially available from Tracor.

Statement of Work: The first phase of the project is a proof of concept study, where Tracor is taking their existing gas-kick expert system, modifying it where necessary to model a geothermal well, and entering the CalEnergy field data into the system to demonstrate how the system would operate in the field. This phase will be completed in FY97. It consists of the following tasks: review of the CalEnergy drilling database with Sandia; development of the preliminary data interpretation algorithms; assessment of the algorithms' capabilities for accurately detecting and diagnosing loss zones in the CalEnergy database; and documentation of the effort with both a written final report and a demonstration of the system to GDO members.

Phase 2, System Development, will be conducted in FY98 if Phase 1 is successful. Under Phase 2, the following tasks will be completed: develop functional specifications of the expert system that meet all participants' expectations; modify the set-up and standard data portions of the software to reflect geothermal drilling practices; develop system modules for monitoring incoming rig data and detecting abnormal conditions; develop the expert system shell knowledge base and an advisor module that correctly specifies appropriate operating procedures contained in the knowledge base. The deliverable of Phase 2 will be a prototype expert system.

In Phase 3, Testing and Implementation, the prototype system will be tested in the lab and in the field. Sandia's Wellbore Hydraulics Flow Facility will be used to simulate several hydraulics-related events for testing the system response. When it is ready, the expert system will be taken to the field and tested in cooperation with a geothermal operator and mud-logging service company. Final modifications to the system will then be made and re-tested where necessary. The deliverable of this phase will be a working, field-tested expert system for geothermal drilling.

Milestones: The following milestones have been adopted for this project:

- *Complete development of preliminary data interpretation algorithms (1/97).*
- *Complete assessment of expert system's detection and diagnosis capabilities using existing field data (3/97).*
- *Complete Phase 1 expert system work with software ready to demonstrate to the industry (6/97).*
- *Complete initial expert system demonstrations for potential industry users (8/97).*

- *Complete Sandia Report on Phase 1 expert system work (9/97).*
- *Initiate Phase 2, System Development of the expert system (11/97).*
- *Complete expert system functional specifications and reach agreement with all participants (2/98).*
- *Complete development of system modules for monitoring incoming data and detecting abnormalities (5/98).*
- *Complete development of the expert system shell knowledge base and an advisor module (9/98).*
- *Complete Sandia Report on Phase 2 expert system work (9/98).*
- *Initiate Phase 3, Testing and Implementation of the expert system (10/98).*
- *Complete lab testing of expert system at Sandia (12/98).*
- *Complete first field test of expert system (2/99).*
- *Complete final modifications to expert system (6/99).*
- *Complete final field test of expert system (9/99).*
- *Complete Sandia Report on Phase 3 expert system work (9/99).*

Deliverables: This project will result in the following deliverables:

- *Commercially available expert system software for lost circulation diagnosis and control.*
- *Conference papers and reports on the development and testing of the expert system.*

Automated Mud Monitoring System

Program Area: Lost Circulation Technology

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The fractured, under-pressured nature of geothermal reservoirs often makes control of the drilling fluid properties even more critical than for oil and gas, because increases in either mud weight or viscosity can induce lost circulation. Moreover, the high temperatures encountered downhole in a geothermal well lead to a degradation of mud properties that is not experienced in typical oil and gas wells. In both geothermal and oil and gas drilling, automated monitoring of mud properties would ensure more precise control of those properties.

For instance, mud weight (density) and viscosity are the two most important drilling fluid properties that must be controlled. Drilling with excess mud weight can lead to formation fracturing and induced lost circulation. Mud weights that are too low can lead to gas or steam kicks. If the mud viscosity is too high, excess frictional pressures in the drill pipe and annulus can result, which wastes energy and can also lead to formation fracturing and induced lost circulation. If the viscosity is too low, hole cleaning may be inadequate and can lead to stuck drill pipe. Monitoring and precisely controlling these two mud properties could significantly improve the drilling process, allowing techniques such as under-balanced drilling to be used more effectively.

Under this project, techniques for automated monitoring of mud density and viscosity are being developed. Two techniques for density measurement are under evaluation. One technique uses precise pressure gradient measurements in a mud-tank-mounted column of static drilling fluid to calculate the mud density. The other technique employs a resonating Coriolis mass-flow meter to measure both the density and inflow rate.

Two techniques for viscosity measurement are also under evaluation. One technique uses a Sandia-developed thickness shear-mode (TSM) crystal resonator to measure viscosity directly. The second technique uses accurate measurement of frictional pressure drop in the flow line to calculate the mud viscosity and frictional pressure drops downhole. The most promising of these techniques will be developed and field tested under this project.

The automated mud-monitoring system could be used alone or in conjunction with the expert system under development in another project. When fully deployed, the system has the potential for avoiding induced lost circulation, preventing and helping to control gas or steam blow-outs, and avoiding stuck pipe due to inadequate hole cleaning. Any one of these events could easily cost one or more days of rig time. Each day of time the mud monitoring system saves over the life of the well represents about 1/2% of the total well cost.

Project Participants:

- Sandia National Laboratories: Conduct design, fabrication, and lab testing of mud property measurement hardware; work with industry to evaluate the new hardware and techniques in the field; document and publish results.
- Fischer-Rosemont: Provide Coriolis mass-flow meter to Sandia for evaluation on drill rigs.
- Epoch Well Logging: Participate in field testing effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$80k	Sandia salary, hardware, travel, field expenses
DOE Geothermal - Drilling Tech.	FY98	\$100k	Sandia salary, hardware, travel, field expenses

Fischer-Rosemont has offered to loan us at no cost a Coriolis mass-flow meter for evaluation under this project, saving the project approximately \$10k. Epoch Well Logging will provide funding to cover its own expenses on this project. Their services are sometimes worth several thousand dollars per field test.

Status: This is an ongoing project. It has been under way since the middle of FY96, when work began to explore the feasibility of measuring drilling mud viscosity using a TSM crystal resonator system under development at Sandia for another purpose (Spates and Mansure, 1995). The resonator interacts with the mud by propagating a shear wave into the mud and measuring changes in the mud response with changes in viscosity. The crystal is electrically driven by an RF voltage applied to electrodes deposited on opposite faces of the crystal. The power required to drive the crystal at a pre-determined frequency is a function of the mud rheology. Initial tests have shown that the crystal response is, in fact, quite sensitive to changes in mud viscosity, but certain problems remain to be overcome. One of these is preventing the mud from sticking to the crystal face. Applying a low voltage to charge the crystal face may accomplish this because drilling clays are susceptible to electrical charges. Another challenge is to determine whether the responses seen in the initial tests are repeatable and can be calibrated to provide quantitative data.

The other viscosity measurement technique that will be evaluated is potentially very simple. It includes measuring both the borehole's inflow rate and the frictional pressure drop across a section of flow line between the mud pumps and the rig. The data are used together with pressure-drop models for the flow of drilling fluid to calculate the mud viscosity. That number is useful itself for detecting changes in viscosity over time, indicating a need to condition the mud. The data should also be useful because it can be used to estimate downhole pressure drops, such as in the drill pipe and annulus. Simple drilling engineering calculations could be done automatically by an expert system, which could show an alarm if the downhole pressure drops exceed proper limits. For example, the driller could be notified when mud viscosity exceeds some pre-set level or when the calculated annular pressure drop reaches levels that could lead to induced lost circulation.

One technique for measuring mud density, conceived in FY96, utilizes a very simple device, in principle. It consists of a portable stilling well that is placed in the drilling mud tank to obtain a measurement. By accurately measuring the hydrostatic pressure differential between the bottom and top of the stilling well, the density of the fluid in the stilling well can be calculated.

The other technique that will be evaluated for measuring the drilling mud density involves a new resonating Coriolis mass-flow meter from Fischer-Rosemont. The meter determines density by measuring the resonant frequency of a U-tube of known volume (period of vibration is proportional to the mass of fluid in the tube). The Coriolis force as the fluid flows around the bend imparts a rotational torque to the tube. Thus the mass flow rate of the fluid can be determined by measuring the angular rotation of the tube. Discussions with Fischer-Rosemont during FY96 have indicated that the meter has very high accuracy and is operable in drilling mud. They have agreed to loan us a meter to evaluate on geothermal drilling rigs in the field. Although the meter is rather expensive (around \$10k for the size needed), it does measure both mud density and inflow rate, so it may be cost-effective as a dual-purpose instrument.

Statement of Work: Work on this project will continue at a modest level in FY97 and will concentrate on determining the feasibility of all four candidate techniques described above. This will, in most cases, probably require the fabrication or acquisition of one or more instruments and evaluation of the technique both in the laboratory and in the field. Sandia's Wellbore Hydraulics Flow Facility will be used for the lab tests. This facility consists of a versatile, full-scale drilling mud flow loop that simulates the inflow and outflow lines on a drill rig. Any of the techniques that continue to show promise will then be evaluated in the field in cooperation with Epoch Well Logging, which has volunteered access to its mud logging operations.

By the end of FY97, a decision will be made as to which techniques, if any, will be further developed and transferred to industry in FY98. A comparable level of effort is anticipated for FY98 as in FY97. We will refine the selected techniques, publish the results of the tests to date, and try to generate interest in their use among the drilling community. We will continue to work with Epoch and other interested industry partners in evaluating the techniques in the field. Commercial suppliers of any hardware associated with the techniques will be sought. Our effort in this project is expected to be completed by the end of FY98.

Milestones: The following milestones have been adopted for this project:

- *Complete design and fabrication of the differential-pressure mud-weight meter (10/96).*
- *Complete initial laboratory testing of differential-pressure mud-weight meter (11/96).*
- *Complete initial laboratory testing and analysis of the differential-pressure mud-viscosity meter (11/96).*
- *Complete first field test of both the differential-pressure mud weight and mud viscosity meters (1/97).*
- *Select method for preventing mud fouling of the TSM crystal resonator viscosity meter (3/97).*
- *Complete laboratory testing of Coriolis mass-flow meter (3/97).*
- *Complete first field test of Coriolis mass-flow meter (5/97).*
- *Complete initial feasibility assessment of the TSM crystal resonator viscosity meter (6/97).*
- *Complete Sandia Report on feasibility studies and selection of surface mud monitoring techniques (9/97).*
- *Complete final design changes to selected mud monitoring techniques (12/97).*

- *Complete final field testing of selected mud monitoring techniques (6/98).*
- *Complete final Sandia Report on selected mud monitoring techniques (9/98).*

Deliverables: This project will result in the following deliverables:

- *Drawings of equipment needed for an automated mud monitoring system.*
- *Possible commercial availability of various components of an automated mud monitoring system.*
- *Conference papers and a final report on the design, testing, and operation of the automated mud monitoring system.*

Drillable Straddle Packer

Program Area: Lost Circulation Technology

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Justification: It is difficult to seal lost circulation zones that are off bottom because the open-end drill pipe technique of cementing does not allow for precise placement of the cement. In large-diameter wellbores, the cement does not necessarily flow into the loss zone, but rather channels through the lower-density drilling fluid beneath it to sink to the bottom of the wellbore. For a good seal, enough cement must be pumped to fill the entire wellbore beneath the loss zone, then enough to plug the zone itself. If there were some way to "force feed" the loss zone with cement, it could be assured that the cement goes into the loss zone; consequently, more reliable seals would be obtained, much smaller cement volumes could be pumped, and the wellbore would have less cement to drill out, saving time and mud conditioning costs.

Under this project, a downhole tool is being developed for this purpose. The drillable straddle packer is a low-cost, low-pressure, cement-inflatable packer assembly that is left downhole and is drilled through when the cement has set. Several features distinguish the DSP from conventional packers. First, the DSP is a low-pressure packer, meaning that the flexible fabric bags are designed to withstand only 20-50 psi of pressure differential. This should be sufficient for this purpose because it is not necessary to achieve total zonal isolation, merely guidance of the cement. The bags can also slightly pressurize the wellbore region at the loss zone (between the bags), if necessary, to force the cement into the loss zone. If the zone readily accepts the cement, of course, no excess pressure will develop in that region of the wellbore. The inflated bags also help prevent wellbore fluids that may be produced above or below the loss zone from entering the loss zone and diluting the cement placed there.

Secondly, the packer's inflation mechanism is exceedingly simple, using no downhole valving or controls. The bags are inflated by the differential pressure that develops across the cement ejection ports located on the pipe between the two bags as the cement is ejected into the wellbore between the bags. The bags' inflation pressure can thus be controlled from the surface by controlling the flow rate of cement pumped downhole. Third, the DSP has a low cost. We estimate that the entire packer assembly can be made for less than \$1500. Fourth, the packer assembly is drillable. After a pre-determined volume of cement has been pumped, a brass ball is dropped down the drillstring, which unlatches the packer assembly from the drillstring. The packer can thus be left downhole, filled with setting cement, until drilling resumes.

The estimated cost savings achievable with the DSP were derived from a detailed time-line and cost analysis of conventional and DSP cement treatments (Glowka, 1990a). This analysis predicted a typical conventional cement plug to cost \$16,600. The estimated savings resulting from use of the DSP are derived from an assumed reduction in the volume of cement pumped and improved cement effectiveness. For instance, if it is assumed that only 100 ft³ of cement are pumped using a DSP (versus 300 ft³ with a conventional cement treatment), then a 10% savings in the cost of each plug results. This alone represents 1-2% of the total well cost. If it is further

assumed that the DSP is so effective that only one plug per loss zone is required, whereas two plugs per zone may be required without the DSP, then a 36% cost savings per loss zone results. This represents another 3-7% reduction in wellbore costs. Savings with the DSP could be even greater if it produces cement plugs that are of such quality that they do not fail later in the drilling process, as is common with conventional cement plugs. Each separate plug the DSP eliminates would save about 1/2% of the total well cost. Assuming two such plugs are eliminated during the the drilling of each well, another 1% of the total well cost could be saved. Altogether, the DSP could save about 5-10% of the total well cost.

Project Participants:

- Sandia National Laboratories: Complete design, fabrication, and lab testing of drillable straddle packer; work with industry to evaluate the packer in the field; document and publish results.
- Geothermal Operator (to be determined): Participate in field testing of the drillable straddle packer.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$390k	Sandia salary, hardware, travel, field expenses
DOE Geothermal - Drilling Tech.	FY98	\$300k	Sandia salary, hardware, travel, field expenses

A geothermal operator will be sought which will volunteer the use of its well to field test the DSP. In most cases like this, the industry partner would cover its own rig and cementing expenses during the field test, and Sandia would cover additional costs associated with the use of the DSP. We are flexible in negotiating the terms of field testing, however, so other arrangements are possible.

Status: This is an ongoing project. It has been under way at a low level of effort since FY90, when this drillable straddle packer concept was developed. The design of the packer bags began with a search for an appropriate material. It became clear early in this process that woven fiberglass fabric, coated with silicone on both sides, was a cost-effective material that had sufficient strength for this application. Several types of fabric were acquired and tested in a tensile testing device to determine tensile strength, and an optimal fabric type was selected (Glowka *et al.*, 1992a; Glowka *et al.*, 1993a)).

Several ways of manufacturing the bags were investigated. In all configurations, a tube with a diameter slightly larger than the wellbore diameter was sewn from the fabric, with a single longitudinal seam. Stress analysis of the bag showed that if it is properly inflated, this seam is not heavily stressed. Fastening the ends of the fabric tube to a small (2-inch) diameter aluminum pipe was a design issue. The technique finally chosen is actually a commercially available swaging technique developed by Peterson Products of Fredonia, WI, for their pipeline and plumbing stoppers. The technique employs an aluminum tube that is swaged in place over the ends of the fabric tube and around the aluminum pipe. We have worked with Peterson to optimize the design of 16-inch-diameter bag assemblies using the fiberglass fabric we selected. The final design has been extensively lab tested in Sandia's Packer Test Facility using water, and has a reliable bursting pressure of 50 psi. This will allow the bag to be operated at 20 psi with a significant safety margin (Glowka, 1995b).

The Packer Test Facility was built for this project in 1990 (Glowka, 1991). It consists of a 14-ft-high, vertical section of 16-inch casing, with a lid on top and three side penetrations that simulate fluid production and lost circulation zones. The packer bags were placed in the simulated wellbore and inflated by flowing into the bags at rates typical of those used in field cementing operations (100-200 gpm). Increasing the flow rate caused an increase in the bag inflation pressure until the bag burst. Many design improvements were made and tested in this facility before we finally exceeded our 40-psi burst pressure design goal in 1994.

During the 1990-94 time period, we also designed, fabricated, and tested other components of the DSP assembly. The central part of the DSP consists of two bags and a pipe that separates them by a pre-determined distance. A plastic or aluminum tube shroud assembly was designed that slips over the bags to protect them from abrasion during the trip downhole. Once downhole, a ball is dropped down the drillstring and causes the shroud assembly to be pumped downward, uncovering the bags. The piston mechanism that deploys the shroud also serves as a simple means for shutting off a port that is open on the trip downhole to allow wellbore circulation to be established when necessary. Shutting off the circulation port redirects the flow to inflate the bags and then exit through the cement ejection ports between the bags. This assembly was also successfully tested in the Packer Test Facility and is ready for field testing. (It should be noted that if a bit stabilizer is used on the drill pipe above the packer assembly, the bags would be centralized on the trip down and would not contact the wellbore wall. Hence, this shroud assembly may not be necessary, unless the hole is very crooked or there is some reason a bit stabilizer cannot be used.)

The grapple mechanism that connects or disconnects the packer assembly with the drill pipe was also successfully tested in the Packer Test Facility. It was shown that the mechanism reliably operates when the brass ball is placed in the flow line above the grapple mechanism. The pressure that must be applied to the ball to activate the grapple mechanism can be varied from 100 to 500 psi by selecting the proper size shear pin for the grapple mechanism. The grapple was also designed so that once the packer assembly is released, relief ports are opened above the ball and piston plug that remain in the grapple. These ports allow the cement remaining in the drill pipe to be flushed into the wellbore, and wellbore circulation can be established at any time as the pipe is tripped out of the hole.

As far as we could tell from the successful tests of the drillable straddle packer in the laboratory, it appeared to be ready for the field in late 1994 (Glowka, 1995). Questions remained on the part of some industry observers, however, about the utility of the concept and the effectiveness of the fabric bags in sealing the loss zone. It was difficult to successfully answer those questions when the DSP had never been tested with cement; and we did not feel comfortable suggesting that a field test be conducted until such testing could be done. We cannot pump cement in our Packer Test Facility, so it was decided that another approach was necessary.

The Engineered-Lithology Test Facility was built for this project in 1994-95. It consists of a 15-ft X 15-ft X 15-ft test section, walled on three sides and open in the front. Various geologic materials can be emplaced to a height of 15 ft in the test section. In the tests conducted to date in support of this project, we emplaced three 1-ft-thick gravel layers, sandwiched between layers of clay, in the test section. The gravel and clay layers represented permeable and impermeable zones in the underground strata. Stacked sections of 16-inch concrete pipe simulated a wellbore. The sections were spaced apart at the gravel layers to simulate horizontal fractures of known thickness in the wellbore wall. The gravel layers were connected to an external piping network so that fluid could be pumped into or out of each of the gravel zones. This arrangement allows the layers to simulate fluid production or lost circulation zones. Thermistors and pressure transducers were emplaced in the gravel layers to allow monitoring of the cement location during

and after the tests. The emplaced clay and gravel layers were mined back after the tests to map the location of the cement.

Three tests have been run to date in the ELTF. In the first two, an open-end pipe was placed at the middle gravel layer, which simulated a loss zone and was connected to atmospheric pressure through the external facility piping. Cement was pumped at a rate typical of conventional cementing practices. The bottom and top gravel layers simulated additional wellbore volume below and above the loss zone and were closed off to the exterior piping. In both tests, the cement flowed to and sealed the bottom gravel layer first, then flowed into and sealed the middle, then the top gravel layers. These test results show that gravity dominates the flow of cement in large-diameter wellbores, and cement plugs will develop from the bottom of the wellbore up.

The third ELTF duplicated the second test, except that a drillable straddle packer assembly was attached to the lower end of the open-end drill pipe so that the middle gravel layer was straddled by the two packer bags. The cement was pumped as in the first two tests. Both the thermistors and the post-test excavation showed that the bags properly inflated and confined all the cement to the region between the bags and the straddled gravel zone. The wellbore section enclosing the packer bags was removed intact from the facility and sawed in half lengthwise. It was discovered that the bags had indeed inflated properly and sealed tightly against the wellbore wall. No leakage of cement either above or below the bags was found. Even though the packer was disconnected from the cement flow line before the cement set up, as it would be in a real wellbore, the bags showed no sign of relaxing in the wellbore or permitting cement leakage. This test was considered a complete success.

These test results indicate that the drillable straddle packer is ready for field testing. We will try to interest a geothermal operator in such a test next fiscal year. In the meantime, we will continue with a modified series of cementing tests in the ELTF to help answer other questions about the operation of the packer assembly and conventional cementing practices.

Statement of Work: A valuable series of tests will be run in the ELTF in FY97 to support the drillable straddle packer project. Instead of using concrete pipe, gravel, and clay zones to simulate a downhole wellbore environment, however, we will use large-diameter plexiglass tubing, mounted upright inside the ELTF structure, to simulate the wellbore. At three elevations along the simulated wellbore, penetrations through the side wall will be made to simulate fractures that carry the fluids to or away from the wellbore, through hoses to a tank or from a pump. Cement can be injected into the wellbore both with and without a drillable straddle packer. The pumping process can be video-taped to document the flow of cement throughout the wellbore. Fluid that flows out the simulated loss zone can also be easily measured in a holding tank plumbed to that zone. At least part of the clear simulated wellbore will be sacrificed in each test. After laying the wellbore on its side, it can be cut with a rotary diamond concrete saw to expose various cross-sections for diagnosis of the test.

The first two tests with this test configuration will duplicate two of the ELTF tests conducted previously with full-scale gravel zones. In these tests, the bottom and top penetrations to the wellbore will be closed and the middle penetration will be open. In the test with open-end drill pipe, the flow of the cement will be viewed directly and videotaped to determine whether the cement flows directly into the loss zone or first fills the wellbore volume below the loss zone. In the test with the DSP, we will view and videotape the inflation of the packer bags and the flow of cement into the wellbore and loss zone.

Following these two tests, we will complete a series of four additional tests in plexiglass wellbores that address the following issues: the effects of fluid being produced at other wellbore zones on both conventional and DSP cementing techniques; the effects of cement free-fall in the

drill pipe above the DSP; and the effects of wellbore diameter on the effectiveness of conventional and DSP cementing techniques. These tests should help define the applications where the DSP would be useful.

We will also begin in FY97 to search for a field test opportunity for the DSP. Although a test in a geothermal well experiencing lost circulation would be ideal, we may take advantage of any suitable opportunity to inflate a packer with cement in a wellbore where it could be re-drilled to evaluate its integrity. Although it is possible that a field test could be run in FY97, we will approach the opportunity slowly and with careful planning in order to test the DSP correctly.

We plan to complete one or more field tests of the DSP in FY98. The ideal opportunity would be an initial field test, followed by a period to correct any deficiencies in the DSP, then followed by another one or more field tests. Our testing schedule will depend on too many unknown factors to be estimated accurately at this time.

It is planned to essentially complete this project by the end of FY98, although some technology transfer activities will undoubtedly extend beyond that time. If we can secure field testing opportunities, we should be able to complete within one year all the required testing to attract commercialization interests.

Milestones: The following milestones have been adopted for this project:

- *Complete open-end drill pipe cementing test in plexiglass with top and bottom zones closed (12/96).*
- *Complete DSP cementing test in plexiglass with top and bottom zones closed (12/96).*
- *Initiate discussions with geothermal operators regarding DSP field testing (1/97).*
- *Complete open-end drill pipe cementing test in plexiglass with top zone producing fluid into the wellbore and bottom zone closed (4/97).*
- *Complete DSP cementing test in plexiglass with top zone producing fluid into the wellbore and bottom zone closed (4/97).*
- *Present results of DSP lab testing at DOE Program Review (4/97).*
- *Complete open-end drill pipe cementing test in plexiglass with 8-inch simulated wellbore (8/97).*
- *Complete DSP cementing test in plexiglass with 8-inch simulated wellbore (8/97).*
- *Identify a field testing opportunity for the DSP (9/97).*
- *Present results of DSP lab testing at GRC Conference (10/97).*
- *Complete first field test of DSP (11/97).*
- *Complete refinement of DSP (3/98).*
- *Complete second field test of DSP (4/98).*
- *Identify DSP supplier (9/98).*

- *Complete final Sandia Report on DSP (9/98).*

Deliverables: This project will result in the following deliverables:

- *Drawings for a drillable straddle packer that can be fabricated by an operator, service company, or manufacturer.*
- *Possible commercial availability of the drillable straddle packer.*
- *Conference papers and a final report on the design, testing, and operation of the drillable straddle packer.*

Field Evaluation of Cementitious LCM

Program Area: Lost Circulation Technology

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Justification: Portland cement with silica added for temperature stability has long been the material of choice for lost circulation treatment in geothermal drilling. It is relatively low-cost, pumpable, predictable (assuming the downhole temperature and fluid chemistry are known), and can be drilled relatively easily after it sets. Its disadvantages include a long setting time and its incompatibility with drilling mud when it has been drilled into fines.

The setting time of cement is generally accelerated by high temperatures. To prevent premature setting that might stick the drill pipe, a retarder is added to intentionally slow the reaction. The cement setting time, before the cement is hard enough to drill, typically ranges between 6 and 10 hours and entails significant waiting time for the rig. Reducing the setting time can be accomplished with additives, but at the expense of the safety margin against stuck pipe. Reducing the setting time safely thus implies an improvement in reliability of the setting process, with perhaps less sensitivity to temperatures that might be encountered in the wellbore.

Cement drilling fines are difficult to remove from drilling mud because of their small size and chemistry. Yet it is imperative to remove as much of the cement as possible. First, just like any other type of drilling fines, cement fines are abrasive to the mud pumping equipment and reduce the hole cleaning efficiency if they are pumped back downhole with the drilling fluid instead of being removed at the surface. Secondly, cement fines continue to hydrate over time, absorbing water from the drilling mud and increasing mud viscosity. A substitute material that sets faster in a controllable manner and is more compatible with drilling mud is needed for lost circulation control.

Under this project, a cementitious LCM developed by Halliburton Services as a substitute for portland cement is being field tested. The composition of the material is proprietary. Its advantages are reportedly faster setting time (2-4 hours), less sensitivity to temperature, and better compatibility with the drilling mud. The strength of the material is much less than that of portland cement, so if premature setting occurs, it is thought that the drill pipe can be pulled out before sufficient strength is developed to stick it. Sandia is assisting Halliburton and CalEnergy in the field evaluation of this product.

An estimate of the cost savings that could result from the use of this cementitious LCM can be made by assuming the material saves six hours of rig time per plug. This would reduce the cost of each plug by about \$2000, or 10-20%. For a typical well where lost circulation accounts for 10-20% of the total costs, this material could therefore save 1-4% of the total well costs.

Note that this project is a Geothermal Drilling Organization (GDO) project. It is described here rather than in the GDO section of this document because Sandia initiated the project as part of its lost circulation program.

Project Participants:

- Sandia National Laboratories: Lead field evaluation effort; provide surface instruments and monitoring; document results.
- Halliburton Services: Develop cementitious LCM; conduct laboratory testing; assist in field evaluation effort.
- CalEnergy: Assist in field evaluation effort; provide access to drilling operations; provide rig time for field tests.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$90k	Sandia salary, hardware, travel, field expenses; CalEnergy contract for \$150k (\$53k remaining to be spent in FY97).

A portion (\$53k) of this funding will be paid to CalEnergy to cover a fee for lost production, downhole logging expenses, and mud logger support of surface data acquisition. CalEnergy will cover normal rig expenses, cementitious LCM material costs, and pumping costs, an estimated \$100k contribution. Halliburton will cover its own expenses on this project, approximately \$50k.

Status: This is an ongoing project. It has been under way since 1994 when it was initiated as a GDO project. Halliburton's product was ready for testing, and CalEnergy was preparing to drill a well in which significant lost circulation was anticipated. Sandia instrumented the drill rig for inflow and outflow rates, ran wireline temperature logs, and coordinated the field testing effort. Magnetic flow meters and a Doppler flow meter were installed on the inflow line, and a rolling float meter was installed on the outflow line. These instruments were used to measure the fluid loss rate and test the effectiveness of the treatments. Sandia also funded three borehole televiewer logs of the hole to provide images of the lost circulation zones.

Several conventional cement and several cementitious LCM plugs were placed in the well. Some of the loss zones required several plugs to seal. In general, it was concluded that the cementitious LCM was capable of sealing relatively minor loss zones (thin fractures) but not large ones. With the cementitious LCM plugs that were successful, drilling was resumed about 2-4 hours earlier than after the conventional cement plugs, so they did save costs. The problem with the material's capability for sealing larger fractures was deemed to be viscosity control: the fluid was apparently too thin to plug a larger fracture.

Halliburton conducted more laboratory development work on the material and was ready for the second phase of testing in 1995. In the second field test, all the same preparations were made as in the first test. Sandia again installed a rolling float meter and a Doppler flow meter as diagnostic equipment. The cementitious LCM was on hand, and preparations were made to run a formation micro-scanner (FMS) to study the loss zone characteristics. The well, however, never lost circulation severely enough to require cementing. The field mobilization effort was not wasted time, however, because it allowed us another opportunity to field test the rolling float meter and Doppler flow meter.

This project is currently on standby, waiting for another well to be drilled by CalEnergy.

Statement of Work: If CalEnergy drills another well which they will make available for this project, we should be able to complete the project in FY97. Essentially the same approach will be taken as in the previous two field tests. Sandia will again install diagnostic equipment and will use the opportunity to field test additional surface measurement equipment if possible. One additional field test where multiple loss zones are encountered should be sufficient to test the new formulation.

Milestones: The following milestones have been adopted for this project:

- *Complete third field test of cementitious LCM (5/97).*
- *Complete final Sandia Report on the cementitious LCM field evaluation project (9/97).*
- *Present paper on cementitious LCM field evaluation at GRC conference (10/97).*

Deliverables: This project will result in the following deliverables:

- *A rigorously tested, commercially available cementitious LCM for lost circulation control.*
- *A final report on the field evaluation of the cementitious LCM.*

Advanced Lost Circulation Materials

Program Area: Lost Circulation Technology

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Justification: No program on lost circulation research would be comprehensive without a project for investigating advanced lost circulation materials and emplacement methods. In fact, a major part of Sandia's past efforts in lost circulation focused on lost circulation materials (LCMs) such as ground walnut shells, ground rubber tires, fired clay, ground battery casings, and polyurethane foam. We developed several facilities for testing the mechanical strength and fracture plugging capability of LCM particles. We also developed mathematical models for using the mechanical strength data to predict the sealing performance of a given candidate LCM (Loeppke *et al.*, 1990b). We conducted an extensive survey of potential high-temperature LCMs and tested many that looked promising. Although we never discovered a viable LCM material for high temperature applications ($> 150^{\circ}\text{C}$) we did find several bridging materials that have adequate moderate-temperature strength to seal significant fractures. In recent years, our lost circulation work has focussed in the other the other areas described in this plan.

Under this project, we will resume at a low level of effort a project to identify and evaluate alternative materials and techniques for plugging lost circulation zones. If a promising material or technique is identified and considered worth pursuing, a project plan will be written and included in this program plan at its next update. Several interesting candidates include: a new commercial tool known as the expandable slotted tube (EST) that may be adapted for this application; expandable LCMs such as ground rubber tires; LCM pill delivery with a standby system that mixes and pumps a pill down the drillstring; and expanding polyurethane foam for shallow-well applications.

In estimating the cost savings that could result from this project, it is recognized that some fluid losses are currently treated by adding LCM to the drilling mud; many other loss zones currently require cement for proper sealing. If a more effective LCM treatment could be developed, then fewer cement treatments would be necessary. Assuming an effective LCM treatment could be applied for 10% of the cost of a cement plug, then a savings of \$9,000-18,000 or about 1/2% of total well cost, would result for every cement plug eliminated by the LCM treatment.

Project Participants:

- Sandia National Laboratories: Lead evaluation of materials and techniques; develop project plan.
- Industry Partner (to be determined): Participate in laboratory and field evaluation effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$40k	Sandia salary, hardware, travel

Due to the exploratory nature of this project, it is not known at this time how various industry partners may participate in the project. In most cases, participating companies pay their own expenses related to a project.

Status: This is a proposed new project that builds upon the previous work at Sandia. Because of the exploratory nature of this work, it is described below as a one-year effort.

The EST is a downhole tool developed for the oil and gas industry by Shell Oil Company that emplaces an expandable slotted tube into a wellbore to stabilize the wellbore wall. The tube is expanded in place by withdrawing a mandrel through the tube that stretches it out against the wellbore wall. The tool may have some applicability for treating severe lost circulation zones encountered in geothermal drilling. Shell has been contacted and is interested in exploring the possibility of working together on this project.

In the late 1980s, Sandia conducted several tests with ground rubber tire particles to evaluate their potential as a high-temperature LCM. Mechanical properties were measured at elevated temperatures, slot-plugging tests were conducted, and a mathematical model was initiated to describe the plugging of fractures with this type of highly deformable material. The tire particles showed significant promise. Their elasticity allows them to be forced into fractures, where they can form sealing bridges that are more reliable than bridges formed at the fracture aperture on the wellbore wall by rigid particles. Several field trials were conducted with ground rubber tires at the Long Valley Exploratory Well in 1989. The tire particles were found capable of plugging one of the loss zones that had not been pluggable with other mud-based LCMs. Problems with plugging of the mud pumps, however, caused the field trials to be terminated. This work was suspended in 1990 because of other, more urgent lost circulation projects.

Sandia also studied the use of polyurethane foam as a lost circulation material in the mid-1980s (Glowka *et al.*, 1989e; Loepke *et al.*, 1990a). The conclusion of that laboratory and field work was that the material *as is* may make an excellent loss-zone sealant for shallow-well applications; and with the use of a device preventing jet mixing of the foam chemicals with the wellbore fluid when they are injected into the wellbore, it could be effective in deep-hole applications. The key is to obtain substantial expansion of the foam chemicals after they are mixed and injected downhole. In shallow wells (<1000 ft), where the ambient pressure is not too high, the foam chemicals expand sufficiently to effectively seal almost any type of loss zone if sufficient volume can be pumped downhole. In deep applications where it is not practical to pump the foam chemicals from the surface, it is necessary to emplace them with a tool attached to the end of the drill pipe that carries a limited volume of foam chemicals. The chemicals must expand to have enough volume for sealing, and that is difficult to achieve at high ambient pressures.

Statement of Work: In FY97, the EST will be evaluated in cooperation with Shell Oil Company for its applicability in sealing lost circulation zones in geothermal drilling. This evaluation will include discussions on EST capabilities and specifications and conceptual design of EST-related lost circulation treatments. The goal will be to determine whether or not an EST-related lost circulation treatment should be attempted in the field.

The possible use of ground rubber tires or ground nitrile rubber as an LCM will also be re-examined in FY97. Data obtained with ground rubber tires in Sandia's modified-API slot tester several years ago will be analyzed, and the development of a bridging model for this material that was initiated several years ago will be completed. If a case can be made for testing the material in the field, a test plan will be developed and an industry partner will be sought to implement it.

The possibility of pumping ground rubber tire particles as an LCM raises the possibility of needing an LCM pill delivery system. Such a system would consist of a pill mixing tank, jet mixers, and a slurry pump, all skid mounted and portable. The purpose for such a system is to enable concentrated LCM pills to be mixed and pumped independently of the rig's mud system. The procedure would be to pump a concentrated pill into the drill pipe when the bit is pulled off bottom to make a connection (add new drill pipe). After the connection is made and the mud pumps are started, the pill would be pumped downhole with the drilling mud, without the need for the pill to pass through the mud pumps. This would be advantageous for several reasons. First, some materials would be excellent LCMs but happen to plug positive displacement pumps like those used in drilling operations. Second, there is no need to add LCM to the entire mud system when the target loss zone is usually limited in vertical extent. If the LCM particles are correctly sized and have adequate strength at the intended temperature, a reliable seal can be obtained with very little fluid volume or LCM. Smaller LCM pills are more economical and easier to mix. Third, by starting with small particles and gradually increasing the LCM particle size used in a pill, the optimal size for achieving a good seal can be experimentally determined and utilized for each loss zone. Of course, care must be taken in this process to use particle sizes small enough that they do not bridge across the drill bit nozzles. The concept of an LCM pill delivery system will be discussed with members of the geothermal community in FY97 to determine whether or not the idea should be pursued by assembling and field testing such a system.

During FY97, discussions will be also held with members of the geothermal community who may have shallow loss zones that could be treated by pumping the foam from the surface. If the idea appears attractive, a test plan will developed and pursued as appropriate.

Finally, this project will provide opportunities to study and evaluate any other advanced LCM materials or techniques that may show promise. As with the other potential materials and techniques, those that seem to be feasible will be more fully evaluated after a project plan is developed.

Milestones: The following milestones have been adopted for this project:

- *Complete initial feasibility assessment of EST-related loss zone treatment and determine further FY97 evaluation work (1/97).*
- *Complete initial industry discussions on LCM pill delivery system and polyurethane foam field test (3/97).*
- *Complete analysis of existing lab test data on ground rubber tires and determine further course of action for FY97 (3/97).*
- *Develop a project plan for any alternative LCM material or technique that should be further studied (9/97).*
- *Complete Sandia Report on the project (9/97).*

Deliverables: This project will result in the following deliverables:

- *A feasibility study of several alternative LCM materials and techniques.*
- *Program plans for any new alternative LCM materials or techniques that should be further evaluated in FY98.*

Encapsulated-Accelerator Cements

Program Area: Lost Circulation Technology

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Justification: Prior to pumping cement for a lost circulation treatment, the bit is invariably removed from the drillstring, requiring a round trip on the drill pipe that takes about 1 hour for each 1,000 ft of hole depth. The bit is removed because of the fear of plugging a bit nozzle and having the cement set up inside the drill pipe. If it could be guaranteed, however, that the cement would not set up in the drill pipe for a significant length of time, the cement could be pumped through the bit nozzles with less trepidation. By not removing (then replacing) the drill bit, two hours of rig time would be saved for every 1,000 ft of hole depth. For a typical 3,000 ft loss-zone depth, this amounts to 6 hours per loss zone.

Under this project, we will cooperate with Brookhaven National Laboratory to develop and test a cement with an encapsulated accelerator that does not react to set the cement until the encapsulant is somehow ruptured. This could be accomplished when the cement either passes through the bit nozzles and the encapsulant is sheared off the accelerator, or the cement flows into a loss-zone fracture and heats to a temperature that melts the encapsulant. Rapid, controllable setting or thickening once the cement is outside the drill pipe would significantly improve the sealing capability of the cement. Brookhaven briefly studied the feasibility of this concept five years ago but has not had funding to study it since then. Their expertise in developing geothermal cements and environmental grouts suits them for this renewed project.

In estimating the cost savings that could result from this project, it is assumed that 20 loss zones are encountered in a well drilled to an average depth of 2,000 ft. Using the time/trip savings discussed above, this represents 40 hours of savings over the life of the well, or about \$8,000-16,000. This is about 1/2% of the total well cost.

Project Participants:

- Sandia National Laboratories: Participate in industry discussions; define cement specifications; assist in laboratory and field evaluation.
- Brookhaven National Laboratory: Participate in industry discussions; conduct development of encapsulated-accelerator cement; assist in lab testing at Sandia and field testing.
- Geothermal Operator (to be determined): Participate in field evaluation effort.
- Service Company (to be determined): Participate in field evaluation effort.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$120k	Sandia salary, travel; Brookhaven contract for \$100k.
DOE Geothermal - Drilling Tech.	FY98	\$140k	Sandia salary, travel, lab and field expenses; Brookhaven contract for \$100k.

Participating companies will provide funding to cover their own expenses on this project.

Status: This is a proposed new project. It builds upon the previous work at Brookhaven, where ammonium polyphosphate cements were tested with encapsulated magnesium oxide accelerator. Preliminary tests were conducted on various encapsulants, including wax, polyethylene, epoxy, and polyamide. The encapsulants were found to extend thickening time. Disadvantages of the magnesium oxide-ammonium phosphate system were a lack of necessary durability in loss zone environments and evolution of ammonia gas, which was due to the reaction chemistry and was unrelated to the encapsulants.

Brookhaven has recently formulated calcium phosphate cements that meet specifications for viscosity, thickening time, impermeability, strength, shrinkage resistance, and durability. The calcium phosphate cements are produced by mixing calcium aluminate cement, water, sodium polyphosphate, and borax retarder if necessary. The cost of calcium phosphate cements can be reduced significantly through the addition of ground granulated blast furnace slag. Addition of the slag also regulates the thickening and setting times so that the materials can be placed downhole without risk of premature setting. The calcium polyphosphate cement slurries are compatible with conventional mixing and pumping equipment. Without the use of an encapsulant, however, these cements appear to be limited to use where downhole temperatures do not exceed 100°C. Excessive retarder concentrations are required at higher temperatures, and this has a detrimental effect on the physical and mechanical properties of the set cement.

Under this project, alternative cement systems that could be used with the encapsulated-accelerator concept will be evaluated. Calcium phosphate cements, oil well cement-accelerator systems, and other potential materials will be investigated. By coating the sodium polyphosphate accelerator for the calcium phosphate system, or any other accelerator for a different system, rapid setting and strength development could be achieved in the loss zone. This would result in greater control and reliability of reaction kinetics, reduction in waiting-on-cement time, and savings in drilling costs. Reduction or elimination of retarders would enhance the hardened properties of the materials, reduce material costs, and simplify the formulation and mixing procedures.

This project will be substantially completed over a two-year period. During the first year, laboratory work will be done at Brookhaven to characterize possible cement systems. The deliverable at the end of the first year will be a candidate system for field testing. During the second year, a full-scale test of the system will be conducted in Sandia's Engineered-Lithology Test Facility. If it proves effective, a field test will be sought in cooperation with a geothermal operator and service company.

Statement of Work: This work will begin in FY97. Brookhaven and Sandia will begin by discussing the project with cement service companies. The purposes of the discussions will be: to determine whether the cement service industry has evaluated this concept in the past; to assess the technical feasibility of the concept; and to determine whether there is any interest on the part

of the service companies to cooperate with us on this study. If no major obstacles to the work are discovered, Sandia will define the cement specifications and provide them to Brookhaven. These specs will include initial viscosity, setting time, final compressive strength, pumpability without accelerator, stability of encapsulant, and other pertinent parameters.

The first phase of the research at Brookhaven will be to conduct laboratory tests to determine the behavior of different accelerator encapsulant types and application methods on the relevant properties of the cement. Tests will be performed in a high-temperature, high-pressure consistometer to determine thickening time as a function of encapsulant type, mix proportions, accelerator type, temperature, and pressure. Formulations and encapsulants that meet the thickening-time specifications will then be tested for set time, permeability, compressive strength, shrinkage, and durability in the geothermal environment. Cost analysis of the different systems will be conducted concurrently with laboratory testing to ensure that the cements and encapsulating process are economically favorable. The cement formulation and encapsulation type will be optimized for properties in the unhardened and hardened states, in addition to practicality and economics.

By the end of FY97, the feasibility of an encapsulated-accelerator cement will be assessed. If a system appears to have potential, a test plan will be developed for FY98. It is likely that a technique for pumping or injecting the encapsulated accelerator into the cement will need to be developed. A full-scale test in Sandia's Engineered-Lithology Test Facility (ELTF) will then be conducted prior to going to the field. Such a test will allow evaluation of the pumping method and confirmation of the setting characteristics of the cement in large volumes. If successful, the data it provides should be useful in convincing a geothermal operator and/or service company to participate in a field test.

Having a drill bit on the bottom of the drillstring for the first field test of the cement would probably be unwise. Instead, a more conservative approach will be taken, depending on the type of encapsulant system selected. If the encapsulant depends on temperature to degrade, it can simply be emplaced through open-end drill pipe until confidence is built in its performance. If the encapsulant requires shearing in a nozzle to expose the accelerator, it would be possible to develop a drillable sub that contains nozzles and a pressure burst plate. The sub could be placed at the bottom of the drillstring, and the next two or three lengths of drill pipe could be made of aluminum. If necessary the drill pipe could then be pulled apart from the lower assembly if the cement set prematurely and stuck it; and the lower assembly could then be drilled out. The risk of a field test would thereby be minimized.

Following the field test, the commercial viability of the encapsulated-accelerator cement will be evaluated. If further work is required to make it commercial, a project plan will be developed at the end of FY98 to complete the work.

Milestones: The following milestones have been adopted for this project:

- *Initiate encapsulated-accelerator cement project (12/96).*
- *Complete initial project discussions with industry (2/97).*
- *Complete coating of sodium polyphosphate and other accelerators of interest with candidate encapsulants (3/97).*
- *Complete initial formulation studies and measurement of viscosity and specific gravity (4/97).*

- *Complete consistometer tests and select the most promising encapsulated-accelerator cement systems based on thickening time (7/97).*
- *Complete measurement of set time, permeability, compressive strength, shrinkage, and durability of selected encapsulated-accelerator cement systems (9/97).*
- *Complete cost analysis of optimized encapsulated-accelerator cement systems (9/97).*
- *Complete feasibility study of encapsulated-accelerator cement (9/97).*
- *Complete testing plan for selected encapsulated-accelerator cement (9/97).*
- *Complete test of encapsulated-accelerator cement in the Engineered-Lithology Test Facility (2/98).*
- *Complete field test of encapsulated-accelerator cement (9/98).*
- *Complete final report on the encapsulated-accelerator cement project (9/98).*

Deliverables: This project will result in the following deliverables:

- *A feasibility study of encapsulated-accelerator cement.*
- *A field-tested encapsulated-accelerator cement for lost circulation control.*
- *A final report and conference papers on the encapsulated-accelerator cement project.*

IV. Hard-Rock Drill Bit Technology

a. Background

When polycrystalline diamond compact (PDC) bits became widely available to the oil and gas drilling industry in the 1980s, they quickly found use in soft to medium-hard rock types, where they have often been responsible for at least doubling the penetration rate and bit life over those typical of roller-cone bits. The literature contains several case histories where drilling cost savings exceeding \$100,000 per bit run have resulted from the use of PDC bits. PDC bits presently account for roughly one-third of the total worldwide rock bit market, achieving annual sales in excess of \$200 million. Their high penetration rate and long life are annually responsible for millions of dollars in reduced drilling costs related to energy extraction (Falcone, 1995).

In hard-rock drilling, however, PDC bits have not been so successful. Hard rock is generally more abrasive and requires the use of higher cutter forces to drill at economical rates. This results in higher frictional temperatures at the cutter-rock interface, thereby thermally accelerating the cutter wear (Glowka and Stone, 1986a). Higher cutter forces also amplify any imbalance in the bit design, leading to greater bit wobble and vibration downhole (Glowka, 1989b). Such vibration and the resulting impact can cause damage to the cutters, including chipping of the diamond faces, cleavage of sections of the cutters, or breakage of entire cutters. Consequently, PDC bits have not yet found a market in hard-rock drilling.

Most geothermal production wells are, therefore, drilled with tungsten-carbide-insert roller-cone bits. Although the performance of today's geothermal roller-cone bits is much better than before, penetration rates and bit lives are still significantly lower than in typical oil and gas wells. A penetration rate of 10 ft/hr and bit life of 300 ft is not uncommon in geothermal drilling. In most soft rocks, PDC bits drill faster than 30 ft/hr and often last thousands of feet. Extending even a portion of the drilling performance benefits of PDC bits to harder rock types would significantly improve the economics of geothermal drilling.

Sandia spent several years in the late 1970s and early 1980s investigating the use of PDC bits in geothermal drilling. The dual problem of thermally accelerated cutter wear and cutter impact damage was encountered when these bits were tested in hard rocks. We conducted fundamental and applied studies related to frictional heating, downhole cooling, bit design principles, and computer software to address the problem (Finger and Glowka, 1989b). Our conclusion when we ended the work in 1986 was that material properties somewhat limited the use of PDC bits in hard rock, but with better design, harder rocks could be successfully drilled than were previously possible with drag bits. The industry was active in pursuing better PDC bit designs at that time, and Sandia ended its work on PDC bits after publishing a bit design code (Glowka, 1987) that has been widely used in the industry.

In 1992, the Geothermal Research Department at Sandia was requested by DOE's Oil Technology Partnership to develop a project addressing the need for better drill bits in the oil and gas drilling industry. We discussed this with a number of drill bit manufacturers and other researchers, who convinced us that there was a returning role Sandia could play in fostering the development of synthetic-diamond drill bits for harder-rock applications.

We developed a program plan (Glowka and Schafer, 1993b) with eight companies to conduct a variety of cost-shared projects addressing different approaches to synthetic-diamond bit design for hard rocks. Known as the Advanced Synthetic-Diamond Drill Bit Development Program, it was funded in 1993 and 1994 by the Partnership, but not at the level originally requested. Consequently, we requested and received additional funding from the DOE Office of Geothermal Technologies during those two years and since then to continue the program.

b. Justification for Technology Development Effort

A drilling cost system study conducted by Sandia in the early 1980s (Carson and Lin, 1982; Carson *et al.*, 1983) concluded that in a typical geothermal well, a doubling of penetration rate and bit life over that currently available would reduce total well costs by about 15%. This is similar to a more recent study by Maurer Engineering that concluded that doubling penetration rate and bit life in deep gas wells would reduce costs about 20%.

As a quantitative goal, a doubling of penetration rate and bit life over that obtained with current roller-cone bits may seem rather arbitrary, but it is both significant and possibly achievable with our current projects. A 15% drilling cost reduction results in about a 5-7% reduction in geothermal project costs.

c. Hard-Rock Bit Projects

Twelve projects are planned in the hard-rock drill bit technology program area. Five of these projects are ongoing, industry cost-shared projects on advanced synthetic-diamond drill bits. Three other projects have recently been initiated with earmarked FY96 DOE funding and NADET Institute funding. Four are proposed new projects that cover a number of other topics related to hard-rock drilling. These projects are all described in the following pages.

Claw Cutter Optimization

Program Area: Hard-Rock Drill Bit Technology

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Justification: A conventional polycrystalline diamond compact (PDC) cutter consists of a thin layer of synthetic diamond sintered onto a tungsten carbide substrate. As the cutter wears against the rock, a sharp cutting edge is maintained because of the difference in wear rates between the diamond and the tungsten carbide. The sharp cutting edge maintains a high stress concentration on the rock and, hence, rapid rock penetration at lower cutter forces. This self-sharpening effect is one of the most important attributes of PDC cutters.

PDC *claw* cutters, manufactured by Dennis Tool Co. for Security DBS bits, take further advantage of this self-sharpening effect. Prior to sintering on the diamond layer, the tungsten carbide substrate is machined with grooves that fill with diamond during the sintering process. As the cutter wears, the wearflat develops a series of parallel ridges or "claws" of diamond that stand out from the surrounding tungsten carbide. These sharp-edged claws impose concentrated stress on the rock, thereby removing rock at lower cutter forces. This cutter configuration also increases the percentage of the wearflat composed of diamond, which has a lower friction coefficient and lower abrasive wear rate than tungsten carbide.

These characteristics should all improve the hard-rock cutting capability of claw cutters. In fact, field evidence indicates that this is the case. Claw cutters have been shown to drill more effectively than conventional PDC cutters in relatively hard rocks, but their design has not yet been optimized, and they have not been fully tested in rocks as hard as those encountered in geothermal drilling. There are several design parameters that can be optimized on claw cutters, such as number of grooves, groove depth, groove width, groove spacing, and diamond face thickness. Optimizing these parameters to minimize cutter stresses would maximize cutter life in hard rock.

Under this project, we are cooperating with Dennis Tool Company to optimize the design of the claw cutter. This study is an experimental and analytical effort to identify a claw cutter configuration that has improved life over both conventional PDC cutters and current claw cutters. Sandia is using a unique laboratory test facility and a unique finite-element meshing capability in this study. Dennis Tool is manufacturing experimental cutters, and Sandia is testing them.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is difficult to predict the ability of this project alone to achieve that level of improved bit performance. This project addresses one component of an improved bit design, namely the cutter's material distribution. Combined with other improvements in bit design, such as those addressed in other projects in

this program plan, this work should help reach the goal. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Dennis Toll Co.; conduct numerical stress modeling and cutter wear tests; participate in design discussions; coordinate testing of full-scale bit; document results.
- Dennis Tool Company: Fabricate experimental cutters; participate in design discussions; participate in testing of full-scale bit; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$175k	Sandia salary, travel, hardware, rock specimens; Dennis Tool contract for \$65k (\$23k to be spent in FY97).
DOE Geothermal - Drilling Tech.	FY98	\$150k	Sandia salary, travel, hardware, rock specimens; Dennis Tool contract for \$65k (\$10k to be spent in FY98).

Dennis Tool Company is cost-sharing their portion of the project work, a \$65k contribution.

Status: This is an ongoing project. It has been under way since 1993 as one of the projects in the Advanced Synthetic-Diamond Bit Technology Development Program (Glowka and Schafer, 1993). Under this project, Sandia and Dennis Tool developed a matrix of nine claw cutter designs with different combinations of number of grooves, groove depth, width, spacing, and diamond face thickness. Dennis Tool fabricated claw cutters to those designs, while Sandia studied the designs with three-dimensional finite-element modeling. An automated mesh-generating program developed at Sandia for other applications was used to create a finite-element model of each design. A typical model in this study has over 16,000 nodes, a measure of the fine detail incorporated into the model. Thermal and mechanical stresses were calculated based on imposed boundary conditions that are typical of hard-rock drilling. Claw cutter designs that have the lowest total maximum stresses were identified. Presumably, these designs will experience lower wear rates than designs that have higher operating stresses (Glowka *et al.*, 1996a).

To confirm the numerical results, it was intended to wear test each claw cutter design in the laboratory to measure comparative wear among the nine designs. A wear testing technique using a vertical lathe was developed whereby a large (3-ft X 3-ft X 3-ft) rock sample was placed on the turntable and rotated beneath a translating cutter. The cutter, mounted on a 3-axis force dynamometer, moved radially across the top face of the rock sample, thereby cutting tightly wound spiral cuts in the rock. After each pass over the top face, a linear cutting distance of about 1200 ft, the cutter was removed from the dynamometer and examined. Its wearflat was photographed and measured using a video microscope system. This allowed the cutter wear to be plotted against volume of rock removed as a comparative wear measure for a given cutter.

A baseline wear rate was established for conventional PDC cutters and shown to be highly repeatable. It was also demonstrated that the rotary speed of the turntable had an effect on cutter wear that was a function of the frictional temperature at the cutter-rock interface. Although this testing method provided interesting and informative results, deficiencies in the method were

identified, including: a change in the linear speed of the cutter relative to the rock at different radial locations on the rock; an inability to precisely control the depth of cut because of changes in the stiffness of the lathe at different radial locations on the rock; cutter interaction that was not very similar to that on a bit; and a fluid environment that was not similar to that on a bit.

Because of these deficiencies, it was decided to develop a new wear-test facility that did not share these deficiencies. The Cutter Wear Test Facility (CWTF) was developed in 1994-96 and is essentially a small laboratory drill rig. It uses a three-cutter core bit on which the test cutter is located between the inner and outer gage cutters. The test cutter, therefore, has a cutter interaction pattern similar to that on a bit. The 3-inch-diameter bit can be rotated at speeds up to 500 rpm in order to simulate linear test cutter speeds that a gage cutter on an 8-3/4-inch bit experiences at 60 rpm. The tester can be operated at a constant rock penetration rate, thereby ensuring a constant depth of cut. It has the thrust (6,000 lb) and torque (500 ft-lb) capability to drill hard rock like Sierra White Granite at 30 ft/hr, even with significant cutter wear. Water or drilling mud are used to provide a fluid cleaning and cooling environment similar to that on a downhole bit. A 3-ft X 3-ft X 3-ft rock specimen is mounted on an air pallet beneath the bit so the rock can be easily moved laterally after drilling each hole. Up to eighty-five 3-inch-diameter holes nearly three feet deep can be drilled in each rock sample, making efficient use of the rock. Photographs and measurements of the cutter wearflat are taken with a video microscope after each hole to monitor the progress of the cutter wear as testing proceeds (Glowka *et al.*, 1996a).

The CWTF has been used to establish baseline wear rates for a conventional PDC cutter manufactured by General Electric. In FY97, the various claw cutter designs will be tested to compare them with each other and with a conventional PDC cutter.

Statement of Work: The laboratory wear testing of single claw cutters will be completed in FY97. All nine designs will be used to drill enough holes to determine the relative wear rates of the various designs. The results will be evaluated and compared with the results of the numerical modeling.

If the numerical and experimental results agree in identifying the most wear-resistant claw design, the numerical model will be further exercised to study changes that may further reduce cutter stresses in order to "fine-tune" the design. The optimized claw cutter design that results from this study will then be evaluated in a full-scale bit test. The original plan for this test was to build a full-scale core bit and test it in facilities owned by Security DBS. This plan will be re-examined to determine if it is still the best choice, and a final plan will be developed by the end of FY97.

In FY98, Dennis Tool will fabricate enough optimized claw cutters for a full-scale bit test. The bit will be built by Security DBS and tested in a selected manner in the laboratory or the field. An identical bit with conventional PDC cutters will also be built and tested under identical conditions. The cutting performance and wear of the two bits will be compared to evaluate the results of this project.

Milestones: The following milestones have been adopted for this project:

- *Initiate claw cutter testing in the Cutter Wear Test Facility (10/96).*
- *Complete claw cutter testing in the Cutter Wear Test Facility (6/97).*
- *Complete comparison of numerical and experimental claw cutter studies (7/97).*
- *Complete refinement of optimized claw cutter (9/97).*

- *Complete test plan for full-scale bit using optimized claw cutters (9/97).*
- *Present conference paper on claw cutter optimization (10/97).*
- *Complete fabrication of optimized claw cutters for full-scale bit (12/97).*
- *Complete fabrication of claw-cutter and conventional-cutter bits (3/98).*
- *Complete testing of full-scale claw-cutter and conventional-cutter bits (6/98).*
- *Complete final Sandia Report on claw cutter optimization project (9/98).*

Deliverables: This project will result in the following deliverables:

- *An optimized, commercially available claw cutter with improved hard-rock cutting capability.*
- *A final report and conference papers on the claw cutter optimization project.*

Track-Set Bit Optimization

Program Area: Hard-Rock Drill Bit Technology

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Justification: To avoid the onset of PDC bit vibration in hard rock drilling and the resulting impact damage to cutters, Security DBS markets a series of bits with a self-stabilizing "track-set" cutting structure. Track-Set bits employ greater radial spacing of cutters than conventional PDC bit designs. Consequently, each cutter travels in a deeper groove or track on the rock surface than does a typical cutter on a conventional bit. The sides of these tracks help stabilize the bit against lateral vibration by constraining the cutters to travel within the established tracks.

Track-Set bits have been shown capable of successfully drilling harder rock than conventional PDC bits, but their design has not been optimized, and they have not been fully tested in rocks as hard as those encountered in geothermal drilling. Optimal placement of PDC cutters on a Track-Set bit and accurate prediction of bit performance are highly dependent on a detailed knowledge of the cutter-rock interaction process. There are several design parameters that can be adjusted on a Track-Set bit, such as cutter radial spacing, cutter redundancy, and the configuration of groove-depth trimmers, that affect the depth and width of the tracks. Optimizing these parameters would maximize bit performance and minimize bit vibration and wear in hard rock.

Under this project, we are cooperating with Security DBS to develop design information and models that can be used to optimize Track-Set bit performance. Sandia is using a unique laboratory test facility to characterize the forces and rock breakage mechanisms associated with cutters on a Track-Set bit. Security DBS is using this data to develop algorithms that can be used to design Track-Set bits.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is difficult to predict the ability of this project alone to achieve that level of improved bit performance. This project addresses one component of an improved bit design, namely the cutter distribution on the face of the bit. Combined with other improvements in bit design, such as those addressed in other projects described in this plan, this work should help reach the goal. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Security DBS and New Mexico Tech; conduct single- and dual-cutter interaction tests; provide raw and analyzed data to Security DBS; coordinate testing of optimized Track-Set bit; document results.

- Security DBS: Assist in planning single- and dual-cutter interaction tests; develop bit design algorithms based on Sandia data; design and fabricate optimized Track-Set bit; participate in testing optimized Track-Set bit; document results.
- New Mexico Institute of Mining and Technology: Assist in data acquisition and reduction; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$250k	Sandia salary, travel, hardware, rock specimens; Security DBS contract for \$93k (\$25k to be spent in FY97); New Mexico Tech contract for \$10k.
DOE Geothermal - Drilling Tech.	FY98	\$150k	Sandia salary, travel, hardware, rock specimens; Security DBS contract for \$93k (\$15k to be spent in FY98); New Mexico Tech contract for \$10k.
DOE Geothermal - Drilling Tech.	FY99	\$30k	Sandia salary, travel; Security DBS contract for \$93k (\$10k to be spent in FY99); New Mexico Tech contract for \$10k.

Security DBS is cost-sharing their portion of the project work, a \$93k contribution.

Status: This is an ongoing project. It has been under way since 1993 as one of the projects in the Advanced Synthetic-Diamond Bit Technology Development Program (Glowka and Schafer, 1993). Under this project, Sandia and Security DBS defined an extensive test matrix for Track-Set cutter interaction tests that were conducted in Sandia's Single-Cutter Test Facility. The first test series examined the lateral restoring force generated when a cutter moves laterally in a track. These tests were conducted in three rock types representing soft, medium, and hard rocks. The results showed that a lateral restoring force of several hundred pounds develops to push the cutter back into the center of the track (Glowka *et al.*, 1996a).

Another completed test series developed a database for penetrating and drag forces on a cutter as a function of the depth of the track, the incremental depth of cut, the cutter wearflat area, and the rock type. These data were fit to equations that can be used by Security DBS directly in a computer model of Track-Set bits.

The effects of cutter siderake and backrake angle were also investigated in the three rock types with sharp and worn cutters. Although these data confirmed trends that had been known for years, they also provided previously unavailable quantitative data that can be fit to equations for use in a computer model.

Work will continue in FY97 with the completion of additional test series focusing on other aspects of Track-Set bit design.

New Mexico Tech is assisting in this project by providing graduate students to help generate and reduce data from the single-cutter tests. These data have also been used in some cases by New Mexico Tech to support development of a PDC bit dynamics model.

Statement of Work: Documentation of the single-cutter tests conducted over the past year will be completed in FY97. A Sandia Report and ASME conference paper will be written.

Additional single and dual-cutter tests will also be conducted in FY97. Tests on a new cutter design will establish the dependence of cutter force on chamfer size and formation strength. Restoration force tests will determine the loads experienced by a single cutter when its cutting axis is both vertically and laterally displaced relative to a track. The strength of the formation between parallel grooves will be investigated by measuring the forces on a single cutter as it cuts the ridge. The concept of using a leading scribe to pre-fracture the formation ahead of a cutter will be evaluated by cutting first with a scribe, then following that cut with a round cutter. Mechanisms of formation-ridge removal will be revealed by first examining the dependence of cutter side force on the proximity of an adjacent groove, then by simultaneously forming parallel grooves with dual cutters while noting any physical manifestations of web breakout and changes in combined cutter forces.

The FY96 and FY97 single-cutter test results will be examined during the last half of FY97 to determine parameter combinations (backrake angle, siderake angle, groove depth, ridge removal method, etc.) that provide the most efficient rock breakage. Models will be developed where necessary to provide mathematical relationships that can be used for bit design and simulation. This work will be completed by Sandia, New Mexico Tech, and Security DBS by the end of FY97.

In FY98, Security DBS will incorporate the models into their proprietary bit design code. This will allow numerical simulations of bit performance to be conducted that will enable design optimization. A Track-Set bit will then be fabricated according to the optimized design by the end of FY98. A plan for testing the bit will also be completed by the end of FY98. The plan for this test was originally to build a full-scale bit and test it in Amoco's Catoosa Field Test Facility. This choice will be re-examined to determine if it is still optimal or whether laboratory tests are first necessary.

Testing of the optimized Track-Set bit will be completed in early FY99. A conventional PDC bit or an original Track-Set bit will also be built and tested under identical conditions. The cutting performance and impact damage of the two bits will be compared to evaluate the results of this project.

Milestones: The following milestones have been adopted for this project:

- *Complete Sandia Report and ASME conference paper on FY96 linear single-cutter test data (1/97).*
- *Complete new series of single- and dual-cutter tests (4/97).*
- *Complete review and analysis of linear single-cutter data and issue interim report describing modeling results (9/97).*
- *Complete incorporation of Track-Set cutting models into Security's bit design code (3/98).*
- *Complete design of optimized Track-Set bit (7/98).*
- *Complete fabrication of optimized Track-Set bit (9/98).*
- *Complete test plan for optimized Track-Set bit (9/98).*
- *Complete lab and/or field test of optimized Track-Set bit (2/99).*
- *Complete final Sandia Report on development and testing of optimized Track-Set bit (5/99).*

Deliverables: This project will result in the following deliverables:

- *Optimized, commercially available Track-Set bits with improved hard-rock drilling capability.*
- *A final report and conference papers on the Track-Set bit optimization project.*

TSP Bit Optimization

Program Area: Hard-Rock Drill Bit Technology

Project Leader: David Raymond, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8026, Fax 844-3952; John Cohen, Maurer Engineering, 2916 West T. C. Jester, Houston, TX 77018, (713) 683-8227, Fax 683-6418

Program Area Leader: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Thermally stable polycrystalline (TSP) diamond cutters differ from conventional PDC cutters in that the cobalt that remains in the diamond structure after the sintering process is removed from the diamond by chemical leaching. Because of the differential thermal expansion between the diamond and cobalt grains, the presence of cobalt causes thermal damage to the diamond structure at temperatures above 700°C and accelerated wear at temperatures as low as 350°C. By removing the cobalt, a more thermally stable and wear-resistant diamond structure is obtained. This is especially important at high rotary speeds where more frictional heat is generated at the cutter-rock interface.

Unfortunately, removing the cobalt also makes the PDC structure more brittle and makes it difficult to bond the diamond to the tungsten carbide substrate. Consequently, TSP cutters have traditionally been marketed as small cubes or similar shapes that are matrix-mounted on a tungsten carbide bit body like a natural diamond bit. The small exposure of the TSP cutters is necessary to prevent the brittle TSP material from breaking off; but the small exposure also results in slow rock penetration. Consequently, TSP cutters have not found a wide market despite their excellent abrasion resistance against hard rocks.

Under this project, we are cooperating with Maurer Engineering and SlimDril International to test different TSP cutter shapes in order to identify shapes that have the best potential for hard-rock drilling. Sandia is using a unique laboratory facility to obtain comparative wear data with various TSP cutters. Maurer is supplying the TSP cutters and working with SlimDril Int'l to fabricate and lab test small-diameter (3-inch) TSP bits in hard rock in Maurer's laboratory.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is not likely that this project alone will achieve that level of improved bit performance in all geothermal applications. Instead, this project addresses one type of bit that may have specialized markets in geothermal drilling, namely downhole motor drilling at high rotary speeds and wireline coring. Combined with improvements in bit designs for conventionally drilled sections of the hole, this work will help reach the overall bit performance goal. As previously noted, such an improvement in overall bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Maurer/Slimdril; conduct comparative wear testing of TSP cutters; coordinate field testing activities; document results.

- Maurer Engineering/SlimDril Int'l.: Provide TSP cutters to Sandia for wear testing; design, fabricate, and lab test TSP bits in hard rock; fabricate bit for field testing; participate in field test; document result.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$95k	Sandia salary, travel, hardware, rock specimens; Maurer/SlimDril contract for \$80k (\$15k to be spent in FY97).
DOE Geothermal - Drilling Tech.	FY98	\$50k	Sandia salary, travel, hardware, rock specimens; Maurer/SlimDril contract for \$80k (\$11k to be spent in FY98).

Maurer/SlimDril are cost-sharing their portion of the project work, an \$80k contribution.

Status: This is an ongoing project. It has been under way since 1993 as one of the projects in the Advanced Synthetic-Diamond Bit Technology Development Program (Glowka and Schafer, 1993). To date under this project, Sandia has conducted extensive TSP cutter wear testing, and Maurer Engineering has worked with SlimDril Int'l to laboratory test TSP bits in hard rock.

The TSP cutter wear testing conducted thus far was performed with the vertical lathe set-up described under the claw cutter optimization project. Six different TSP cutter shapes and sizes were tested to determine comparative wear resistance. Cutter wear volume was measured as a function of the rock volume removed. Five of the TSP cutters were so much smaller than conventional PDC cutters that they could not be tested at the same depth of cut as PDC cutters and, therefore, could not be compared directly with the conventional PDC cutter baseline data on wear. Comparing those cutters among themselves, it was shown that one particular shape, known as the housetop, wore at a significantly lower rate than the other shapes (cubic, sharp-set, and roundtop).

The sixth TSP cutter was an experimental disk cutter in which a thin, 1/2-inch-diameter TSP layer had been bonded to a 1/8-inch-thick wafer of tungsten carbide. The cutting configuration was identical to that of a conventional PDC cutter, and this cutter could therefore be tested at the same depth of cut (0.060 inch) for direct comparison with the wear of a PDC cutter. In both tests with this TSP cutter design, it wore nearly an order of magnitude slower than conventional PDC cutters at speeds that result in thermally accelerated wear conditions with PDC bits. This demonstrated again that the TSP cutter is more thermally stable and abrasion resistant than a PDC cutter. When the experimental cutters attained a certain large wearflat area, however, they repeatably broke because of the elevated forces on the cutter. The TSP cutter tests thus demonstrated two primary characteristics of TSP material: its thermal stability and its brittle structure. The tests showed a significant potential for TSP cutters in hard-rock drilling if the brittle fracture problem can be overcome. If the experimental TSP cutter had been mounted on a thicker tungsten carbide backup, it may have survived the higher forces and outperformed the PDC cutter (Glowka *et al.*, 1996a).

Statement of Work: TSP cutter wear testing was suspended after the vertical lathe testing described above, pending the development of the Cutter Wear Test Facility (CWTF). Now that the facility has been completed (see claw cutter project plan), TSP cutter wear testing will resume in FY97.

Maurer Engineering was encouraged by the results of the TSP disk cutter testing and has concentrated further TSP investigations on that type of cutter. TSP bonding is currently an active topic, with several cutter manufacturers and other investigators working on better ways to bond TSP material to tungsten carbide. Maurer has obtained several other TSP disk cutters that Sandia will test in the CWTF. Beyond those cutters, Maurer will continue to arrange cooperation with TSP fabricators to test promising TSP hard-rock candidates. This work will be substantially completed in FY97 unless further important single-cutter testing is identified.

Maurer and SlimDril will fabricate a 3-inch diameter TSP bit using the best cutters identified by wear testing and will then test the bit in hard rock in the laboratory. If it is successful in drilling at high penetration rates with extended bit life, a plan will be developed for a field test. The plan for this test was originally to perform it in Amoco's Catoosa Field Test Facility. This choice will be re-examined to determine if it is still optimal.

If a field test is conducted, an optimized TSP bit will be fabricated and tested along with a conventional PDC bit. The cutting performance, wear performance, and impact damage of the two bits will be compared to evaluate the results of this project.

Milestones: The following milestones have been adopted for this project:

- *Initiate TSP cutter testing in the Cutter Wear Test Facility (11/96).*
- *Complete TSP cutter testing in the Cutter Wear Test Facility (4/97).*
- *Complete design of lab-prototype optimized TSP bit (6/97).*
- *Complete fabrication of lab-prototype optimized TSP bit (7/97).*
- *Complete lab testing of optimized TSP bit (8/97).*
- *Complete field test plan for optimized TSP bit (9/97).*
- *Complete design of field-prototype optimized TSP bit (1/98).*
- *Complete fabrication of field-prototype optimized TSP bit (3/98).*
- *Complete field testing of optimized TSP bit (6/98).*
- *Complete final Sandia Report on development and testing of optimized TSP bit (8/98).*

Deliverables: This project will result in the following deliverables:

- *Design guidelines for hard-rock TSP drill bits.*
- *Optimized, commercially-available hard-rock TSP bits for slimhole applications.*
- *A final report and conference papers on the TSP bit optimization project.*

Microwave Brazing of TSP Cutters

Program Area: Hard-Rock Drill Bit Technology

Project Leader: David Raymond, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8026, Fax 844-3952;
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Program Area Leader: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The hard-rock drilling potential of thermally stable polycrystalline (TSP) diamond drill bits has not yet been fully exploited because of some peculiarities related to the material's properties. Because the cobalt has been leached from the diamond structure after it has served its catalytic role in the sintering process, TSP cutters are more thermally stable than PDC cutters and, hence, are inherently more resistant to abrasive wear. The impact resistance of TSP cutters, however, is lower than that of PDC cutters because of the missing cobalt.

Consequently, TSP bits are made with small TSP cutters imbedded in the bit body, resulting in small cutter standoff and, hence, low penetration rates. If the impact resistance of TSP cutters could be improved by brazing them to tungsten carbide studs or directly to a bit body to achieve greater standoff, penetration rates similar to those of PDC bits would be achievable, along with better bit life under high temperature conditions. Such bits would have direct applicability to geothermal drilling, particularly in the directionally drilled well sections where downhole motors are used and the higher rotary speeds make thermal stability more crucial.

In this project, Sandia is assisting Technology International, Inc., the Jet Propulsion Laboratory, and the Colorado School of Mines to develop and field test two promising new brazing techniques for bonding TSP diamond cutters to a drag bit body. The first technique involves the use of special braze alloys. The second bonding process involves the use of multi-phase alloys that can be heated using a microwave technique that is superior to the induction heating technique normally used in PDC bonding applications. Sandia will conduct wear tests of TSP cutters bonded with the methods developed in this project. Our Cutter Wear Test Facility (CWTF) will be used for this lab work. We will also assist in the field testing of bits with bonded TSP cutters. This project is being funded by the NADET Institute.

The goal of this project is to develop thermally stable bonds with shear strengths in excess of 35,000 psi that can be used to attach TSP cutters to bit bodies with greater exposure and, hence, obtain the outstanding penetration rate performance obtained with PDC bits. If this goal can be accomplished, it is possible that TSP bits could drill faster and much longer than PDC bits in some hard rock formations. The goal for this project is, therefore, the same as in all the bit projects, namely, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Wear test bonded TSP cutters in the CWTF; document results.
- Technology International, Inc.: Lead brazing development effort; coordinate all joint work activities; document results.
- Jet Propulsion Laboratory: Participate in brazing development effort ; document results.
- Colorado School of Mines: Participate in brazing development effort; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
NADET Institute	FY97	\$20k	Sandia salary, rock specimens, supplies, travel; funding received from NADET through Technology International.
NADET Institute	FY98	\$20k	Sandia salary, rock specimens, supplies, travel; funding received from NADET through Technology International.
NADET Institute	FY99	\$30k	Sandia salary, rock specimens, supplies, travel; funding received from NADET through Technology International.
NADET Institute	FY00	\$30k	Sandia salary, rock specimens, supplies, travel; funding received from NADET through Technology International.
NADET Institute	FY01	\$30k	Sandia salary, rock specimens, supplies, travel; funding received from NADET through Technology International.

This project was selected by the NADET Institute as one of its seven funded projects in FY97. The first year funding for this project will thus not be counted in the program totals for requested FY97 funding from DOE Geothermal. Note that the funding levels shown above are only Sandia's portion of the project budget, which is \$150k in FY97. The other \$130k will be distributed among Technology International and JPL. CSM is contributing \$50,000 worth of in-kind services of graduate student to the project.

Status: This is an ongoing project that has recently received funding from NADET. Sandia is not the lead investigator on this project but is assisting the other participants.

The current state-of-the-art TSP cutter attachment procedure is to braze the TSP diamond to tungsten carbide substrates with proprietary brazing metals. The braze filler metal, when heated to 800°C, flows and wets the TSP diamond to form a uniform microstructure. Average attachment shear strength levels of 20,000 to 35,000 psi have been reported using direct resistance, induction, and furnace heating methods. These shear strength levels are not adequate for commercial drag bit performance.

In this project, two new methods for brazing TSP diamonds to tungsten carbide will be investigated. Both methods involve the use of microwaves, which preferentially heat the filler metal with very little absorption by the TSP diamond. Technology International will coordinate the development work, and Sandia will evaluate the test cutters resulting from the work in our Cutter Wear Test Facility.

Statement of Work: This project will begin in FY97 and, if successful, take five years to complete. Phase 1 is development of the basic microwave brazing technique and will be completed in FY97. In FY98, Phase 2 will be completed, investigating the use of the custom brazing metals with microwave heating. Phase 3 is laboratory and field testing, which will be completed in FY01.

In Phase 1, custom braze filler compositions will be fabricated into foil by Technology International, Inc. Brazing trials will be performed at JPL to determine optimal ranges of the microwave parameters: power, component temperatures, plasma on-time, compressive pressure, and heating duration. A test matrix will be followed to examine microwave parameters, braze filler metals, and base material combinations. Computer-controlled process controls will be augmented, and an optical pyrometer will verify that the TSP diamond does not exceed its 1200°C maximum safe temperature.

Optimal parameters will be chosen, and cutters will be bonded for laboratory evaluation. Sandia's CWTF will be used to test the cutting performance and wear characteristics of the resultant cutters. These results will be compared with baseline test results that have been established for conventional PDC cutters. This work will be completed and documented by the end of FY97.

In FY98, Phase 2 work will begin with CSM developing custom braze metal compositions. JPL will then perform brazing trials with the material, similar to those done in Phase 1. Cutters utilizing the custom braze metal will again be tested at Sandia for comparative wear evaluations. This work will be completed by the end of FY98.

In FY99-01, Phase 3 will be performed if either of the Phase 1 or 2 processes results in TSP bond shear strengths adequate for hard-rock drilling (>35,000 psi). The objective of this phase will be to evaluate the performance of TSP drag bits employing the new bonding technology during laboratory hard-rock simulations and in the field. TSP bits designed by Technology International will be fabricated by a commercial bit manufacturer and tested in several hard-rock applications. The bit performance and life will be compared to those of roller-cone bits and conventional PDC bits under the same conditions when possible.

Milestones: The following milestones have been adopted for this project:

- *Initiate TSP bonding project (10/96).*
- *Complete fabrication of custom braze-metal foils for microwave brazing tests (2/97).*
- *Complete first microwave brazing trial (6/97).*
- *Complete fabrication of TSP test cutters using optimized microwave brazing method (7/97).*
- *Complete cutter wear testing in the CWTF using microwave-bonded TSP cutters (8/97).*
- *Complete Phase 1 final report on microwave brazing technique (9/97).*
- *Complete fabrication of custom braze-metal foils for microwave brazing tests (2/98).*
- *Complete second microwave brazing trial (6/98).*
- *Complete fabrication of TSP test cutters using custom brazing metals (7/98).*

- *Complete cutter wear testing in the CWTF using TSP cutters with custom brazing metals (8/98).*
- *Complete Phase 2 final report on microwave brazing technique using custom brazing metals (9/98).*

No milestones are given for Phase 3 (FY98-01) because it has not yet been defined.

Deliverables: This project will result in the following deliverables:

- *A field-tested, commercially available method for bonding TSP cutters that results in TSP bits with cutting structures similar to those of PDC bits but with improved abrasive wear resistance in hard-rock drilling.*
- *Reports and conference papers on the TSP bonding development and testing effort.*

Impregnated-Diamond Bit Optimization

Program Area: Hard-Rock Drill Bit Technology

Project Leader: Jack Wise, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-6359, Fax 844-3952, jlwise@sandia.gov;

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Impregnated-diamond drill bits employ small synthetic or natural diamonds embedded in a tungsten carbide matrix. As the tungsten carbide wears against the downhole rock surface, it exposes the diamonds which cut the rock. As the supporting tungsten carbide wears away, or if the diamond fractures, the crystal falls off the bit. More wear of the tungsten carbide exposes more diamonds, and the process continues. Although this type of bit is extremely durable and long lived in hard, abrasive rock, it typically drills at a very low rate (less than 10 ft/hr) because of the small standoff of the diamonds relative to the surrounding tungsten carbide matrix. Consequently, impregnated-diamond bits receive most of their geothermal use in wireline coring operations for exploration.

There is a complex relationship between the diamonds and the tungsten carbide matrix in this type of bit. If the tungsten carbide does not wear fast enough, new diamonds do not become exposed quickly enough to maintain good coverage as the exposed diamonds wear, break, and dislodge. If the tungsten carbide wears too quickly, it exposes too much diamond and promotes diamond breakage or dislodging. In addition to proper selection of the tungsten carbide grade for a given rock type, other bit design factors include the concentration of diamonds in the matrix, and the size and quality of the diamonds. The interrelationship of all these factors has not been well understood in the past.

Under this project, Sandia is cost-sharing a study at Hughes Christensen Company to investigate the effects of these design parameters on bit performance. The objective is to develop the understanding to enable impregnated-diamond drill bits to be designed for specific types of hard rock. HCC is conducting parametric drilling tests using impregnated-diamond core bits with various grades of tungsten carbide and various diamond concentrations, sizes, and quality. Bit wear rates are measured in three different hard rock types. In addition, a mechanistic model of the impregnated-diamond bit drilling process is being developed by Dr. Fred Appl for HCC. The model will be used together with the experimental data to develop design guidelines for various types of hard rocks. A proprietary diamond coating technology for promoting retention of the diamond within the tungsten carbide matrix is also being evaluated. If the diamonds could be retained in the matrix longer, larger diamond standoff and greater rock penetration rates could be achieved.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits, resulting in a 15% reduction in drilling costs. It is not likely that this project will achieve that level of improved bit performance

in all geothermal drilling operations. This project is working on one type of bit that may have a specialized market in geothermal drilling, namely wireline coring for exploration. Assuming exploration drilling costs account for 10% of the total drilling costs for a project, a 15% reduction in exploration drilling costs represents a 1.5% reduction in total drilling costs and a 1/2% reduction in overall project costs.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Hughes Christensen for all technical work; help coordinate field tests; document results.
- Hughes Christensen Company: Conduct laboratory drilling tests; sub-contract with F. Appl to develop mechanistic model; design and fabricate bit for field test; participate in field test; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$25k	HCC contract for \$125k (\$25k to be spent in FY97).
DOE Geothermal - Drilling Tech.	FY98	\$25k	HCC contract for \$125k (\$25k to be spent in FY98).

HCC is cost-sharing their portion of the project work, a \$125k contribution.

Status: This is an ongoing project. It has been under way since 1993 as one of the projects in the Advanced Synthetic-Diamond Bit Technology Development Program (Glowka and Schafer, 1993). To date, HCC has conducted extensive parametric laboratory drilling tests with various bit designs and three rock types. The results of these tests will allow the parameters to be optimized in order to maximize the penetration rate capability of impregnated-diamond drill bits in a given type of hard rock (Glowka *et al.*, 1996a).

Fred Appl has also developed a mechanistic model that describes the effects of the various design parameters on penetration rate and bit wear. The drilling test results allow the calibration of the various algorithms in the model. Once verified, the model can be used to simulate drilling with an impregnated-diamond drill bit in order to develop rock-specific guidelines for the design of such bits.

Statement of Work: HCC will complete their experimental work under this contract in FY97. The data will be analyzed, summarized, and incorporated into the mechanistic model. The model will then be used to design an optimized impregnated-diamond drill bit for each of three selected types of hard rock. The bits will be fabricated and tested in HCC's facilities. The penetration rate and wear rate of each bit will be determined and compared with the performance of bits designed prior to this project. This work will also be completed by the end of FY97.

Early in FY98, a field test plan will be developed for the optimized impregnated-diamond drill bit. A well characterized site, such as Amoco's Catoosa Test Facility, will be selected, and a bit will be designed for specific target zones at that site. The bit will then be fabricated and tested at the site. A bit designed according to procedures developed prior to this project will also be tested under the same conditions. The penetration rate and wear performance of the two bits will be compared to evaluate the results of this project.

Milestones: The following milestones have been adopted for this project:

- *Complete parametric testing of impregnated-diamond core bits (2/97).*
- *Complete incorporation of drilling data into mechanistic model (3/97).*
- *Complete design of optimized impregnated-diamond drill bits for three rock types (5/97).*
- *Complete fabrication of optimized impregnated-diamond drill bits for lab testing (6/97).*
- *Complete lab testing of optimized impregnated-diamond drill bits (9/97).*
- *Complete field test plan for optimized impregnated-diamond drill bits (11/97).*
- *Complete design of optimized impregnated-diamond drill bits for field testing (1/98).*
- *Complete fabrication of optimized impregnated-diamond drill bits for field testing (3/98).*
- *Complete field testing of optimized impregnated-diamond drill bit (6/98).*
- *Complete final Sandia Report on development and testing of optimized impregnated-diamond drill bit (8/98).*

Deliverables: This project will result in the following deliverables:

- *Parametric drilling test data for impregnated-diamond drill bits in three rock types.*
- *Optimized, commercially-available impregnated-diamond drill bits for various hard rock types.*
- *A final report and conference papers on the impregnated-diamond drill bit optimization project.*

Self-Induced PDC Bit Vibrations

Program Area: Hard-Rock Drill Bit Technology

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Program Area Leader: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: PDC bit vibrations are responsible for much of the impact damage that occurs under many conditions in hard-rock drilling. Bit vibrations originate from three primary sources: bit imbalance, where cutter forces sum to a net side force on the bit; drillstring instability, where drilling forces along the entire borehole strike a resonance in the drillstring; and cutter chatter, where individual cutters vibrate at a relatively high frequency against the rock surface. Sandia has addressed the first two sources in its previous PDC bit work. The cutter forces that develop due to the third source, cutter chatter, can cause individual cutter damage and can combine to cause the drillstring to become dynamically unstable.

These phenomena have been studied at the University of Southwestern Louisiana. USL has shown that cutter chatter, also known as self-induced vibration, can be initiated in rock cutting experiments with PDC cutters on lathes and mills. They have defined design and operating conditions under which the chatter occurs, both theoretically and experimentally.

Under this project, USL will advance the concepts from analytical theory to field application by developing guidelines for designing and operating PDC bits so they do not chatter. USL will be funded in this work by Sandia, Unocal, Baker Hughes Inteq, Hughes Christensen, and Stokes and Spiehler. Sandia's Single-Cutter Test Facility will be used to obtain fundamental cutting parameters for the analytical model, and Sandia's Cutter Wear Test Facility will be used to obtain experimental data under actual drilling conditions with a small-diameter bit.

This project has the potential for significantly improving the hard-rock drilling capability of PDC and other drag bits. It will develop design specifications for stable drag bits, shock absorbers, and bottomhole assemblies; will define stable and unstable operating combinations, such as weight-on-bit and rotary speed; and will analyze drillstring and drill bit failures.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits, resulting in a 15% reduction in drilling costs. This project has applicability to all types of drag cutters and thus could result in performance improvements in all the bits under investigation in the various Sandia projects.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to USL for technical work; assist USL in lab testing at Sandia; document results.

- University of Southwestern Louisiana: Perform technical work; conduct lab testing at Sandia; document results.
- Unocal: Provide funding to USL for technical work.
- Baker Hughes Inteq: Provide funding to USL for technical work.
- Hughes Christensen Company: Provide bits for laboratory testing.
- Stokes and Spiehler: Provide technical services to USL.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$66k	Sandia salary, rock specimens, supplies, travel; USL contract for \$40k.
DOE Geothermal - Drilling Tech.	FY98	\$70k	Sandia salary, rock specimens, supplies, travel; USL contract for \$40k.
DOE Geothermal - Drilling Tech.	FY99	\$70k	Sandia salary, rock specimens, supplies, travel; USL contract for \$40k.

Unocal and Baker Hughes Inteq will each provide USL \$10,000 per year, in cash funding. Hughes Christensen will provide roughly \$10,000 worth of bits for lab testing; and Stokes and Spiehler will provide \$10,560 in technical services. The FY97 funding listed above is actually earmarked, carry-over FY96 funding that is already in hand. The funding needs of this project will, therefore, not be counted in the program totals for requested FY97 funding from DOE Geothermal.

Status: This is an ongoing project that was recently begun with earmarked FY96 funding allocated by DOE.

USL has conducted research on PDC cutter chatter for the past three years with funding from the National Science Foundation. This work has its foundations in cutter-tool theory for machining applications. Self-excited vibrations, also known as chatter, are produced by time varying forces in a sustained feed-back process. Because rock is a non-homogeneous and brittle material, cutter forces are not constant but vary about a mean as rock chips are created and burst from the rock surface. If the drilling system is not totally stiff, it will respond to these force variations by varying the depth of cut, leaving a rough or undulating rock surface.

The next cutter to pass over that undulating surface can experience an amplification of the force variations, creating vibrations that lead to larger undulations, which in turn lead to larger vibrations in a feed-back loop. If the phase angle between the undulations is favorable, the vibrations die out and the system is stable. Other phase angles, however, cause the system to be unstable, leading to growing vibration amplitudes. The limit of stability can be represented as a plot of the maximum bit diameter above which the system is unstable for a given speed. This is a so-called stability diagram. Regions where there is a substantial increase in stability have been observed and are labeled "pockets of stability". It is these pockets that provide the most favorable drilling conditions.

The research thus far has been primarily theoretical with a small amount of experimental work that seems to confirm the theory. The next phase of this work will examine the practical aspects of the concept.

Statement of Work: In FY97, USL will measure fundamental cutting parameters related to rock stiffness and process parameters. Sandia's Single-Cutter Test Facility will be used in this work to make instrumented linear cuts. Modifications to the machine will be made to obtain the necessary system compliance to initiate cutter chatter. USL will design the modifications and direct the testing at Sandia. The analytical models will be updated to incorporate the experimental data.

In FY98 and FY99, USL will use Sandia's Cutter Wear Test Facility to evaluate the analytical models with small-diameter drill bits. Modifications to the drillstring in the CWTF will be made to obtain the necessary system compliance. The onset of chatter will be verified and correlated with theory to map pockets of stability. If the theory can reasonably model the experimental results, it will then be used to develop design and operating guidelines for stable PDC bits. By the end of FY99, if the project is successful, a test plan will be developed for full-scale laboratory and field tests to verify the guidelines.

Milestones: The following milestones have been adopted for this project:

- *Initiate contract with USL for three-year project on bit chatter (10/96).*
- *Complete design of cutter chatter tests in the Single-Cutter Test Facility (1/97).*
- *Complete modifications to Single-Cutter Test Facility for cutter chatter tests (6/97).*
- *Initiate cutter chatter tests in the Single-Cutter Test Facility (6/97).*
- *Complete cutter chatter tests in the Single-Cutter Test Facility (8/97).*
- *Complete analysis and report of cutter chatter tests in the Single-Cutter Test Facility (10/97).*
- *Complete design of cutter chatter tests in the Cutter Wear Test Facility (1/98).*
- *Complete modifications to Cutter Wear Test Facility for cutter chatter tests (6/98).*
- *Initiate cutter chatter tests in the Cutter Wear Test Facility (6/98).*
- *Complete cutter chatter tests in the Cutter Wear Test Facility (8/99).*
- *Complete analysis and report of cutter chatter tests in the Cutter Wear Test Facility (9/99).*
- *Develop test plans for full-scale bit tests in the laboratory and field (9/99).*

Deliverables: This project will result in the following deliverables:

- *Experimental results related to PDC cutter chatter.*
- *Design and operating guidelines for stable PDC bits.*
- *A final report and conference papers on the PDC cutter chatter project.*

Advanced Numerical Modeling of Drag-Bit Rock Cutting

Program Area: Hard-Rock Drill Bit Technology

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Justification: The drag cutting process is not well understood despite more than 40 years of directed research worldwide. This is because of the complexity of the process, the difficulty of investigating all the important effects experimentally, and the difficulty of interpreting the results. An accurate, versatile computer simulation of the process would allow the effects of cutter design and downhole conditions to be investigated far more efficiently, in much the same way that numerical modeling tools are routinely used for stress analysis in engineered materials. Until recently, the development of an accurate, economical computer simulation for rock failure during drag cutting was not feasible. Recent advances in finite-element modeling and other computational tools have changed that situation.

Under this project, Sandia will apply its numerical modeling and rock characterization capabilities to the drag cutting process. These capabilities have been developed for other applications and employ advanced and, in some cases, unique computational software and test facilities. Two separate, three-dimensional numerical models will be developed that describe the drag cutting process in rock under elevated temperatures and pressures. Laboratory tests will be conducted to validate the models. The models will then be used to investigate the effects of cutter design on the rock cutting process, with the objective being to define cutter geometries having improved performance and to understand more clearly the effects of operating conditions on bit performance. The project will be concluded by designing a bit according to the findings of this project, then fabricating and testing it in the laboratory or field.

The potential cost savings resulting from this project are more difficult to estimate than some of the other bit projects because this project does not begin with an idea for an alternative bit design. Rather, it will develop a computational tool that can be used identify alternative bit designs. It is, therefore, a more uncertain (i.e., risky) project, but the potential payoff is higher. A conservative goal for this project is the same as in all the bit projects, doubling of both bit life and penetration rate over that achievable with current roller-cone bits, which would result in a 15% reduction in drilling costs.

Project Participants:

- Sandia National Laboratories: Develop numerical models and conduct lab testing; coordinate design and testing of new PDC bit; document results.
- Drill Bit Company (to be determined): Design and fabricate new PDC bit.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$375k	Sandia salary, rock specimens, supplies, travel, computer time.
DOE Geothermal - Drilling Tech.	FY98	\$375k	Sandia salary, rock specimens, supplies, travel, computer time.
DOE Geothermal - Drilling Tech.	FY99	\$350k	Sandia salary, rock specimens, supplies, travel, computer time.
DOE Geothermal - Drilling Tech.	FY00	\$70k	Sandia salary, travel, bit fabrication and testing costs.

It is assumed that one or more bit companies may be interested in participating in the design, fabrication, and testing of the new PDC bit on a cost-shared basis.

Status: This is a proposed new project; however, it builds on work successfully completed at Sandia more than a decade ago. The objective of that work was to develop a numerical code that could be used to predict forces on individual cutters so that cutter wear rates could be predicted and cutter placement on drag bits could be optimized. A two-dimensional finite-element model for drag bit cutting was developed that was capable of accurately predicting results of single-cutter tests conducted at atmospheric pressure, including forces on a worn cutter, rock chip shapes, and damage patterns in the rock. The model also predicted the effects of an increasing wellbore pressure on both the rock cutting mechanism and rate; however, these predictions were never tested in the lab (Swenson, 1983; Zeuch *et al.*, 1985).

Under the current project, we will accomplish two broad objectives. First, building upon past success and more than a decade of steady improvements in computing technology, we will develop advanced numerical models using both the tested finite-element (FE) technique and a new, element-free Galerkin (EFG) method. Second, we will perform fracture toughness measurements on representative rocks, including the coupled effects of temperature and pressure. This data will be used in the EFG model. We will then refine and validate the models against additional laboratory experiments that simulate drag bit cutting under downhole conditions. The final product will be two powerful software tools that can be economically used to identify cutter geometries with improved overall hard-rock cutting performance, particularly at depth.

Statement of Work: This project will be carried out over four years. In FY97, we will implement existing rock failure models in the established FE code, PRONTO. Initial failure models will correspond to those used in the earlier Sandia work. The primary advance over the earlier work will be the availability of an automated meshing algorithm that can re-mesh the FE model as fractures develop. Preliminary code runs will be used to predict the effects of confining pressure on geometrically simple indentation tests performed on three selected rock types, soft, medium, and hard. The tests will consist of pressing a rectangular bar into a jacketed rock cube and will be conducted using a servo-controlled MTS Systems compression-tension apparatus and pressure vessel. Failure models will be modified as needed to predict the stresses, strains, and rock damage patterns observed in these experiments.

Also in FY97, we will develop and conduct laboratory experiments that quantify the effects of confining pressure and temperature on indentation and chip formation, using actual PDC cutters. The cutters will be pressed and twisted on rock specimens under both confined and unconfined conditions, both at elevated and room temperatures, using an existing rock-creep testing apparatus and a newly designed test fixture on an MTS Systems compression-torsion apparatus. In addition to measuring the forces required to indent and cut the rock, specimens and chips will

also be studied to identify changes in the cutting process as a function of changing physical conditions. This test series will extend into the second year of the project. The model's predictions will be compared with the results of these more complex experiments, and the model will again be iteratively "tuned" to replicate test results. This work will continue into FY98.

In FY98, we will also begin development of a two-dimensional EFG extension of the rock cutting model. The EFG method is a very new computational tool that has not yet been applied to this type of problem; hence, the conservative two-pronged approach using both the new EFG method and the proven FE method. The EFG method, however, is ideally suited to tracking the propagation of multiple discrete fractures, which is precisely the problem that drag cutting presents. It is further able to handle changes in local material properties as fractures grow and create new surfaces, without re-meshing. EFG thus offers the greater potential for an economical yet powerful and accurate software tool.

Also in FY98, we will begin laboratory testing of the combined effects of temperature and pressure on the fracture toughness of a selected hard rock. We will use an accepted ASTM fracture toughness test, but will carry it out inside a heated pressure vessel. If a definite effect is identified, more than one rock type may be tested. These data will be used in the EFG model, whose predictions can be compared with the indentation experiments performed the year before under elevated temperatures and pressures. This model can also be iteratively tuned using these test results. This work will continue into FY99, by which time we hope to have two quite different models for the rock cutting process that nevertheless converge to similar answers for the same problem. By the end of FY99, the models will be used to identify new PDC cutter shapes with improved rock cutting performance at depth.

In FY00, we will seek an industry partner with whom to jointly undertake the design, fabrication, and testing of a PDC bit incorporating the new cutters. The bit will likely be tested first in the laboratory under simulated downhole conditions, i.e., elevated pressure and temperature. The results will be compared with those for a conventional PDC bit. Field testing of the bit will follow if the lab test is successful.

Milestones: The following milestones have been adopted for this project:

- *Initiate project on advanced numerical modeling of drag-bit rock cutting (11/96).*
- *Complete development of initial FE model (3/97).*
- *Complete rock indentation experiments under elevated confining pressures (3/97).*
- *Complete design and fabrication of PDC cutter test fixture (6/97).*
- *Initiate development of EFG model (10/97).*
- *Initiate PDC cutter indentation tests at elevated pressures and temperatures (12/97).*
- *Complete PDC cutter indentation tests at elevated pressures and temperatures (12/97).*
- *Complete refinement and validation of FE model (12/97).*
- *Initiate fracture toughness tests on one selected rock type (1/98).*
- *Complete fracture toughness experiments on one selected rock type (8/98).*

- *Complete development of initial EFG model (9/98).*
- *Complete refinement and validation of EFG model (3/99).*
- *Complete fracture toughness tests on other selected rock types (9/99).*
- *Complete identification of new cutter shape with improved cutting performance (9/99).*
- *Complete Sandia Report on the development of advanced numerical models of the drag-bit rock-cutting process (9/99).*
- *Complete design of laboratory prototype PDC bit with new cutter shape (11/99).*
- *Complete fabrication of laboratory prototype PDC bit with new cutter shape (2/00).*
- *Complete laboratory test of PDC bit with new cutter shape (3/00).*
- *Complete design of field prototype PDC bit with new cutter shape (5/00).*
- *Complete fabrication of field prototype PDC bit with new cutter shape (7/00).*
- *Complete field test of PDC bit with new cutter shape (8/00).*
- *Complete final Sandia Report on the design and testing of the PDC bit with new cutter shape (9/00).*

Deliverables: This project will result in the following deliverables:

- *Rock indentation test results at elevated pressures and temperatures.*
- *Two advanced numerical models of the drag-bit rock-cutting process.*
- *A laboratory-tested, field-tested, commercially available PDC bit with a new cutter shape for improved hard-rock drilling performance at depth.*
- *Reports and conference papers on the advanced numerical modeling project.*

Mechanics of Percussive Rock Drilling

Program Area: Hard-Rock Drill Bit Technology

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Justification: Percussive hammer drilling is highly effective in hard, brittle rock, achieving much higher penetration rates than conventional rotary drilling in some cases. There is currently significant interest in percussive hammers in the drilling industry. Air hammers are finding increasing use but are limited to the upper sections of most holes because of water inflow to the well. A mud-driven percussive hammer is under development as a Geothermal Drilling Organization (GDO) project. There is some concern, however, that the increased drilling efficiency achieved with percussive hammers in air-filled holes may not be obtained under elevated hydrostatic pressures when the hole is full of drilling mud. This is because the hydrostatic pressure, coupled with the lithostatic stress in the rock, places the rock in triaxial compression, suppressing its brittle failure behavior and making it appear more ductile.

Under this project, Lawrence Berkeley Laboratory will conduct a theoretical and experimental study of the mechanics of rock failure during percussive hammer drilling at depth. The project will build on LBL's previous work, where they developed a technique for preserving the microfractures that develop in the rock during the loading half of the impact of an indenter against rock. They were thus able to show that rock chips are actually formed during the unloading half of the impact cycle. This technique will be used in this project to study the mechanics of the rock-bit interactions under dynamic percussion loading at elevated pressures and temperatures. An understanding of these mechanics should result in better design and operating solutions to enhance percussive drilling performance at depth.

The potential cost savings resulting from this project are more difficult to estimate than those for some of the other bit projects because this project does not begin with an idea for an alternative bit design. Rather, it will develop an understanding of the rock failure mechanism in percussive hammer drilling, which can be used to design better percussive hammers and bits for operation at greater depth. It is, therefore, a more uncertain (i.e., risky) project, but the potential payoff is higher. A conservative goal for this project is the same as in all the bit projects, doubling of both bit life and penetration rate over that achievable with current roller-cone bits, which would result in a 15% reduction in drilling costs.

Project Participants:

- Sandia National Laboratories: Coordinate LBL work with other bit projects.
- Lawrence Berkeley National Laboratory: Perform technical work; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$250k	Sandia salary, travel, LBL contract for \$250k.
DOE Geothermal - Drilling Tech.	FY98	\$250k	Sandia salary, travel, LBL contract for \$250k.
DOE Geothermal - Drilling Tech.	FY99	\$250k	Sandia salary, travel, LBL contract for \$250k.

Status: This is a proposed new project; however, it builds on a long-time interest of Sandia in percussive hammers (Finger, 1980; Finger, 1984). It also builds on previous work at LBL that investigated the micromechanics of failure of sedimentary rocks. They developed a technique that allowed them to preserve and image the state of rock failure at any particular load during normal load indentation. The technique, which uses molten Wood's metal to flow into the open microfractures, was able to differentiate the two modes of failure that occur during the loading and unloading cycle of the indentation. These two modes are: compaction under a localized hydrostatic stress field during loading, without chip generation; and fracturing and chip generation due to the elastic rebound of the compacted region during unloading.

A similar technique will be used in this project, but the tests will be performed under dynamic loading conditions instead of quasi-static conditions. Also, the tests will be conducted under elevated temperatures and pressures to simulate deep-hole conditions.

Statement of Work: This project will be carried out over 3 years. In FY97, LBL will conduct a literature review; design and construct the experimental impact-loading apparatus; and conduct experiments to study the effects of varying mud pressure, confinement pressure, loading rate, and temperature on normal load indentation using Wood's metal porosimetry. The objective of this work is to provide a micro-mechanical explanation of failure modes observed at the macroscopic scale. Relations between these observed macroscopic phenomena and the microscopic processes will be developed.

In FY98, the effects of other parameters will be experimentally studied, including the effect of shear stresses, loading frequency, and indexing between impacts. A pulsating waterjet will be added to the impact-loading apparatus to allow study of the combined mechanical-hydraulic loading on rock failure. The objective of this work is to identify the loading conditions that enhance brittle fracturing of the rock and the mechanisms by which this enhancement is achieved.

In FY99, the dominant parameters contributing to brittle rock failure will be selected, and selected experiments will be conducted to determine the optimal combination of these parameters to enhance brittle fracturing. It is anticipated, for example, that it will be important to find appropriate combinations of mechanical and hydraulic loading frequencies. A global review of the experimental program will also be conducted to identify the fundamental phenomena. The objective of this work will be to provide recommendations for bit design, bit selection, and drilling techniques to improve the rate of penetration of percussive mud hammers in geothermal drilling.

Milestones: The following milestones have been adopted for this project:

- *Complete literature review and preliminary design of experimental apparatus (11/96).*
- *Complete construction of experimental apparatus (2/97).*
- *Complete experimental study of the effects of varying mud pressures and confinement (5/97).*
- *Complete experimental study of the effects of temperature and loading rate (11/97).*
- *Complete experimental study of the effects of shear stress (2/98).*
- *Complete experimental study of the effects of loading frequency and indexing between impacts (5/98).*
- *Complete experimental study of the effects of combined mechanical-hydraulic loading (11/98).*
- *Complete experiments to determine optimal combination of selected parameters (2/99).*
- *Complete global review of experimental program to identify fundamental phenomena (5/99).*
- *Provide recommendations for bit design, bit selection, and drilling techniques to improve percussive mud hammer performance in geothermal drilling (11/99).*

Deliverables: This project will result in the following deliverables:

- *Rock indentation test results at elevated pressures and temperatures.*
- *Conceptual model of rock failure during percussive hammer drilling at depth.*
- *Reports and conference papers on the mechanics of percussive rock drilling.*

Mudjet-Augmented PDC Bit

Program Area: Hard-Rock Drill Bit Technology

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Justification: Several attempts have been made over the years to commercialize high-pressure (>10,000 psi) water- or mud-jet drilling systems, based on the laboratory evidence that high-pressure jets can significantly improve rock penetration rates. These attempts have invariably failed because of the difficulties of using such high pressures on a drill rig. Equipment maintenance can be costly when an abrasive fluid like drilling mud is pumped at high pressure, and there are significant safety issues.

Several investigators have studied a different approach to effectively using fluid pressures downhole for drilling, namely the use of moderate-pressure (<10,000 psi) fluid jets directed at the rock surface immediately ahead of the drag cutters on a bit. Single-cutter lab tests have repeatedly shown this technique to significantly reduce cutter forces and, consequently, extend cutter life. Although this technique has been used in underground hard-rock mining applications, to our knowledge it has never been applied to deep-hole drill bits.

Under this project, Sandia is teaming with Security DBS, Dynaflow, Inc., and Terra Tek to design, fabricate, and test a mudjet-augmented PDC bit that: 1) takes advantage of the synergistic effects obtained with a moderate-pressure (<6,000 psi) fluid jet and a mechanical cutter when the jet is directed at the cutter-rock interface; and 2) uses pulsating, cavitating jet nozzles to enhance the synergy of the jet and cutter. This project is being funded by the NADET Institute.

Sandia will lead the overall development effort and assist in bit design. The bit will be based on Security's best hard-rock PDC bit and will use Dynaflow's cavitating jet nozzles. It will first be tested at Terra Tek under elevated-pressure conditions, then tested in the field and compared with roller bit and conventional PDC bit performance under the same conditions.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is difficult to predict the ability of this project alone to achieve that level of improved bit performance. This project addresses one component of an improved drag bit design, namely optimal use of available drilling hydraulics. Combined with other improvements in bit design, such as those addressed in

other projects in this plan, this work should help reach the goal. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer NADET funding to Security DBS, Dynaflow, and Terra Tek; coordinate joint work activities; assist in design of prototype bit; coordinate laboratory bit tests; document results.
- Security DBS: Design and fabricate prototype bit; participate in laboratory bit tests; document results.
- Dynaflow, Inc.: Design and laboratory test cavitating jet nozzles; fabricate nozzles for prototype bit; document results.
- Terra Tek: Laboratory test prototype bit under simulated downhole conditions; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
NADET Institute	FY97	\$150k	Sandia salary, travel; Security DBS contract for \$36k; Dynaflow contract for \$37k; Terra Tek contract for \$44k.
NADET Institute	FY98	\$150k	Sandia salary, travel; Security DBS, Dynaflow, and Terra Tek contracts.
NADET Institute	FY99	\$150k	Sandia salary, travel; Security DBS, Dynaflow, and Terra Tek contracts.
NADET Institute	FY00	\$150k	Sandia salary, travel; Security DBS, Dynaflow, and Terra Tek contracts.

This project was selected by the NADET Institute as one of its seven funded projects in FY97. The first year funding for this project will thus not be counted in the program totals for requested FY97 funding from DOE Geothermal.

Status: This is an ongoing project that has recently received funding from NADET. It builds on an idea that, although not new, has never been seriously implemented in PDC bits for deep-hole drilling. That idea is the synergy derived from directed, moderate-pressure waterjets and PDC cutters.

Several investigators have studied the reduction in cutting forces that occurs when a moderate-pressure waterjet is directed at the rock surface immediately ahead of a drag cutter. Hood found that a 7,000-psi waterjet reduced cutting forces on a tungsten carbide cutter in Norite (44,000-psi compressive strength) by about 50%. Glowka (1987) found essentially the same result with a 4,500-psi cavitating jet and a PDC cutter in Sierra White Granite (21,500-psi compressive strength). Dubugnon showed 10-20% reductions in drag cutter forces with nozzle pressures as low as 1,000 psi in Bohus Granite (29,000-psi compressive strength). This effect is thought to be caused by two mechanisms: 1) the jet blasts away the very fine rock flour (debris) created by the surface-crushing action of the cutter against the rock, increasing the stress concentration in the rock and decreasing the forces required to cut the rock; and 2) the fluid enters rock fractures created by the cutter, hydraulically extending the fractures and reducing the mechanical forces required to form a rock chip.

Pulsating, cavitating jet nozzles are particularly effective in this application. Dynaflow, Inc., holds several patents on tuned nozzle designs that produce vortex-shedding jets that not only

cavitate more effectively and at greater wellbore depth than jets produced by conventional nozzles, but also pulsate passively (i.e., no moving parts) due to a resonance set up in a tuned chamber upstream of the nozzle orifice. (These nozzles were used in the experimental work by Glowka, described above.) Collapsing cavities at the rock surface spawn microjets that produce very high impact pressures capable of breaking the rock. Pulsating jets are themselves more effective than conventional jets in eroding and cleaning a rock surface. These nozzles continue to pulsate even when the downhole pressure is high enough to suppress cavitation (Conn *et al.*, 1981; Johnson *et al.*, 1981; Chahine *et al.*, 1984).

Bit performance predictions using Sandia's PDCWEAR bit design code have shown that reduced cutter forces due to mudjet augmentation result in lower abrasive wear rates, lower cutter temperatures, and consequently, longer bit life (Glowka, 1987). PDCWEAR does not model dynamic impact loading; but it is reasonable to expect that lower cutter loading with a properly balanced PDC bit and properly designed bottomhole assembly would lead to reduced impact loading on cutters. These principles will be used to design the bit developed under this project.

Statement of Work: This project will begin in FY97 and, if successful, take four years to complete. Phase 1 is demonstration of feasibility and will be completed in FY97. Phase 2 is bit development and field evaluation and will be completed in FY00.

The objective of the first phase is to demonstrate that a mudjet-augmented PDC bit can be built that drills with increased penetration rate in hard rocks. This will be accomplished by designing, fabricating, and laboratory testing a prototype bit. The laboratory testing will be conducted under elevated ambient pressures so that meaningful penetration-rate data can be obtained and the effects of suppressing the jet cavitation can be investigated. Comparative data will also be obtained for both a non-augmented PDC bit and a geothermal roller-cone bit. Phase 1 consists of the following tasks:

Task 1 - Selection of Bit for Mudjet Augmentation;

Task 2 - Mudjet Nozzle Design Study;

Task 3 - Fabrication of Nozzles for Laboratory Testing and Bit Fabrication;

Task 4 - Mudjet-Augmented, Single-Cutter PDC Tests;

Task 5 - Design of Mudjet-Augmented Bit;

Task 6 - Fabrication of Laboratory Prototype Bit;

Task 7 - Laboratory Testing of Prototype Bit; and

Task 8 - Reporting.

Data related to bit life will be recorded during Phase 1, but an adequate evaluation of expected improvements in bit life cannot be conducted within the constraints of the first phase. Bit life will, therefore, be the focus of field testing conducted during the multi-year Phase 2.

Phase 2 will be conducted only if Phase 1 is successful in demonstrating that a mudjet-augmented PDC bit can be designed and built that drills faster in hard rock than both a conventional PDC bit and a geothermal roller-cone bit. The objective of Phase 2 is to demonstrate that a mudjet-augmented PDC bit can be built that not only drills in the field with increased penetration rate but also demonstrates extended bit life in hard rock. This will be

accomplished by conducting a program of iterative design, fabrication, and field testing of prototype bits under a variety of conditions.

In order to optimize the orientation of directed nozzles, it will be necessary in Phase 2 to conduct mudjet-augmented, single cutter tests. This work will be performed at Sandia using an existing horizontal milling machine and high-pressure water pump. Tests will be run to determine the effects of nozzle inclination angle (relative to vertical), nozzle standoff distance (relative to the rock), and jet impact distance in front of the cutter. Depending on the results of the Phase 1 work, this lab testing will either be performed in the first or second year of Phase 2. This testing will be a relatively small, but important, part of Phase 2.

The project team will devote the majority of Phase 2 to securing and utilizing field testing opportunities covering a variety of lithologies and depths in both geothermal and petroleum reservoirs. Bits will be designed, fabricated, and tested at the selected field sites. In all cases, comparative drilling performance data will also be obtained for a non-augmented PDC bit and/or a geothermal roller-cone bit (as appropriate) in either the same hole or in offset holes with similar lithologies. Limited laboratory testing of some of the field prototype bits may also be done under elevated ambient pressures.

Phase 2 is anticipated to require \$450k and three years of effort at the funding levels that may be available (\$150k/yr assumed). This funding level would allow the project to proceed cautiously, and it could be terminated at the end of any given year if the field results do not look favorable. Under these conditions, a successful conclusion to this project would imply that a commercial product is almost certain to develop.

Milestones: The following milestones have been adopted for this project:

- *Initiate mudjet-augmented PDC bit feasibility study (10/96).*
- *Complete selection of the bit to be modified for mudjet augmentation (11/96).*
- *Complete nozzle design study (4/97).*
- *Complete prototype bit design (5/97).*
- *Complete fabrication of nozzles for prototype bit (6/97).*
- *Complete fabrication of prototype bit (7/97).*
- *Complete prototype bit laboratory testing (8/97).*
- *Complete Phase 1 final report on mudjet-augmented PDC bit feasibility study (9/97).*

No milestones are given for Phase 2 (FY98-00) because it has not yet been defined.

Deliverables: This project will result in the following deliverables:

- *A field-tested, commercially available mudjet-augmented PDC bit that drills with improved performance in hard rock using mud pump pressures that are currently available or can be economically installed on a rig.*
- *Reports and conference papers on the mudjet-augmented PDC bit development and testing effort.*

Downhole Pump for Ultra-High-Pressure Drilling

Program Area: Hard-Rock Drill Bit Technology

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Several attempts have been made over the years to commercialize high-pressure (>10,000 psi) water- or mud-jet drilling systems, based on the laboratory evidence that high-pressure jets can significantly improve rock penetration rates. These attempts have invariably failed because of the difficulties of using such high pressures on a drill rig. Equipment maintenance can be costly when an abrasive fluid like drilling mud is pumped at high pressure, and safety is a concern.

Another approach being investigated by FlowDril Corporation is to generate the high pressures downhole with a tool called the Downhole Pump (DHP). This approach completely eliminates the safety concerns and costs associated with generating the high fluid pressures at the surface. The DHP is a pressure intensifier that boosts a portion of the drilling fluid flow to a pressure as high as 35,000 psi, which is classified as an ultra-high pressure (UHP). This portion of the drilling fluid is directed through nozzles that blast the rock surface with high-speed jets capable of breaking the rock, even without mechanical assistance. These jets have been used to augment the cutters on a PDC bit, which serve to keep the hole in gage. In a sense, the mudjets act as additional cutters that do not wear out. Rock penetration rates up to 2.5 times those of conventional drilling have been observed in laboratory tests with the DHP.

In this project, FlowDril will continue development of their DHP and evaluate its potential for use in geothermal drilling. This project will complement ongoing work FlowDril is conducting with Gas Research Institute (GRI) and DOE Morgantown Energy Technology Center (METC) funding. The current primary objective of that work is to improve reliability of the DHP so that it can repeatedly operate downhole for 40-60 hours between overhauls. Laboratory and field tests to date have achieved up to 40.5 hours, but not yet reliably. With design refinements, FlowDril expects to achieve the goal within the next few months. Under this project, they will assess and evaluate potential technical problems and solutions for drilling at higher temperatures in geothermal applications. They will also conduct jet-assisted laboratory drilling tests in igneous and other hard-rock types. If the results look favorable, a plan will be written for developing a high-temperature DHP for geothermal applications.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is difficult to predict the ability of this project alone to achieve that level of improved bit performance. This project addresses one component of an improved bit design, namely ultra-high-pressure jet assistance. Combined with other improvements in bit design, such as those addressed in other projects in

this plan, this work should help reach the goal. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer funding to FlowDril to augment their GRI, DOE-METC, and internal funding; assist in defining geothermal requirements.
- FlowDril Corporation: Conduct all technical work; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$300k	Sandia salary and travel; FlowDril contract for \$300k.

FlowDril is providing \$500k of its own internal funding for DHP development. GRI is expected to provide an additional \$500k to FlowDril's basic development effort beginning in January, 1997. Also, FlowDril submitted a supplementary budget request to DOE-METC in July, 1996 for an additional \$650k.

Status: This is a proposed new project for Sandia, although it does build upon the first DHP feasibility study that Sandia funded FlowDril's parent company Flow Industries to perform in the early 1980s. That study (Kelsey *et al.*, 1985) concluded that the DHP approach is the most favorable of several potential techniques for delivering high-pressure drilling fluid downhole. Because of budget constraints at the time, Sandia was not able to fund development of the system.

FlowDril was able to secure funding from GRI beginning in FY93 to conduct a market analysis and an updated technical feasibility assessment. Funding support from DOE-METC began in FY94. Technical feasibility was established with the demonstration of a high-pressure dynamic seal for pumping drilling mud at 35,000 psi and inlet temperatures of 250°F, and by establishing the ability to rapidly valve the drilling mud without the valve sticking, silting, or exhibiting excessive wear or erosion.

A prototype DHP for 8-3/4 inch holes was designed and fabricated. It was tested downhole seven times in five wells, between January and September 1995, achieving operating times between one hour and 40.5 hours. Jet-assisted ROP enhancement as high as 1.7 times the conventional drilling rate was demonstrated.

Design and fabrication of a smaller prototype for drilling 7-7/8 inch holes was begun in October 1994 and first lab tested in September 1995. It was field tested in March, 1996, with downhole circulating temperatures of 160-175°F. Penetration rates 1.5 times those of conventional drilling were observed. An operating life of 12-16.6 hours was obtained.

Laboratory tests have also been run with the DHP in sedimentary rocks in FlowDril's drill bit test stand, demonstrating penetration rates up to 2.5 times those of conventional drilling. Although high-pressure jet cutting tests with various types of granites and basalts have been conducted, FlowDril has not yet conducted laboratory drilling tests with UHP jet assistance.

Statement of Work: This is a one-year project. If the project proves the feasibility of developing a DHP for geothermal applications, a project plan will be written at the end of FY97 to continue the work in FY98.

The primary thrust in FY97 will be to achieve the reliability goal of 40-60 hours of operation between overhauls. Design refinements, laboratory testing, and two field tests will be conducted to achieve this goal. This part of the project will be funded jointly by GRI, DOE Geothermal (through Sandia), and possibly DOE-METC. The jointly sponsored field tests will provide dual benefits at this stage in the tool's development: demonstration of the practicality of DHP technology; and the opportunity for more iterations in refining the design and testing it.

FlowDril will assess and evaluate potential technical problems and solutions for drilling at higher temperatures in geothermal applications. They will assess possible required differences in the DHP component designs and evaluate possible material and design issues that may arise at higher temperatures.

Laboratory drilling tests in hard rock types will also be conducted with UHP assistance. These tests, which will be conducted under elevated borehole pressures, will demonstrate the potential for jet assistance in geothermal drilling and will quantify the effects of borehole depth on the effectiveness of the technique.

If the results look favorable for the DHP concept in geothermal drilling, a plan will be written for developing a high-temperature DHP. This plan will be completed by the end of FY97, with the work beginning in FY98.

This project differs from the mudjet-augmented bit project. These two projects represent two approaches to mudjet enhancement. In the mudjet-augmented PDC bit project, moderate-pressure (< 6,000-psi) jets are directed at the cutter-rock interface, thereby assisting the drag cutters in the rock-cutting process. In this project, ultra-high-pressure (35,000-psi) jets are directed at the rock surface between the cutters, but not at the cutter-rock interface; these jets cut the rock on their own.

Milestones: The following milestones have been adopted for this project:

- *Complete two field tests of DHP in a gas well to demonstrate UHP jet assistance capability (1/97).*
- *Complete evaluation of the effects of temperature on component design for a DHP (3/97).*
- *Identify all material or design issues requiring further research (6/97).*
- *Complete laboratory drilling experiments using ultra-high pressures in hard rock types (8/97).*
- *Complete project plan for future DHP development for high-temperature applications (9/97).*
- *Complete Sandia Report on the feasibility assessment of DHPs for geothermal drilling (9/97).*

Deliverables: This project will result in the following deliverables:

- *A final report assessing the feasibility of developing and using an ultra-high-pressure (UHP) downhole pump (DHP) in geothermal drilling.*

Explosively-Compacted Drag Cutters

Program Area: Hard-Rock Drill Bit Technology

Project Leader: Doug Drumheller, Sandia National Labs, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8920, Fax 844-3952, dsdrumh@sandia.gov
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Program Area Leader: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: It is clear that drag bits can achieve higher penetration rates than roller bits in most rock types. The best drag cutters currently made incorporate polycrystalline diamond compact (PDC), which combines the fracture toughness of tungsten carbide with the hardness of diamond to effectively drill soft and medium rocks; but PDC bits have thus far failed to be commercially successful in hard rock drilling. The problem is that bit life rapidly degrades under the high-temperature, high-impact conditions inherent to hard-rock drilling. If drag cutters with improved fracture toughness and high-temperature abrasion resistance could be developed, the penetration rate advantages of drag bits could be made available to hard rock drilling.

The objective of this project is to develop and test explosively consolidated boron sub-oxide (B_6O) ceramics for use as rock cutters in high-temperature, hard-rock drilling. Preliminary experiments at New Mexico Institute of Mining and Technology have produced cutters with a fracture toughness ($5-6 \text{ MPa m}^{1/2}$) rivaling that of tungsten carbide ($7-23 \text{ MPa m}^{1/2}$), a hardness (44 GPa) rivaling that of polycrystalline diamond (50 GPa), and temperature stability ($>1800^\circ\text{C}$) that dramatically exceeds that of PDC cutters ($350/750^\circ\text{C}$). Refinement of the explosive compaction process as proposed in this project could produce ceramic material with greatly improved properties. If so, the new material may have a good potential as a hard-rock cutter, where high-temperature wear- and impact-resistance are important.

The goal for this project is the same as in all the bit projects, a doubling of both bit life and penetration rate over that achievable with current roller-cone bits. It is difficult to predict the ability of this project alone to achieve that level of improved bit performance. This project addresses one component of an improved bit design, namely improved cutter materials. Combined with other improvements in bit design, such as those addressed in other projects in this plan, this work should help reach the goal. As previously noted, such an improvement in bit performance would reduce well costs by about 15%.

Project Participants:

- Sandia National Laboratories: Administer funding to New Mexico Tech; test experimental drag cutters.
- New Mexico Institute of Mining and Technology: Conduct all explosive compaction work; fabricate experimental drag cutters; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$35k	Sandia salary and travel; New Mexico Tech contract for \$30k.

Status: This is a proposed new project for Sandia, although New Mexico Tech has been studying the process for several years. In this process, boron sub-oxide is produced by explosive consolidation of powdered mixtures of either B and B₂O₃ or B and ZnO. These powders are loaded into a recovery fixture, which is then surrounded by explosive. Detonation of the explosive compresses and heats the powders. This process has produced ceramics with impressive properties, as noted earlier. Sandia test several cutters produced in this manner in our Single-Cutter Test Facility. The measured cutter forces were found to be comparable to those of a PDC cutter of the same size. In this project, New Mexico Tech will continue development of the process to reduce the voids in the material and increase its strength and fracture toughness.

Statement of Work: This is a one-year project. New Mexico Tech will perform additional explosive compaction process variable testing, including container design and measurement of mechanical properties. The optimized process will be used to fabricate cutters for rock cutting tests at Sandia. At least two cutters will be fabricated in a shape similar to that of a PDC cutter. Sandia will first test the cutters in the linear Single-Cutter Test Facility, where cutter drag and penetrating forces will be measured as a function of depth of cut. The performance of these cutters will be compared with that of conventional PDC cutters. The cutters will then be tested for wear performance in the Cutter Wear Test Facility. The wear rates will again be compared with those of conventional PDC cutters.

The rock cutting results will be examined to determine the feasibility of using explosively compacted drag cutters for rock cutting. If the material appears promising, a program plan will be written by the end of FY97 for further work in FY98.

Milestones: The following milestones have been adopted for this project:

- *Initiate explosive compaction process variable testing (11/96).*
- *Complete explosive compaction process variable testing (3/97).*
- *Complete fabrication of explosively compacted drag cutters (5/97).*
- *Complete testing of explosively compacted drag cutters in the Single-Cutter Test Facility (6/97).*
- *Complete testing of explosively compacted drag cutters in the Cutter Wear Test Facility (8/97).*
- *Complete Sandia Report on the feasibility of explosively compacted drag cutters for rock drilling (9/97).*
- *Complete project plan for future work on explosively compacted drag cutters (9/97).*

Deliverables: This project will result in the following deliverables:

- *A final report assessing the feasibility of fabricating and using explosively compacted drag cutters for rock drilling.*

V. High-Temperature Instrumentation

a. Background

Accurate knowledge of reservoir conditions is mandatory for proper development and management of geothermal fields. Downhole temperatures and pressures under static and flowing conditions are necessary for understanding the short- and long-term productivity of a well. The location and orientation of producing fractures must be known in order to properly locate, drill, complete, and produce the well. Downhole fluid chemistry must be known and understood in order to properly select downhole materials and to understand the reservoir. All of these data can be obtained with downhole logging tools.

The geothermal environment is a challenge for logging tools. High pressures require special design techniques. High temperatures require the use of high-temperature electronics and/or heat-shielding such as a dewared housing. Corrosive fluids can be a challenge, particularly for costly logging cables.

Because of these technical problems and the small size of the geothermal market, the cost of individual wells logs in the geothermal industry is high. Consequently, operators do not order as many logs as they could use. Sandia has undertaken the dual task of both developing logging technologies that reduce the cost of obtaining downhole data, and demonstrating the utility of the data in understanding the reservoir, thereby increasing the demand for wellbore logs.

The technology on which we have focused is high-temperature memory tools. The advantages of this type of logging tool are that it does not require a multi-conductor wireline and is relatively low cost to operate. Memory tools are self-contained and can be run on a "slickline" that is available on every rig or can be hauled in the back of a pickup truck. The data is stored in memory downhole as a function of time, while the tool location is recorded at the surface as a function of time. Once back on the surface, the tool's data are merged with the surface data to attain downhole data as a function of depth. The concept here is that well logs can be run any time during or after the drilling process by the operator or a low-cost service company.

To attain high-temperature capability, the memory tools are designed to fit inside a stainless-steel, dewared housing. This allows conventional, commercially available electronics to be used at high temperatures downhole for extended periods of time. The basic memory tool can serve as a platform for a variety of measurements.

b. Justification for Technology Development Effort

It is difficult to estimate the cost savings that could result from increased use of high-temperature logging technology. It is obvious from the wealth of logging tools and ongoing well analysis research within the hydrocarbon industry that logging instrumentation has a valued place. Hydrocarbon exploration geologists and reservoir engineers must be receiving information that is of greater value to them than the cost of the survey.

For the geothermal reservoir engineer, better wellbore information and data analysis could lead to better understanding of the reservoir, resulting in optimal production and injection strategies to maximize the life of the reservoir and minimize the need for replacement wells. For the exploration geologist, better wellbore information while drilling could lead to better characterization of the reservoir, thereby potentially reducing drilling costs and improving wellbore productivity. It is not difficult to imagine a situation where better reservoir knowledge could eliminate the need for one well out of a total field of 20 wells, saving 5%. Every

replacement well eliminated as a result of better reservoir management would save roughly another 5% of the well-field costs for that size field.

c. High-Temperature Instrumentation Projects

Eight projects are planned in the high-temperature logging program area. Four of these projects are ongoing projects that are nearing completion. Four are new proposed projects that address other needs and opportunities for high-temperature instrumentation.

Temperature/Pressure Memory Tool

Program Area: High-Temperature Instrumentation

Project Leader: Joe Henfling, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-6720, Fax 844-3952, jahenfl@sandia.gov

Program Area Leader: Randy Normann, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 845-9675, Fax 844-3952, ranorma@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Because of the nature of the geothermal resource, the most basic downhole measurements for this industry are probably fluid temperature and pressure. These two properties determine the enthalpy, or usable energy content, of the wellbore fluid. Downhole temperature data are also valuable during drilling because of the role that temperature plays on degradation of drilling fluids and setting characteristics of cement.

Under this project, Sandia has developed a state-of-the art temperature/pressure memory tool. The purpose of this development has been two-fold: 1) to demonstrate the use of advanced, commercially available microprocessors and memory devices as the basis for a multitude of commercially-viable downhole tool designs; and 2) to demonstrate the use of the temperature/pressure tool to obtain reliable, economical downhole data that is of significant utility to the geothermal operator in managing a reservoir. The 2-inch diameter tool employs on-board power, data processing, and memory, and it uses a dewared housing that serves as a heat shield. It is rated for operation to 400°C for 8 hours.

Estimated cost savings resulting from the use of the temperature/pressure memory tool are difficult to estimate, as previously noted. The primary benefit of the tool would be the capability for obtaining large amounts of needed temperature and pressure data in an economical manner. This project addresses part of an overall program to reduce well-field costs 5% by improving reservoir knowledge and eliminating the need for one or more wells.

Project Participants:

- Sandia National Laboratories: Conduct tool development; work with industry to evaluate the tool; document and publish results.
- Southern Methodist University: Assist in field evaluation of the tool; document results.
- Service Company and/or Tool Manufacturer (to be determined): Participate in field evaluations; commercialize the tool.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$90k	Sandia salary, hardware, travel, field expenses; SMU contract for \$10k.

Other industry participants will provide funding to cover their own expenses on this project.

Status: This is an ongoing project. It has been under way at a modest level of effort since 1992. The objective has been to build a calibrated tool that can be easily transported to the site, even to the extent of using commercial airline travel when convenient (Lysne, 1992). This objective has been accomplished. The tool can be transported in two airline-checkable cases, and the data can be downloaded to a notebook computer.

The tool is capable of storing more than 10,000 data points from one logging run. The temperature measurement is the most accurate of any tool known to Sandia. The temperature profile obtained with the tool is generally so detailed that even small increases of 0.01°C can be detected, thereby opening new avenues of investigation, such as lithology tracking using temperature gradients. Using the programmable interface, the tool can be set up to start taking data after it contacts the wellbore fluid, thus allowing the tool to sit in standby mode, ready to be deployed by the drilling crew. This is another capability not found in commercial tools. The Sandia-developed software can correct temperature measurement errors created by fast, poorly controlled drill-rig slicklines, correcting for logging rates up to 300 ft/min. This is another feature not yet found in industry (Normann *et al.*, 1996a).

The temperature/pressure tool and software is forming the baseline system for the other logging tools under development at Sandia. The fluid sampler and the core-tube data logger share virtually all the same electronic components and software. The spectral gamma tool shares part of the same software.

The temperature/pressure tool has been extensively field tested. Over forty logs in geothermal wells have been consecutively run without a single failure.

In light of the reliability demonstrated thus far with the tool, a notice was placed in the *Commerce Business Daily* in early August, 1996, stating that the technology developed and used in the temperature/pressure memory tool would be made available to parties interested in commercializing and using the tool. By the end of August, twelve responses to the ad had been received, two of which have already initiated site visits to examine the instrument. This commercial interest will be pursued in FY97, with the intent of substantially completing the project by the end of the year.

Statement of Work: By the beginning of FY97, additional information on the temperature/pressure memory tool design will be sent to respondents who answered the *CBD* ad. We will continue to pursue these commercial interests by holding discussions, providing technical information, and participating in laboratory and field evaluations with the respondents.

SMU will participate in the field testing effort by providing a slickline trailer and qualified personnel to run temperature/pressure logs. Professor David Blackwell will evaluate the measurements for credibility and meaning. The quality of the temperature measurements made with the Sandia tool is aiding research at SMU on wellbore lithology discrimination.

Sandia will supply technical design information to industry partners. For example, one respondent has asked for design suggestions for adding interface components to the tool to fit within their logging system. Software has been sent to respondents which we will assist in modifying to fit their systems, as requested. The temperature/pressure tool is a versatile tool and could be used in a variety of manners for various commercial purposes.

Milestones: The following milestones have been adopted for this project:

- *Complete initial discussions with interested industry representatives (12/96).*
- *Complete Web site for temperature/pressure tool with data (3/97).*
- *Complete transfer of temperature/pressure memory tool technology to industry (8/97).*
- *Complete final Sandia Report on development and testing of temperature/pressure memory tool (9/97).*

Deliverables: This project will result in the following deliverables:

- *Commercial temperature/pressure memory tools that use Sandia-developed designs or technology.*
- *Greater use of downhole temperature and pressure data in the geothermal community.*
- *Conference papers and a final report on the development and testing of the temperature/pressure tool.*

Downhole Steam Sampler

Program Area: High-Temperature Instrumentation

Project Leader: Joe Henfling, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-6720, Fax 844-3952, jahenfl@sandia.gov

Program Area Leader: Randy Normann, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 845-9675, Fax 844-3952, ranorma@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Fluids produced from geothermal wells are often corrosive and necessitate the use of chemical treatment and corrosion-resistant materials in the fluid-handling components of geothermal power plants. In some cases, corrosion-abatement procedures are costly enough that alternatives are desirable. It may be possible in some reservoirs to isolate and plug certain production zones that produce the most corrosive fluids. Before this can be done, the chemistry of the fluid produced in each production zone must be studied. Obtaining reliable fluid samples from each production zone, however, is not simple because of the temperatures and pressures involved. Previous fluid samplers have been prone to leakage and contamination of the fluid samples.

Under this project, a prototype downhole steam sampler has been developed to capture and condense steam samples in fields such as the Geysers. The 2-inch tool is self-contained, dewatered, and can be run on a slickline. It employs a microprocessor for timing and operation of the high-pressure valve, and eutectic material is used to condense the steam sample. On-board sensors provide a temperature log of the wellbore and the pressure-temperature states of the sampled material. These latter measurements are unique to the Sandia tool. They provide important thermodynamic information as well as verifying the proper operation of the valve system.

Initially, the tool will be used to evaluate the chloride and non-condensable gas increase that has been noted in the Geysers. These problems may be coupled and perhaps are due to the depletion of the reservoir. Other geotechnical problems may arise when effluent waters are introduced into the reservoir upon the completion of the Lake County waste water project. Estimates of cost savings attainable with a valid geotechnical model of the Geysers run into the multi-million-dollar range.

Project Participants:

- Sandia National Laboratories: Conduct tool development; work with industry to field-evaluate the tool; assist development of proposal; document and publish results as they apply to the initial funding from the DOE Office of Basic Energy Sciences.
- Unocal Geothermal: Overall project management; proposal development.
- Thermochem: Assist in open-solicitation proposal; assist in field evaluation of the tool; design of sample extraction system; chemical analysis of samples.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$105k	Sandia salary, hardware, travel, field expenses.

Major funds for this project are being sought through a proposal under preparation at Unocal Geothermal. Funds noted above are to enable Sandia to help in the development of the proposal, and this activity may require additional testing in the Geysers. Industry participants will provide the seed funding to develop the proposal.

Status: This has been ongoing project since 1992. The steam sampler was developed with funding from the DOE Office of Basic Energy Sciences (Lysne, 1991a).

The steam sampler has been extensively tested in an industrial steam plant to ensure reliable operation. It has also been field tested on the surface at the Geysers, where it was used to obtain steam samples from a Unocal well (Normann *et al.*, 1996a). These tests were very encouraging and have led to a Unocal management decision to pursue a project of extensive deployment. Calpine, a partner with Unocal in the Geysers, also has an interest in seeing that the project moves forward.

The next step in the development process is to further test the tool downhole in a well and to develop surface sample extraction techniques to recover the sample. An agreement has been reached with Unocal Geothermal and Thermochem to jointly seek funding for this work through the open-solicitation process established by the reservoir technology portion of DOE's Geothermal Program. Unocal and Thermochem will lead this effort, and Sandia will provide technical assistance where appropriate.

Statement of Work: Work in FY97 will concentrate on two areas: 1) working with Unocal and Thermochem to develop a proposal for the open-solicitation process and to secure funding for the next phase of steam sampler development; and 2) testing a high-pressure valve in the laboratory to evaluate its potential for converting the steam sampler to a downhole liquid sampler.

A proposal has been mostly written but has not yet been finalized. Sandia will continue to work with Unocal and Thermochem to provide information that can be used in the proposal. The goal is for Unocal and Thermochem to submit the proposal by December, 1997. Assuming a several-month review process, it is possible that funding for continued development will be available before the end of FY97. A project plan will then be written that includes the work specified in the proposal.

A high-pressure valve that has potential for use in a downhole liquid sampler will be tested in Sandia's steam plant to assess its sealing capabilities. If the valve passes the tests, it will be incorporated into a design for a liquid sampler. Industry interest in such a tool will be assessed, and if it exists, a project plan will be written for further development, fabrication, and testing of a downhole liquid sampler for geothermal wells.

Milestones: The following milestones have been adopted for this project:

- *Provide all data needed by Unocal and Thermochem for open-solicitation proposal (12/96).*

- *Complete high-pressure valve tests in Sandia steam plant (3/97).*
- *Complete design of downhole liquid sampler (4/97).*
- *Complete project plan for further development and field testing of the downhole steam sampler (7/97).*
- *Complete survey of industry interest in a downhole liquid sampler (8/97).*
- *Complete project plan for development and testing of a downhole liquid sampler (9/97).*

Deliverables: This project will result in the following deliverables:

- *Project plans for further development of a downhole steam sampler and a downhole liquid sampler.*

Spectral Gamma Memory Tool

Program Area: High-Temperature Instrumentation

Project Leader: Randy Normann, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 845-9675, Fax 844-3952, ranorma@sandia.gov

Program Area Leader: Randy Normann, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 845-9675, Fax 844-3952, ranorma@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The interaction between hot fluids and the host rock of a geothermal system commonly leads to dissolution of the host rock and reprecipitation of secondary minerals. In many geothermal systems being developed in silicic volcanoclastic terrain, abundant potassium is available for remobilization. The appearance of potassium minerals not present in the background host rock is characteristic of precipitation in zones of hydrothermal activity. Detecting potassium with downhole logging could therefore prove to be a powerful technique for identifying steam- or hot water-bearing fractures.

Variations in the natural radioactivity of rocks in the subsurface have proven to be a valuable exploration tool for natural resources. Downhole gamma-ray detectors have been especially useful because of the ability of natural gamma to penetrate well casings. The natural gamma-ray log is commonly used by the oil and gas industry to delineate the occurrence of high concentrations of clay minerals in shale layers, which is indicative of petroleum-bearing structures. Assignment of lithology solely on the basis of its total gamma-ray emission can be ambiguous, however, so a spectral gamma log capable of resolving the gamma count into the three principal components of the total gamma-ray spectrum is more useful. One of these components is potassium (^{40}K); the other two are the thorium (Th) and uranium (U) series. Certain minerals can be differentiated on the basis of the ratios among these three gamma signals.

Under this project, Sandia has developed a high-temperature spectral gamma memory logging tool that can be run on a slickline. It employs an on-board microprocessor for timing and data acquisition, memory modules, and a sodium iodide spectral gamma detector. The tool has been successfully tested at The Geysers, where it revealed increased levels of potassium at a fractured, permeable zone encountered during a coring project. The primary remaining work with this tool is to improve its sensitivity, then work with industry to deploy the tool in multiple wellbores to determine the characteristic spectral gamma signatures of typical geothermal formations. This will provide the basis for using the tool for fracture identification by the industry.

Potential cost savings resulting from the use of the spectral gamma memory tool are difficult to estimate. The primary benefit of the tool would be its capability for mapping fractures, which may lead to better understanding of the fracture network associated with lost circulation and production zones. A secondary benefit is tracking borehole lithology through well casings to improve reservoir models using cased wells. Better reservoir and fracture knowledge could optimize well placement and productivity, possibly leading to a reduction in the number of wells required for a given geothermal project. A reduction of one well in twenty represents a 5% drilling cost savings for the project.

Project Participants:

- Sandia National Laboratories: Conduct tool development; work with industry to field-test the tool and collect data; document and publish results.
- Unocal Geothermal: Participate in field-testing the tool and collecting data.
- Other Geothermal Operators (to be determined): Participate in field-testing the tool and collecting data.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$160k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY98	\$80k	Sandia salary, hardware, travel, field expenses.

Industry participants will provide funding to cover their own expenses on this project.

Status: This has been ongoing project since 1992. The spectral gamma tool was built by GRC, Inc., under contract to Sandia. Since that time, Sandia has improved the tool's calibration and high-voltage stability and has developed algorithms for data analysis (Lysne, 1992).

The spectral gamma memory tool is 10 ft long and 2 inches in diameter. It is designed to operate at 400°C for 8 hours. This is the only known spectral gamma tool suitable for geothermal applications.

The tool was field tested in 1994 in a deepened portion of borehole SB-15 at The Geysers. This logging revealed a statistically significant ⁴⁰K signal covering two intervals rich in sericite and transected by fractures. Sericite contains 10% potassium by weight. The signal dropped below significance in the intervening interval where the sericite and fractures are absent. This test indicated that a high-quality spectral gamma log could be used to map fractures in some cases. Little is known about spectral gamma data inside geothermal wells. There may also be correlations between producing lithologies and the presence of thorium and uranium in some cases (Normann *et al.*, 1996a).

Although the spectral gamma memory tool is functional, additional work is needed to make it usable for routine logging. The software is functional but difficult to use, and it does not automatically mesh the spectral gamma data with the depth encoder data to match spectral gamma readings to depth. An additional tool is also needed so that two tools are available for logging, a standard requirement of Unocal.

Statement of Work: This project will be substantially completed within two years. In FY97, an additional spectral gamma memory tool will be built which incorporates several design improvements. One of these improvements is a larger, more sensitive gamma-detection crystal. If possible, the existing tool will also be upgraded.

The tools will then be loaned to industry with the understanding that all data collected will be published. The depths will be reported as relative depths, and the well locations will be withheld

to protect proprietary well field and reservoir information, as necessary. Sandia will support these activities by training industry operators and by participating in the logging activities when possible.

Unocal Geothermal has already agreed in principle to test the spectral gamma memory tools in this manner. Sandia will also seek the participation of other geothermal operators so that a wide database of spectral gamma readings can be assembled. This database will help determine the potential of the tool for geothermal fracture mapping.

If successful, this effort will lead to commercial interest in the tool. Sandia will work to transfer the technology to the industry, either through a well logging service or a geothermal operator.

Milestones: The following milestones have been adopted for this project:

- *Complete testing of depth-encoding software for the spectral gamma tool (1/97).*
- *Order dewars and electronic components for the second spectral gamma tool (2/97).*
- *Assemble electronics for the second spectral gamma tool and initiate testing (4/97).*
- *Complete machining of mechanical parts of the second spectral gamma tool (4/97).*
- *Complete temperature test of assembled second spectral gamma tool (6/97).*
- *Calibrate second spectral gamma tool at Grand Junction, CO (7/97).*
- *Complete first field test of second spectral gamma tool (12/97).*
- *Complete discussions with geothermal operators on field testing the spectral gamma tool (3/98).*
- *Complete Sandia Report on the spectral gamma memory tool, including field data obtained to date (9/98).*

Deliverables: This project will result in the following deliverables:

- *Two spectral gamma tools for use by the industry in obtaining public spectral gamma data in geothermal wells.*
- *Commercially available spectral gamma logging service for the geothermal industry.*
- *Conference papers and a final report on the development and testing of the spectral gamma tool.*

Core-Tube Data Logger

Program Area: High-Temperature Instrumentation

Project Leader: Joe Henfling, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-6720, Fax 844-3952, jahenfl@sandia.gov

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Justification: Wireline core drilling, increasingly used for geothermal exploration, employs a core tube to catch the rock core created during the drilling process and to transport it uphole with a wireline. This process lends itself to the retrieval of information that could be gathered during the drilling process. Information such as downhole temperature, core orientation, drillstring inclination, and drillstring orientation would be very useful to the drilling and reservoir exploration processes. A downhole memory tool that rides with the core tube, measures, and stores this data would require little, if any, additional rig time to use, resulting in essentially "free" information. Downloading data at the surface could be done very quickly, and the tool could be returned downhole with the core tube. Battery changes may require some additional time, but operating two tools would eliminate lost time.

Such a core-tube data logger is under development in this project. This tool, actually any one in a series of tools, attaches to the top of the core tube and has the same top fitting to connect it to the wireline. The tool will be heat shielded for geothermal applications to enable the electronics to survive higher temperatures. To date, an unshielded temperature tool and an unshielded inclination tool have been fabricated and successfully tested on a Tonto Drilling Services wireline core rig. Additional measurements such as core and drillstring orientation will be added as development of this tool series continues.

Estimated cost savings resulting from the use of the core-tube data logger tools can be made as follows. First, it should be noted that the tool will eliminate the need for some time-consuming surveys, such as temperature and directional surveys. Over the entire drilling period, the time saved by receiving free data every time the core tube is pulled could easily add up to three days of drilling. Secondly, conventional core orientation procedures require approximately 1/2 day per orientation. Assuming ten core orientations would be run in a typical exploratory well, this results in five days of rig time saved. Each day of rig time eliminated would reduce exploratory well costs by about 1/2%. This project could, therefore, be responsible for about a 4% reduction in exploratory well costs. Assuming exploration drilling costs account for 10% of the total drilling costs for a project, a 4% reduction in exploration drilling costs represents a 0.4% reduction in total drilling costs.

Project Participants:

- Sandia National Laboratories: Conduct tool development; work with industry to field-test the tool; document and publish results.
- Tonto Drilling Services, Inc.: Participate in field-testing the tool.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$150k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY98	\$30k	Sandia salary, hardware, travel, field expenses.

Industry participants will provide funding to cover their own expenses on this project.

Status: This has been ongoing project since the middle of FY96. The idea for a core-tube data logger has been discussed between Tonto and Sandia over the past year. Using previously developed hardware and software from the Sandia logging tools made implementation simple. Tonto supplied the mating parts of the core-tube, and Sandia manufactured the electronic housings and installed the electronics. Including site testing, Sandia has spent about three weeks on this effort to date.

Two tools were fabricated and tested in August, 1996. The first tool was a simple temperature memory tool. The second tool contained an inclinometer. Both tools were unshielded and were thus rated at a maximum temperature of about 125°C. The tools were tested on a Tonto wireline core rig near Elko, NV. A total of eleven tests were conducted in two different wells, near 2,000 ft and 4,500 ft depths. In all tests, the tools successfully measured and stored the downhole fluid temperature and drillstring inclination during the entire trip of the core tube.

The success of these tests gave rise to two other concepts for core-tube data logging. In one, an inertial navigation system could be packaged into a tool that would travel downhole with the wireline that is used to retrieve the core tube, thus storing and retrieving directional data with each trip of the wireline. In the second concept, a two-axis inclinometer would be packaged in the core-tube data logger and would measure and store data that could be used to orient the rock core to determine its *in situ* direction. Both of these concepts will be pursued in FY97-98.

Statement of Work: This project will be substantially completed within two years. In FY97, the inclinometer tool will be modified to accommodate a two-axis inclinometer. A procedure will be developed for using the data from this tool, coupled with directional survey data, to determine the *in situ* orientation of the rock core. The dual-purpose inclinometer/core-orientation tool will be field tested in cooperation with Tonto Drilling.

Both the temperature and the inclinometer/core-orientation tools will be heat-shielded for high-temperature operation. Approaches other than dewared vessels, such as the use of eutectic materials, are under consideration to reduce cost. The heat-shielded core-tube data loggers will be field tested in FY97, in a high-temperature well if possible.

The inertial navigation wireline memory tool will be designed in FY97 in sufficient detail to enable a price and expected accuracy to be determined. If the cost and accuracy of such a tool attracts industry interest, a plan will be developed by the end of FY97 to fabricate and field test a tool in FY98.

The field tests in FY97-98 will be used as a basis to attract commercial interest for supplying the core-tube data logger to the wireline core drilling industry. A variety of tools could be envisioned, each providing one or more measurements that may be of interest to various parts of

the industry. Sandia will cooperate with commercial interests to transfer this technology and make it available to the geothermal exploration industry.

Milestones: The following milestones have been adopted for this project:

- *Complete design and fabrication of a two-axis inclinometer version of the core-tube data logger (12/96).*
- *Complete first field test of the two-axis inclinometer version of the core-tube data logger to obtain core orientation data (2/97).*
- *Complete heat-shielding of temperature and two-axis inclinometer core-tube data loggers (4/97).*
- *Complete field testing of heat shielded core-tube data loggers (6/97).*
- *Complete advanced conceptual design of inertial navigation wireline memory tool and cost/performance estimate (2/97).*
- *Complete discussions with industry on the cost-effectiveness of the inertial navigation wireline memory tool and determine potential for industry use (8/97).*
- *Complete project plan for development of inertial navigation wireline memory tool (9/97).*
- *Complete fabrication of inertial navigation wireline memory tool (1/98).*
- *Complete first field test of inertial navigation wireline memory tool (3/98).*
- *Complete Sandia Report on the development and field testing of the core-tube data loggers (9/98).*

Deliverables: This project will result in the following deliverables:

- *Designs for four different core-tube data loggers for a variety of wireline core drilling measurements.*
- *Commercially available core-tube data loggers for one or more geothermal applications.*
- *Conference papers and a final report on the development and testing of the core-tube data logger.*

Downhole Flow Tool

Program Area: High-Temperature Instrumentation

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Justification: The flow of fluid in a geothermal wellbore is of significant interest in at least two applications. In drilling, an accurate measure of the flow in the wellbore could be used to locate and characterize lost circulation zones. In production of the wellbore, accurate flow measurements help to determine the location and relative contributions of the various production zones in the well.

The current standard downhole flow tool is a spinner tool, which uses a spinning vane to measure fluid velocity. This type of measurement is not very accurate because the vane measures the fluid velocity at only one point across the velocity profile of the well. Also, spinner tools do not work reliably in drilling mud.

Under this project, the feasibility of developing a downhole flow tool using Doppler flow metering technology will be assessed. Previous DOE-sponsored work will be examined to assess the current state of this technology. If the approach seems feasible and there is a role for Sandia to assume in its development, we will prepare a program plan for that purpose with work beginning in FY98.

Estimated cost savings resulting from the use of a downhole Doppler flow tool can be divided into two parts, direct drilling cost savings and drilling cost savings resulting from improved reservoir management. In the first case, the tool could be useful in locating lost circulation zones, thereby potentially eliminating one or two mis-located cement plugs per well. This would save about 1% of the total well costs. In the second case, improved reservoir data could eliminate the need for one or more wells in a field of twenty wells, thereby saving 5% of the total drilling costs.

Project Participants:

- Sandia National Laboratories: Conduct technical assessment of the downhole Doppler flow tool potential; document results.
- Panametrics, Inc.: Participate in technical assessment.
- Stanford University: Participate in technical assessment.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$50k	Sandia salary, hardware, travel, field expenses; possible contract for \$20k.

Funding for this project is requested from the reservoir technology portion of DOE's Geothermal Program since the primary benefit of the tool will be in providing data for improved reservoir engineering.

Status: This is a proposed new project for Sandia, although it has been under way at Panametrics, Inc., and Stanford for several years. It began in 1993 as a Small Business Innovative Research (SBIR) grant managed by the DOE Office of Geothermal Technologies. Panametrics was funded to develop and laboratory test a quadruple-transducer Doppler flow meter for integrating the fluid velocities over each quadrant of the wellbore, thereby improving accuracy in two-phase flows that may not be uniformly distributed across the wellbore. Sandia was requested by DOE to assist Panametrics in testing the flow meter. We constructed a test facility, but Panametrics ran out of funding and never used it.

After our positive experience with the use of Doppler flow meters for surface measurement of drilling fluid flows, we began in 1995 to assess the current state of the downhole Doppler flow tool project. We learned that Panametrics had been working cooperatively with Stanford University to evaluate the meter in Stanford's lab. We contacted Stanford (Dr. Roland Horne) and learned that there is interest in cooperating with Sandia to further the development of the tool. Sandia will begin this cooperative work in FY97.

Statement of Work: This project is exploratory in nature and will be completed in FY97. We will meet with Panametrics and Stanford University researchers to determine the current state of the downhole Doppler flow tool. We will offer the use of the facility we built in 1993 to test the flow meter under high flow rates with air injection to simulate two-phase flow conditions. Based on these tests, we will assess the potential for the tool to be developed for field use. If the tool appears promising, a development plan will be written by the end of FY97 for initiation in FY98.

Milestones: The following milestones have been adopted for this project:

- *Complete initial discussions with Panametrics and Stanford University on the status of the downhole Doppler flow tool (11/96).*
- *Complete analysis of Stanford data on the downhole Doppler flow tool and make recommendations for further testing at Sandia (1/97).*
- *Complete lab testing of the downhole Doppler flow tool at Sandia (4/97).*
- *Complete feasibility assessment of downhole Doppler flow tool and, if appropriate, complete project plan for further development (9/97).*

Deliverables: This project will result in the following deliverables:

- *Laboratory data on the performance of the downhole Doppler flow meter.*
- *An assessment of the potential of the downhole Doppler flow meter for geothermal applications and a plan for its development.*

High-Temperature Silicon-On-Insulator Evaluation

Program Area: High-Temperature Instrumentation

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Justification: High-temperature silicon-on-insulator (SOI) technology will become available within the next 18 months from two commercial integrated-circuit manufacturers, Honeywell Solid State Electronics Center (SSEC) and Allied Signal. These IC's are designed to operate at temperatures up to 300°C. The implications of this new technology for the geothermal industry are unlimited. Instrumentation will be able to operate in most geothermal wells without heat shielding. Greatly reduced heat shielding will be required for temperatures higher than 300°C. MWD instrumentation will be able to function in geothermal wells with increased confidence. Instrumentation may also find new control applications inside the power plant fluid stream.

Under this project, Sandia will take a lead role in converting electronic designs presently used in high-temperature logging tools to designs that utilize the emerging SOI technology. The SOI components needed to build a universal measurement system have already been identified.

Cost savings resulting from the use of the new high-temperature SOI technology are conservatively estimated as follows. Low-cost, high-temperature components would make available to geothermal drilling a large portion of the MWD and other downhole diagnostic equipment currently used in oil and gas drilling. The use of such equipment could easily save four days over the life of the well due to reduced directional surveying time, optimized bit hydraulics resulting in higher penetration rates, and downhole vibration monitoring to improve bit life. This would reduce well costs by about 2%. Improved downhole logging tools could provide improved reservoir data that could eliminate the need for one or more wells in a field of twenty wells, thereby saving another 5% of the total drilling costs. This project therefore has a total cost-reducing potential of about 7%.

Project Participants:

- Sandia National Laboratories: Conduct development of logging equipment using high-temperature SOI technology; document results.
- Industry Partners (to be determined): Participate in field testing high-temperature logging equipment.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$120k	Sandia salary, hardware, travel.
DOE Geothermal - Drilling Tech.	FY98	\$200k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY99	\$150k	Sandia salary, hardware, travel, field expenses.

Status: This is a proposed new project. It will provide the geothermal industry with a jump-start on using the high-temperature electronics that will become available over the next year and a half. The SOI technology has been driven by the jet engine industry, which has a need for high-temperature electronics. The SOI components needed for a universal logging tool include a CPU controller, voltage regulators, random-access memory, clock/oscillators, voltage references, A/D converters, operational amplifiers, and multiplexers, all of which are already available or expected to become commercially available soon.

A high-temperature battery is also needed if a logging tool is run as a memory tool or communicates with the surface through an optical cable. Lithium batteries operate up to 200°C. Thermal batteries operate at temperatures of 300°C and above. There are currently no batteries that operate in the "thermal gap" of 200-300°C. Consulting with the Battery Development Department at Sandia, we learned that it may be possible to design an insulated and heated battery housing that keeps thermal batteries hot enough to operate in most geothermal wells.

Statement of Work: Work will begin in FY97 to assemble and test SOI components as they become available. One of the first components expected is the 83C51 microcontroller, which will allow the software to be written and de-bugged early. As other components become available, they will be incorporated into the design.

The basic design is universal, offering a multiplexed A/D converter for multi-channel sensor measurements. For sensors with frequency outputs, a high-temperature frequency-to-voltage converter can be constructed using SOI operational amplifiers. Frequency and voltage measurements cover essentially the entire spectrum of signals that need to be measured downhole.

The design will accommodate three communication modes: single-conductor wireline, fiber-optic wireline, and memory storage. The single-conductor wireline can provide power to the logging tool as well as transmit the data uphole. The fiber optic and memory modes require high-temperature batteries.

The Battery Development Department at Sandia will design and test prototype thermal batteries and housings in a logging tool configuration. The tests will be conducted under temperatures as high as 300°C for up to 10 hours. The data collected in these tests will be used to validate an existing computer model of thermal battery operation, which can then be used to identify and evaluate design improvements for improving thermal battery performance for geothermal logging conditions.

In FY98, all SOI components for the universal logging tool will be available and will be incorporated into the tool and tested. Improved high-temperature batteries will also be fabricated and tested. Industry interest will be evaluated, with the goal of identifying an industry partner for

further development and evaluation. By the end of FY98, a prototype SOI logging tool will be tested on a conducting wireline in a high-temperature well.

The SOI logging tool will be tested in memory mode in FY99. Transfer of the technology developed under this project will also be completed. If successful, the universal logging tool could serve as a platform for a variety of downhole measurements.

Milestones: The following milestones have been adopted for this project:

- *Complete SOI universal logging tool design review (1/97).*
- *Complete laboratory testing of SOI microcontroller and software at high temperatures (5/97).*
- *Complete laboratory tests of prototype high-temperature batteries (5/97).*
- *Complete fabrication and lab testing of entire SOI universal logging tool (3/98).*
- *Complete laboratory testing of improved high-temperature battery (4/98).*
- *Complete first field test of SOI universal logging tool in high-temperature well with conducting wireline (5/99).*
- *Complete first field test of SOI universal logging tool in high-temperature well using memory storage mode (8/98).*
- *Complete Sandia Report on development and testing of an SOI universal logging tool and high-temperature battery (9/99).*

Deliverables: This project will result in the following deliverables:

- *Commercially available high-temperature logging services that employ SOI technology.*
- *Conference papers and a final report on the development and testing of an SOI universal logging tool and high-temperature battery.*

High-Temperature Slimhole Televiewer

Program Area: High-Temperature Instrumentation

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Justification: Slimhole drilling is increasingly used as a geothermal exploration tool. In addition to providing information on reservoir temperatures, slimholes can be economically cored and even flow tested to obtain more detailed data necessary to determine the potential for a geothermal project. One type of log that produces very useful data but is not generally available for high-temperature applications is the borehole televiewer. A televiewer log provides acoustically-derived images of the wellbore wall, showing bedding planes, fractures, vugs, and other items of interest, and allowing the thickness, dip, and strike direction of such features to be accurately determined. This information is especially useful in exploratory drilling.

A slimhole televiewer is not available for high-temperature applications. Sandia owns and operates a conventional slimhole televiewer that is capable of operating up to 125°C. It has been used in the cooler sections of several scientific and exploratory slimholes over the years, gathering unique data that has been enthusiastically received by the operating companies and scientific investigators involved. Its temperature limitation, however, has not allowed it to be used to view the producing zones in geothermal wells.

Reservoir identification and location continues to be an enigma for the geothermal industry. Information related to downhole stress directions and fracture directions would be a very important step in understanding geothermal reservoirs. A high-temperature televiewer operable in slimholes would provide this data.

Under this project, Sandia will assist the Earth Science Research Institute (ESRI) to develop a proposal for the DOE Geothermal Program's open-solicitation for reservoir engineering and exploration technology. The proposal will advocate the development and use of a high-temperature (300°C) slimhole televiewer for geothermal exploration. Under the proposed project, Sandia would design and fabricate a prototype televiewer, and ESRI would use the televiewer to conduct relevant fracture-mapping and studies of geologic structures in geothermal reservoirs. This would provide data for improved reservoir modeling and would advance the general state of knowledge related to geothermal production zones.

The cost-reduction goal for this project is the same as in all the downhole logging tool projects: to provide reservoir data that improves understanding of the reservoir so that one or more wells in a typical field of twenty wells can be eliminated, thereby saving 5% of the drilling costs. This project addresses one component of improved reservoir data, namely rock structure and fracture characteristics. Combined with other improvements in reservoir data, such as those addressed in other projects described in this plan, this work should help reach the goal.

Project Participants:

- Sandia National Laboratories: Assist ESRI in developing a proposal for DOE's open-solicitation.
- Earth Science Research Institute: Develop proposal.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$25k	Sandia salary, travel.

Funding for this project is requested from the reservoir technology portion of DOE's Geothermal Program since the primary benefit of the project will be in providing data for improved reservoir engineering.

Status: This is a proposed new project. It will develop a proposal for a project to develop and use a high-temperature slimhole televiwer for geothermal exploration. It builds on the Sandia's strengths in high-temperature electronics and experience in borehole televiwer design and operation (Heard and Bauman, 1983; Duda, 1989); and it builds on ESRI's strengths in the interpretation of downhole logging data.

Sandia was involved for several years in the development of a large-diameter borehole televiwer for geothermal wells. The tool was completed in the mid-1980s, and the technology was transferred to Unocal Geothermal. Unocal operated their high-temperature televiwers for several years, primarily to inspect casing for corrosion. The large diameter of the tool, however, does not lend itself to use in slimholes, where most televiwer usage for geothermal exploration is anticipated.

The commercial availability of a wide range of integrated circuits, including high-temperature chips, now makes the development and operation of a high-temperature slimhole televiwer theoretically more straightforward and less expensive than in the past. Downhole microprocessors should make on-board processing more feasible in order to reduce operator interaction and error in running a log.

Interpretation of televiwer log data is best accomplished by experienced analysts. ESRI will lead the televiwer logging effort and will establish a wide experience base in data interpretation. This growing experience base should help interpret and correlate logs from different wells and different geothermal fields.

Statement of Work: This project will be completed in FY97. Sandia will provide assistance to ESRI in developing a proposal for the DOE Geothermal Program's reservoir engineering open-solicitation process. This proposal will request funding for Sandia to develop a high-temperature slimhole televiwer and ESRI to use the televiwer to log geothermal slimholes and study production-zone fracture patterns in several geothermal fields.

Development of the proposal will require extensive discussions between Sandia and ESRI personnel. The goal is for ESRI to complete the proposal and submit it by December, 1996. The proposal review cycle is assumed to take several months. If the project is funded, work could begin by the middle of FY97.

Milestones: The following milestones have been adopted for this project:

- *Initiate discussions with ESRI on high-temperature slimhole televiewer proposal (10/96).*
- *Complete and submit high-temperature slimhole televiewer proposal (12/96).*

Deliverables: This project will result in the following deliverables:

- *Proposal outlining the need, development, and use of a high-temperature slimhole televiewer for geothermal exploration.*

High-Data-Rate Geothermal Drilling Telemetry

Program Area: High-Temperature Instrumentation

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Justification: Measurement-While-Drilling (MWD) systems have been used extensively over the past decade to reduce costs in oil and gas drilling. Directional drilling and gas-kick detection are two main uses of the systems. These systems are not currently used in geothermal drilling for two primary reasons: 1) current MWD systems are not designed for the high temperatures encountered in geothermal drilling; and 2) directional drilling in geothermal wells is usually done in only one relatively short section of hole. The lack of applicability of current MWD to geothermal drilling is also due, in part, to the data-rate limitations of current systems, 1-10 baud. This slow rate severely limits the amount of data that can be sent uphole, requiring more downhole processing and, hence, a more expensive system.

If a high-data-rate MWD system were available, additional uses for the system could be developed. For instance, downhole accelerometers could be added that measure drillstring vibrations. Hard-rock drilling is often characterized as "rough" drilling, where the bit undergoes significant accelerations and impact. This is hard on any bit but can destroy a PDC bit almost immediately. This situation has prevented the high penetration rate advantages of PDC bits from being used in geothermal drilling. Recent work, however, indicates that pockets of drilling stability may exist at various combinations of weight-on-bit and rotary speed. If such pockets could be found in real time with the use of a high-data-rate MWD system, it may be possible to use PDC bits in many geothermal applications.

Another example where an MWD system would be useful in geothermal drilling is in steam-kick and loss-zone detection and characterization. Downhole pressure transducers could provide both early steam-kick warnings and data that could be used to locate lost circulation zones. Underbalanced drilling techniques, which are becoming popular in oil and gas drilling, could also be implemented in geothermal drilling with greater safety if downhole pressures could be reported in real time at the surface. An economical MWD system that provides downhole directional data would also reduce surveying costs and allow target directions to be more easily maintained. If the data rate is high enough that raw signals can be transmitted uphole, fewer electronic components are needed downhole for data processing. The remaining downhole components can be more easily and cost-effectively heat shielded than present MWD systems.

Under this project, Sandia will develop such a high-data-rate MWD system for geothermal applications. The real-time, wireless electrical telemetry technology known as Surface Area Modulation (SAM) will be adapted to the geothermal drilling environment, demonstrated in the field, and commercialized. This telemetry system, currently under development at Sandia for another application, has been shown capable of transmitting data from a downhole package to the surface at 2400 baud, about three orders of magnitude faster than mud-pulse telemetry used in conventional MWD systems.

Drilling cost savings resulting from the use of the high-data-rate MWD system in geothermal drilling can be estimated as follows. If the system makes it possible to use current PDC bits in some geothermal applications, a doubling of penetration rate and bit life over that currently obtained with roller-cone bits is possible. This would reduce drilling costs by about 15%. If the MWD system makes underbalanced drilling safer and more reliable, the improved well productivity that could result may eliminate one or more wells out of a typical field of twenty wells, saving another 5%. Savings in directional surveys and better maintenance of target direction could result in additional savings. All totaled, this project could result in drilling cost savings that exceed 20%. This project therefore has a higher potential pay-off than most of our other projects, even though it is more costly and long-term.

Project Participants:

- Sandia National Laboratories: Develop high-data-rate MWD system; work with industry to demonstrate the system and transfer technology; document results.
- Industry Partner(s) (to be determined): Work with Sandia to demonstrate the system; commercialize the system; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$300k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY98	\$500k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY99	\$400k	Sandia salary, hardware, travel, field expenses.

Industry partners will provide funding to cover their own expenses on this project. The industry contribution could exceed the DOE funding level in FY98 and FY99.

Status: This is a proposed new project for Sandia's drilling R&D program, but the SAM system has been under evaluation for the last year for another application. That worked was funded with internal Sandia R&D money to prove the concept of the data transmission technology for producing oil wells. A downhole package was placed on the lower end of a sucker rod in a 2700-ft oil well. Data was transmitted at 2400 baud as an electrical signal propagated through the earth.

The SAM technique should be applicable to the drilling environment. The first step in this project is to demonstrate that point with a field test in the first year. Full-scale development of the system will then proceed if it shows good potential and an industry partner can be interested in participating in its development.

Statement of Work: If carried to completion, this project should be completed within three years. In FY97, Sandia will focus on demonstrating the concept under geothermal drilling conditions. The electrical characteristics of a geothermal well will be measured, and electrical modeling of the system will be conducted to determine the voltage and power levels needed for such a demonstration. A downhole instrument package will be designed and fabricated to send signals to the surface from the lower end of a drillstring. It is not necessary in this field test to

actually drill in order to demonstrate the feasibility of the data transmission concept, so the package will not be hardened for the vibration and shock encountered during drilling. The field demonstration will be conducted in a well being drilled by the end of FY97.

If the field demonstration goes as expected, the results will be used to attract commercial interest in the technology. One or more industry partners will be selected in early FY98 to ensure industry buy-in, guide the technical direction of the system's development, and provide a rapid commercialization path. Prototype MWD tools will be developed and field tested to measure and evaluate SAM telemetry in a geothermal drilling environment. Results from these tests will help finalize the design of a commercial system.

By the middle of FY99, the commercial system will be jointly developed by Sandia and the industry partner(s). The system will be tested by drilling a geothermal well with the goal of demonstrating the ability to safely drill underbalanced with better lost circulation control and reduced drilling vibration. The success of the SAM MWD system will be determined by the data rate achieved, the use made of the data, and the overall cost reduction and improved well productivity achieved.

Milestones: The following milestones have been adopted for this project:

- *Initiate project on SAM high-data-rate MWD system for geothermal drilling (11/96).*
- *Complete preliminary system electrical model (1/97).*
- *Measure electrical characteristics of a geothermal well during drilling (4/97).*
- *Field demonstration of SAM telemetry in the drilling environment (8/97).*
- *Complete Sandia Report on the feasibility of the SAM high-data-rate MWD system for geothermal drilling (9/97).*
- *Select industry partner(s) for commercialization of SAM high-data-rate MWD system for geothermal drilling (12/97).*
- *Complete prototype SAM high-data-rate MWD system (3/98).*
- *Field test prototype SAM high-data-rate MWD system (8/98).*
- *Complete design of commercial SAM high-data-rate MWD system (12/98).*
- *Complete field test of commercial SAM high-data-rate MWD system (6/99).*
- *Complete final Sandia Report on the development and testing of the SAM high-data-rate MWD system (9/99).*

Deliverables: This project will result in the following deliverables:

- *Commercially available high-data-rate MWD system for geothermal drilling that employs SAM technology.*
- *Conference papers and reports on the development and testing of the SAM high-data-rate MWD system for geothermal drilling.*

VI. Acoustic Technology

a. Background

Retrieving data from the bottom of a wellbore is not a trivial matter in any application, particularly if downhole conditions are hostile. The use of downhole memory tools is one solution that works in many applications. In other applications, data are either needed in real time, or the application does not allow the use of any type of wireline. In such applications, an alternative way to retrieve data from downhole is by sending the data up the steel tubulars in the hole in the form of sound waves.

Acoustic data transmission is a highly developed science that has thus far seen little application in drilling operations. Technical challenges include designing and building downhole devices that survive the ambient conditions and convert the downhole data to stress waves that can travel uphole in the drill pipe or production tubing. Sandia has several patents on such a device (Drumheller, 1992b, 1993b, 1993e, 1995b). Deciphering the signal received on the surface to extract the actual signal from the rig noise is another challenge. Sandia has developed data acquisition and reduction capabilities for this purpose (Drumheller, 1995a). The technology is, therefore, ready for use in a variety of applications.

Much of this technology evolved under a joint industry project to develop an acoustic measurement-while-drilling (MWD) system that sends data up the drillstring at higher rates than current MWD mud-pulse systems. That project was canceled when the industry partner was sold and the new owner had different business priorities. The technology that was developed is useful, however, in other acoustic data transmission applications.

There are, in fact, less rigorous geothermal environments where acoustic technology can be more easily applied than in drilling. The production environment is one, in which the production tubing can be used to transmit the acoustic signal. Drilling applications that do not require a downhole acoustic source are also favorable applications. We are applying acoustic data transmission technology to three such applications.

b. Justification for Technology Development Effort

The primary benefit of acoustic data transmission technology is the consequent availability of useful data that are otherwise unavailable or more expensive to obtain. How the data can be used to reduce costs depends on the application. Based on the acoustic technology projects we currently have under way, a 5% well cost-reduction goal is reasonable. This would reduce overall project costs by about 2%.

c. Acoustic Technology Projects

Three projects are planned in the acoustic technology program area. They address both slimhole drilling and wellbore production issues. The projects are described in the following pages.

Core-Tube Latching Detector

Program Area: Acoustic Technology

Project Leader: Doug Drumheller, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8920, Fax 844-3952, dsdrumh@sandia.gov

Program Area Leader: Doug Drumheller, Sandia National Laboratories Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8920, Fax 844-3952, dsdrumh@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: In wireline coring operations, the core tube is pulled after every 5 or 10 ft to retrieve a section of cored rock. When an empty core tube is dropped into the drillstring and allowed to free fall to the bottom, the driller must wait until the core tube has landed and latched at the bottomhole assembly before resuming drilling. The driller generally uses a characteristic vibration in the drillstring as an indication that the core tube has landed, but false signals or no signal at all are common in deep wells. Waiting extra time to ensure that the core barrel is in place before drilling ahead contributes an estimated 5% to the average cost of boreholes drilled with wireline core digs.

Under this project a technique will be developed for accurately detecting when the core barrel has landed and latched downhole. The core-tube latching detector under development employs a pair of noise-canceling headphones to reduce audible rig noise, an accelerometer mounted on the top drive to detect the core tube's landing sound, and sound filtering and amplification circuitry to isolate and amplify the landing sound. We are working with Tonto Drilling Services to evaluate the latching detector in the field.

By providing a positive indication of when the core tube has landed, the technology developed under this project could potentially recover all the 5% lost-time costs mentioned above for the average core hole. If it is assumed that exploration drilling costs account for 10% of the total drilling costs for a geothermal project, then a 5% reduction in exploration drilling costs represents a 1/2% reduction in total drilling costs.

Project Participants:

- Sandia National Laboratories: Lead development effort; conduct rig tests to determine design parameters; design and fabricate prototype system; lead field testing effort; document results.
- Tonto Drilling Services, Inc.: Provide access to drilling operations; provide rig time for field tests; consult with Sandia on the design of the prototype system.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$125k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY98	\$90k	Sandia salary, hardware, travel, field expenses.

Tonto Drilling will provide funding to cover its own expenses on this project. This could amount to several thousand dollars worth of rig time before the project is completed.

Status: This is an ongoing project. It began in 1994 at a low level of effort when the core-tube latching detector was conceived. Data were first gathered by conducting two field tests in cooperation with Tonto Drilling to characterize existing coring rig and core-tube latching noises. The data were used to design a prototype latch detector system using commercially available components. We assembled two prototype detectors for field use, and they were tested in late FY96 on several Tonto Drilling Services rigs.

On one of these rigs, it was difficult to locate a place to attach the surface accelerometer where it could pick up the core-tube latching sound. Consequently we used a quick-mounting device to attach the accelerometer to the top of the drillstring on the rig floor as the tube fell downhole. The system was tested at 2,000 ft and 4,500 ft depths. Positive detection of the core-tube landing at the bottomhole assembly was easily accomplished, and the system worked as designed. On the particular boreholes drilled during the field test, however, it was not difficult for the driller to also feel the core tube landing downhole through vibration in the drillstring, without the latching detector. Consequently the full benefit of the latch detector system could not be demonstrated in these tests. Additional field tests will, therefore, be necessary to evaluate the latch detection system under drilling conditions where it is more difficult for the driller to otherwise detect the core tube landing.

Statement of Work: The results of the FY96 field tests will be used to modify and improve the latching detector system. The modified portable system will be deployed in several drilling operations to evaluate the operation and utility of the system. As we and the crews gain experience with the equipment, we will deploy it in remote sites, such as Indonesia, where severe core-tube latch detection problems reportedly occur.

Throughout this process, we will continue to develop signal processing algorithms to improve and automate the sensitivity of the detector. An important goal of this effort will be to reduce the expertise that is required to use the system.

Milestones: The following milestones have been adopted for this project:

- *Complete field test of prototype core-tube latching detector (8/96).*
- *Complete field test of prototype core-tube latching detector on rig exhibiting severe latch-detection problems (7/97).*
- *Complete refinement of design of core-tube latching detector system (6/97).*
- *Complete first field test of refined core-tube latching detector system (2/98).*

- *Complete final Sandia Report on development and testing of the core-tube latching detector (8/98).*

Deliverables: This project will result in the following deliverables:

- *A field-tested core-tube latching detector ready for use by operators of slimhole drilling equipment.*
- *A final report and conference papers on the design and operation of the core-tube latching detector.*

Alignment System for Line-Shaft Pumps

Program Area: Acoustic Technology

Project Leader: Doug Drumheller, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8920, Fax 844-3952, dsdrumh@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Many geothermal production plants operate with a low-quality resource, and as existing operations mature, this will become even more common. Because of the low temperature, these wells are generally pumped to prevent flashing of the fluid in the wellbore. The majority of pumping is accomplished with downhole line-shaft pumps. These pumps are expensive to install and operate. Any reduction in installation costs or increase in pumping efficiency will directly affect the cost of geothermal energy produced with such pumps.

The stator of the pump is attached through the pump housing to the production tubing that carries the fluid uphole. The impeller of the pump is attached to the drive shaft of the pump. The impeller is aligned axially within the stator by moving the drive shaft up and down from the surface (while not turning) and using a force transducer to detect interference between the impeller and stator. As the fluid is pumped, the production tubing and the drive shaft thermally expand by different amounts, thus causing changes in the axial alignment between the pump impeller and stator. The impeller can translate up to several inches with respect to the stator. Because there is currently no way to measure the axial alignment, it cannot be adjusted while the pump is running. Consequently, the pump must be designed for large clearances between the impeller and stator, thereby reducing the efficiency of the pump and increasing its size and cost.

Under this project, we are working with Johnston Pumps to develop a system for aligning geothermal line-shaft pumps. We have invented a very simple mechanical device that continuously senses the misalignment of the impeller and broadcasts the information to the surface. The information is transmitted as a sound wave that travels up the drive shaft to the surface. An accelerometer acquires the signal at the surface. This information will be used to automatically adjust the position of the motor and realign the impeller. This will allow the design and use of a more efficient, more compact pump with greater reliability.

An estimate of the cost savings that may result from this project can be derived by making the following assumptions. If the shaft alignment system allows the design and use of more efficient line-shaft pumps, the parasitic load on the power plant will be reduced. The size and weight of the pump could be reduced by approximately 50%. Perhaps the most significant cost savings would result from reduced maintenance and down-time costs for the pumps. No quantitative estimates on these cost savings are yet available.

Project Participants:

- Sandia National Laboratories: Lead development effort; design downhole sensor; design and assemble surface data acquisition system; lead field testing effort; document results.
- Johnston Pumps: Participate in development effort; engineer and fabricate downhole sensor; participate in field testing; commercialize the system.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$140k	Sandia salary, hardware, travel, field expenses.
DOE Geothermal - Drilling Tech.	FY98	\$150k	Sandia salary, hardware, travel, field expenses.

Johnston Pumps will provide funding to cover its own expenses on this project, which are estimated to be \$300k if the project results in a commercial product.

Status: This is an ongoing project. It was initiated in FY95 when the concept was developed. Since that time, an alignment sensor has been designed, and a patent disclosure has been filed. In FY96, agreement was reached with Johnston Pumps on possible licensing of Sandia's technology. Technical development work began late in FY96. Johnston Pumps is currently developing engineering designs for the prototype system.

Statement of Work: In FY97, Johnston Pumps will engineer Sandia's design of the downhole system, then fabricate the downhole equipment. Sandia will assemble the necessary instruments and data acquisition equipment for the surface system. These components will then be tested in a customer well.

In the first field test in FY97, the prototype system will be used to sense the relative position of the impeller and stator, but no adjustments will be made to the motor position. Any necessary design modifications will be identified and made, then the system will again be tested in the field in early FY98. If the system performs as expected, the design of a commercial system will be initiated. By the end of FY98, the commercial system will be field tested and the technology transferred to industry.

Milestones: The following milestones have been adopted for this project:

- *Design and fabricate downhole components of prototype line-shaft pump alignment system (10/96).*
- *Complete first field test of prototype line-shaft pump alignment system (6/97).*
- *Complete second field test of prototype line-shaft pump alignment system (12/97).*
- *Complete design of commercial line-shaft pump alignment system (2/98).*
- *Complete fabrication of commercial line-shaft pump alignment system (3/98).*
- *Complete field test of commercial line-shaft pump alignment system (7/98).*

- *Complete final Sandia Report on the development and field testing of the line-shaft pump alignment system (9/98).*

Deliverables: This project will result in the following deliverables:

- *A field-tested, commercially available system for sensing and automatically aligning the impeller and stator of line-shaft geothermal well pumps.*
- *A final report on the design and operation of the line-shaft pump alignment system.*

Wireless Telemetry for Production Monitoring

Program Area: Acoustic Technology

Project Leader: Doug Drumheller, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8920, Fax 844-3952, dsdrumh@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Wellbore production testing and monitoring is important for optimizing the production strategy of a reservoir, whether geothermal or petroleum, and for detecting well-related problems that develop over time. Such testing and monitoring requires downhole temperature and pressure measurements while the well is flowing (or being pumped). While making these measurements is not difficult, transmitting the data to the surface can be problematic.

In geothermal wells, production testing is generally accomplished by using a dewatered temperature/pressure tool on a single-conductor wireline; however, high-temperature conducting wirelines are relatively expensive so the use of this tool is costly. Consequently, this approach is used in wellbore production testing, but it is not used for long-term production monitoring as often as it should be used to optimize production from the field.

In oil and gas wells, wires are often strapped to the outside of the production tubing to carry downhole temperature and pressure signals to the surface. These wires are susceptible to breakage and costly replacement procedures. Because of this, monitoring equipment is often not used, even though the data are invaluable for the timely assessment of well performance and corrective action to optimize production. These data can be crucial to both small, independent operators and majors alike, and can affect decisions ranging from the abandonment of a mature well to an expensive workover on an offshore platform. In applications such as these, a wireless technique for transmitting downhole production data to the surface would have a distinct cost advantage over the use of electrically-conducting wires.

In this project, Sandia is working with Baker Oil Tools to develop such a system for oil wells. We are developing a downhole instrument package that measures temperature and pressure, converts the data to a digital acoustic signal, and transmits it uphole in the form of stress waves that travel up the production tubing. An accelerometer mounted on the production tubing at the surface receives the signal, and data processing equipment decodes it. The system is designed to operate for six months on downhole battery power.

This project was initiated with funding from DOE Geothermal, with the idea that the developed technology may ultimately have application in high-temperature geothermal environments. Once the feasibility of the system was demonstrated, additional funding was secured from DOE's Oil Technology Partnership. To date, about equal funding has been received from the two DOE offices to develop this dual-application technology. All the funding required to complete the existing project is either currently in hand or expected to be provided by the Oil Technology Partnership.

Recent developments indicate that the DOE Geothermal investment in this technology may pay off. First, we have been contacted by a logging tool manufacturer about the possibility of developing a dewared, high-temperature production testing tool that transmits data acoustically up a slickline. The use of slickline tools in this application would greatly reduce the cost of production testing and monitoring. Secondly, the advent of high-temperature silicon-on-insulator technology may soon make unshielded downhole electronics available for temperature environments up to 300°C. This, combined with a reliable high-temperature battery, would make the acoustic telemetry system currently under development for oil wells also available for high-temperature geothermal applications.

The cost reductions that could be attributed to the availability of a wireless-telemetry production tool are estimated as follows. In deep, off-shore oil and gas applications, attaching a wire to the production tubing can add two or three days to the time required to emplace the tubing. At \$100,000/day for offshore rigs, a wireless telemetry system can save up to \$300,000 per well. If the wire breaks after the rig has been moved off the hole, the production monitoring of that well is usually terminated because of the cost of pulling the tubing to replace the wire. Another possible use for the tool is in communicating with downhole valves that could be installed to shut off well production. Such technology would have prevented the Kuwaiti oil-field disaster following the Persian Gulf War, where the wellheads were blown off by retreating Iraqi troops.

In geothermal wells, the availability of a wireless-telemetry production tool would reduce the cost of individual logs. Presumably, this would lead to an increase in the number of logs performed. Increased availability of production data would help improve reservoir modeling and optimize production of the field. Assuming this scenario reduces the number of wells needed to achieve a given total production by one well in a field of twenty, this represents a 5% drilling cost savings. If optimal production reduces or delays the need for replacement wells as the reservoir pressure declines, further cost savings could be attributed to the technology developed in this project.

Project Participants:

- Sandia National Laboratories: Lead development effort; design, laboratory test, and field test wireless telemetry system; coordinate industry field testing effort; work with Baker Oil Tools to commercialize; document results.
- Baker Oil Tools: Assist in development effort; fabricate field prototype; assist in laboratory and field testing; commercialize the system.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Fossil Energy - Drilling Tech.	FY97	\$165k	Sandia salary, hardware, travel, field expenses.
DOE Fossil Energy - Drilling Tech.	FY98	\$55k	Sandia salary, hardware, travel, field expenses.

The FY97 funding listed above is actually carry-over FY96 funding that is already in hand. The funding needs of this project will, therefore, not be counted in the program totals for requested FY97 funding from DOE Geothermal. Baker Oil Tools will provide funding to cover its own expenses on this project.

Status: This is an ongoing project that began in 1994. Seed money from DOE Geothermal was used to start this project, but it is being completed solely with Oil Technology Partnership funding from the DOE Office of Fossil Energy.

The work began with assessments of the technical feasibility based on measurements the elastic-wave transmission characteristics of various production components, such as the production tubing and the casing packers. We designed a prototype transmitter and receiver and successfully completed a series of tests at Sandia's surface test facility, Orpheus. This facility has a quarter-mile of drill pipe and production tubing be laid out on supports to test various acoustic transmission schemes. These tests were successfully completed, and some final changes in the microprocessor circuits are being incorporated into the design. Patent licensing agreements with Baker Oil Tools have been formulated and are being negotiated.

We have applied for an additional patent because the downhole transmitter embodies a unique and robust design to integrate the ceramic transducer elements with the steel well tubulars without degrading the strength of the production string. The resulting transmitter operates under principles disclosed in our previous patents. Consequently, the licensing negotiations include several of our patents.

Statement of Work: This project will be completed within the next two years. In FY97, the prototype tool will first be tested on the surface at the Orpheus facility, then a field test will be conducted in cooperation with Baker Oil Tools. Any required design changes identified in these tests will be incorporated into an upgraded tool for further field testing in FY98. With successful tests, Baker is expected to initiate commercialization of the tool. The licensing agreement between DOE/Sandia and Baker Oil Tools should be completed by mid-FY97.

Milestones: The following milestones have been adopted for this project:

- *Complete testing of the prototype wireless telemetry system at the Orpheus surface test facility (12/96).*
- *Complete first field test of prototype wireless telemetry system (3/97).*
- *Complete license agreement between DOE/Sandia and Baker Oil Tools on the wireless telemetry system (5/97).*
- *Complete second field test of prototype wireless telemetry system (2/98).*
- *Complete final Sandia Report on development and testing of wireless telemetry system (9/98).*

Deliverables: This project will result in the following deliverables:

- *A field-tested, commercially available wireless telemetry system for oil well production testing and monitoring.*
- *Acoustic telemetry technology that can be directly applied to geothermal production testing.*
- *A final report on the design and operation of the wireless telemetry system.*

VII. Slimhole Drilling Technology

a. Background

Exploratory drilling for geothermal resources is a costly process. Traditionally, investors have required developers to drill one or more large-diameter, production-sized wells that can be tested to prove the viability of the resource *before* they will finance a geothermal project. Such wells can cost from \$1 million to \$3 million and must be self-financed by the developer. Given that the wildcat success ratio for geothermal wells is only about 25-40%, it can be seen that exploration drilling costs may be the single largest impediment to the development of new geothermal resources.

A lower-cost alternative to large-diameter exploration wells is slimhole drilling. By drilling holes 3-6 inches in diameter instead of 9-12 inches, costs can be dramatically reduced. A much smaller drill rig can be used, thereby reducing mobilization costs, site-preparation costs, and site disturbance. A smaller rig requires fewer rig hands and less fuel, thereby further reducing costs. Casing and cementing costs for small wells are also considerably lower than such costs for large-diameter wells. In all, a total drilling cost reduction of 40% can be achieved by drilling slimholes instead of production-sized wells for geothermal exploration.

The reason this approach has not been traditionally used is that some question has existed as to whether reliable reservoir production data can be obtained from slimholes. Some observers have even questioned whether slimholes can be produced in some cases, such as in low-temperature reservoirs. The issue is the frictional pressure drop of the produced fluid in the wellbore, which is obviously higher in a small wellbore than a large one for a given flow rate. At some point as the wellbore diameter is reduced in size, the wellbore frictional pressure drop becomes so dominant over the pressure drop in the reservoir that it is not possible to "stress" the reservoir sufficiently to characterize its flow behavior. As a minimum, it is necessary to draw down the pressure in some region around the wellbore in order to determine the reservoir transmissivity and effective boundary pressure. Long-term tests are also usually necessary to demonstrate adequate reservoir volume. Even reservoir features such as boundaries and major producing fractures theoretically can be detected if the reservoir can be adequately stressed.

The question, then, is whether a 3-6 inch diameter slimhole is so small that it "chokes" the flow and does not allow reliable reservoir data to be obtained by flow testing. This is the primary question that Sandia is seeking to answer with our work on slimhole drilling technology. A secondary objective of the work is to develop technology to further reduce the cost of slimhole drilling.

Under this program to date, we have drilled and tested three industry cost-shared slimholes, funded the compilation and analysis of an extensive Japanese slimhole production database, initiated several slimhole drilling technology development projects, and sponsored a successful industry workshop on slimhole drilling and testing.

b. Justification for Technology Development Effort

If it can be clearly demonstrated that reliable geothermal reservoir production characteristics can be determined by flow testing slimholes, a 40% reduction in exploratory drilling costs would result from the use of current slimhole drilling technology instead of large-diameter drill rigs. Even further cost reductions are possible through improvements in slimhole drilling technology. If it is assumed that 10% of the total drilling costs of a geothermal field are for exploratory wells, then a 40% reduction in exploratory well costs represents a 4% reduction

in total well field costs. The effect of significant reductions in exploratory drilling costs; however, may be far greater than the 4% total reduction implies, because exploratory drilling costs must usually be self-financed by the developer.

c. Slimhole Drilling Technology Projects

Six projects are planned in the slimhole drilling technology program area. Four of these projects are ongoing, and two are new. The projects are described in the following pages.

Geothermal Slimhole Handbook

Program Area: Slimhole Drilling Technology

Project Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Slimhole drilling is increasingly used for geothermal exploration. Being a relatively new practice, there are currently no industry standards on drilling and testing geothermal slimholes. In the absence of such standards, documentation of the experience gained by Sandia in our slimhole drilling technology program could be useful to developers and operators in planning and executing future slimhole drilling operations. Furthermore, it would be useful to assemble the important conclusions from Sandia's program into one document.

Consequently, this project will provide funding to write a handbook for geothermal slimhole drilling and testing. The Slimhole Handbook will include: narrative accounts of Sandia slimhole drilling projects; a compilation of test data and modeling results from the projects; a synopsis of data from Japanese wells; descriptions of drilling and logging equipment available for slimholes; and guidelines for drilling and testing geothermal slimholes.

This project will not develop any cost-reducing technology; however, it will provide specific staff time to document the results of our past work in this area and will serve a valuable technology transfer function. It is not pertinent or useful to attempt to estimate the cost savings that will specifically result from this project. Exploratory drilling cost savings resulting from the slimhole drilling program as a whole are expected to exceed 40%, as previously noted.

Project Participants:

- Sandia National Laboratories: Write Geothermal Slimhole Handbook.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$125k	Sandia salary, travel.
DOE Geothermal - Drilling Tech.	FY98	\$50k	Sandia salary, travel.

Status: This is an ongoing project that comprises the remaining work required to document the conclusions of our three-year program in slimhole drilling technology. This program has been well documented to this point. Detailed final reports have been published on two of the three slimhole projects we coordinated (Finger *et al.*, 1994c; Finger *et al.*, 1996b); the other will be issued when proprietary data are released according to a negotiated schedule. Several conference

papers have also been published (Finger, 1993 ; Finger, 1994b, Finger, 1995; Finger, 1996a). Papers and reports have also been published by Maxwell Technologies under contract to Sandia, describing the results of their compilation and analysis of the Japanese slimhole production data (e.g., Combs and Garg, 1993). In July, 1996, Sandia sponsored an industry workshop on slimhole drilling and testing in cooperation with the Geothermal Resources Council. The workshop was well attended and served a valuable technology transfer function.

In addition to summarizing some of the pertinent conclusions from the previous published works, the proposed Slimhole Handbook will contain new material not presented in past publications.

Statement of Work: This project will be completed over the next two years. More rapid progress is not possible because of other staff commitments. The proposed content of the Slimhole Handbook is:

1. Overview--Rationale for slimhole drilling, opportunities for exploration cost savings and development for small power plants.
2. Equipment--Description of drill rigs, including minerals-type core rigs, small rotary rigs, and hybrids such as the Tonto top-drive unit for attachment to conventional rotary rigs; description of slimhole logging tools available from industry and under development by Sandia; description of surface instrumentation for drilling/testing and other hardware for flow testing; comparison of core-drilling and rotary technology.
3. Case histories--Narratives of Sandia-sponsored drilling projects and other industry projects as available.
4. Analysis--Sample data from Sandia-sponsored wells and comparison with models; summary of Japanese data with conclusions relevant to productivity/injectivity correlations; appropriate analytical comparison to any data available from industry; description of wellbore simulators (possible distribution of simulators on diskette).
5. Guidelines--Recommendation for well design, surface instrumentation, drilling fluids, logging, testing, and data collection.
6. Bibliography--Collection of other works related to slimhole drilling.

Draft copies of the Handbook will be submitted to industry (service companies, operators, drilling contractors) and other interested parties as appropriate. Publication of the Handbook will be announced in the Department Newsletter, and it will be distributed to those expressing an interest after the announcement.

Milestones: The following milestones have been adopted for this project:

- *Complete draft of Sections 1, 2, and 3 of the Geothermal Slimhole Handbook (6/97).*
- *Complete draft of Sections 5 and 6 of the Geothermal Slimhole Handbook (9/97).*
- *Complete draft of Section 4 of the Geothermal Slimhole Handbook (11/97).*
- *Release draft of Geothermal Slimhole Handbook (3/98).*
- *Publish Geothermal Slimhole Handbook (8/98).*

Deliverables: This project will result in the following deliverables:

- **A Geothermal Slimhole Handbook for use in planning and operating slimhole drilling projects for geothermal exploration.**

Analysis of Kirishima, Japan, Slimhole Data

Program Area: Slimhole Drilling Technology

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov;
Sabodh Garg, Maxwell Technologies, PO Box 1620, La Jolla, CA 92038, (619) 576-7752, Fax 755-0474

Program Area Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: In order to determine in a rigorous manner whether or not slimhole production data can be used to characterize geothermal reservoirs, Sandia embarked on a dual approach of both drilling demonstration slimholes in cooperation with industry and funding the compilation and analysis of slimhole well testing data from Japanese geothermal reservoirs. The Japanese government and industry have drilled hundreds of slimholes in geothermal fields near large-diameter production wells, and they have injection- and/or production-tested many of them. Data are therefore available that should clearly determine in a statistically-significant manner the viability of slimholes as a reservoir characterization tool.

In this project, Maxwell Technologies (formerly S-Cubed) is compiling and analyzing the Japanese slimhole data under contract to Sandia. To date, Maxwell has obtained data from four different geothermal fields and over 130 wells. Data from moderate-temperature reservoirs with liquid feedzone production indicate that the productivity index varies only weakly with wellbore diameter. This means that by applying a scaling factor, the productivity of a large-diameter well can, indeed, be predicted from the measured productivity of a slimhole.

This result has not yet been confirmed for high-temperature reservoirs where the feedzone produces two-phase fluid into the wellbore. Data from such a reservoir was collected by Maxwell in June, 1996, and analysis is currently under way.

This project will not develop any cost-reducing technology; however, it will provide solid evidence of the viability of slimholes as a reservoir characterization tool. As previously stated, if this conclusion can be rigorously documented and accepted by industry, a 40% reduction in exploratory drilling would result from the use of current slimhole drilling technology instead of large-diameter drill rigs.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Maxwell Technologies; provide technical review of data and analysis.
- Maxwell Technologies: Compile and analyze Kirishima slimhole data; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$255k	Sandia salary, travel; Maxwell contract for \$348k (\$248k remaining to be spent in FY97).

Because of the nature of this work, we request funding for this project from the reservoir technology area of the DOE Geothermal Program.

Status: This is an ongoing project. It began in 1992 and has since focused on slimhole data from four Japanese geothermal reservoirs: Oguni, Sumikawa, Takagami, and Kirishima. The first three of these reservoirs are moderate-temperature reservoirs where the fluid entering the wellbore at the feedzones is liquid. Kirishima has higher fluid temperatures, and the fluid entering the wellbore at the feedzone is two-phase, liquid and steam. The differences in these two reservoir types demand different wellbore flow models, with the two-phase flow being the more complex and difficult to model.

Maxwell Technologies was given a contract to visit Japan, negotiate the release of the data with Japanese industry officials, collect, sort, and analyze the data, and use wellbore simulation to interpret the results. To date, Maxwell Technologies has collected data from all four fields, and they have completed analysis of data from the three liquid-feed-zone fields. Analysis of the two-phase feedzone data from Kirishima is still under way and will be completed in FY97.

The results from the liquid-feedzone reservoirs indicates not only that the productivity of a large wellbore can be predicted from the measured productivity of a slimhole, but also that the injectivity index of a slimhole is approximately the same as the productivity index. This means, in the best case, that injection tests in slimholes, coupled with a wellbore simulator, can be used to predict the productivity of a large well. In cases where it is not possible to flow test a slimhole, an injection test may therefore provide the needed data.

The objective of the remaining work on this project is to prove these same relationships for geothermal reservoirs with two-phase feedzones.

Statement of Work: This project will be completed in FY97. The Kirishima data will be evaluated, analyzed, and documented. Specific tasks for the remainder of the ongoing contract include:

1. Evaluate the information obtained at Kirishima and analyze the data to determine reservoir characteristics using both slimhole and large-diameter production well data.
2. Perform theoretical analyses to study the effect of borehole diameter on the discharge capacity of geothermal wellbores with two-phase feedzones.
3. Compare the results of the Kirishima data analyses to determine if geothermal production from large-diameter wells (with two-phase feedzones) can be predicted on the basis of slimhole discharge/injection data.
4. Prepare a final comprehensive written technical report. The report will describe the data, document the analyses, and highlight the conclusions regarding the validity of using slimholes to predict the production characteristics of large-diameter production wells.

Milestones: The following milestones have been adopted for this project:

- *Complete initial evaluation of Kirishima field data and select data sets for further analysis (11/96).*
- *Complete theoretical analysis on the effect of borehole diameter on productivity in reservoirs with two-phase feedzones (4/97).*
- *Complete analysis of Kirishima data and determine whether slimholes with two-phase feedzones can be used to predict large-well productivity (5/97).*
- *Complete final report on the analysis of the Kirishima reservoir slimhole data (9/97).*

Deliverables: This project will result in the following deliverables:

- *Final reports and conference papers documenting the compilation and analysis of Japanese slimhole production data and an assessment of the validity of using slimholes to predict the production characteristics of large-diameter geothermal production wells.*

Analysis of Okuaizu, Japan, Slimhole Data

Program Area: Slimhole Drilling Technology

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov;
Sabodh Garg, Maxwell Technologies, PO Box 1620, La Jolla, CA 92038, (619) 576-7752, Fax 755-0474

Program Area Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Based on work already completed under the Sandia program, it appears that the performance of large-diameter wells with liquid feeds may be reliably forecast using discharge and/or injection data from slim holes with liquid feeds. To date, the production data examined from the Japanese geothermal fields was for the most part obtained in wells with liquid feedzones. A case study of the Kirishima Geothermal Field, Japan is presently underway.

The Okuaizu Geothermal Field is an especially attractive candidate for the case study research in that most boreholes at Okuaizu produce from two-phase feedzones. Data from this reservoir is needed in addition to data from Kirishima to ensure that conclusions drawn for one field are valid in other geothermal fields with two-phase feedzones. Under this proposed project, the data from Okuaizu will be compiled and analyzed.

This project will not develop any cost-reducing technology; however, together with the Oguni, Sumikawa, Takigami, and Kirishima data, it will provide solid evidence of the viability of slimholes as a reservoir characterization tool. As previously stated, if this conclusion can be rigorously documented and accepted by industry, a 40% reduction in exploratory drilling would result from the use of current slimhole drilling technology instead of large-diameter drill rigs.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Maxwell; provide technical review of data and analysis.
- Maxwell Technologies: Compile and analyze Okuaizu slimhole data; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$80k	Sandia salary, travel; Maxwell contract for \$375k (\$75k to be spent in FY97).
DOE Geothermal - Reservoir Tech.	FY98	\$230k	Sandia salary, travel; Maxwell contract for \$375k (\$225k to be spent in FY98).
DOE Geothermal - Reservoir Tech.	FY99	\$55k	Sandia salary, travel; Maxwell contract for \$375k (\$50k to be spent in FY99).

Because of the nature of this work, we request funding for this project from the reservoir technology area of the DOE Geothermal Program.

Status: This is a proposed new project. It will continue and complete the work Maxwell has had under way for several years in compiling and analyzing slimhole data from Japanese geothermal fields. Maxwell has to date completed studies of the Oguni, Sumikawa, and Takigami geothermal fields. The case study of the Kirishima Geothermal Field will be completed during FY 1997. It is proposed to start the Okuaizu Geothermal Case Study in the summer of 1997.

Statement of Work: The proposed work will be performed by Maxwell Technologies, Inc. under a contract with Sandia Laboratories. KBK, Inc. will provide liaison services with the field developer (Okuaizu Geothermal Company, Ltd.). Dr. Jim Combs of Geo Hills Associates has been involved in the Sandia Slim Hole R&D program from its inception. He will work with Maxwell scientists in analyzing the Okuaizu Geothermal Field data.

The proposed work will be performed over a 18 month period, FY 1997 - 1999). During FY 1997, Maxwell scientists will travel to Japan to obtain the Okuaizu data. The bulk of the data analysis will be performed during FY 1998. The final project report will be completed in FY 1999.

Maxwell will perform the following tasks:

1. Negotiate with the Okuaizu Geothermal Company, Ltd. for release of appropriate slimhole, production, and injection well data, including both drilling and well test data.
2. Evaluate the released information and analyze the data to determine reservoir characteristics using both slimhole and large-diameter production well data.
3. Perform theoretical analyses to study the effect of borehole diameter on the discharge capacity of geothermal boreholes with two-phase feedzones.
4. Compare results of Okuaizu data analyses to determine if geothermal production from large-diameter wells (with two-phase feeds) can be predicted on the basis of slim hole discharge/injection data.
5. Prepare a final comprehensive written technical report. The report will describe data, document the analyses, and highlight the conclusions regarding the validity of using slimholes for predicting the production behavior of large-diameter production wells.

Milestones: The following milestones have been adopted for this project:

- *Conclude agreement with Okuaizu Geothermal Company for release of Okuaizu slimhole data (8/97).*
- *Complete trip to Japan obtain Okuaizu slimhole data (9/97).*
- *Complete analyses of Okuaizu slimhole data (9/98).*
- *Complete final report on the analysis of the Okuaizu reservoir slimhole data (12/98).*

Deliverables: This project will result in the following deliverables:

- *Final reports and conference papers documenting the compilation and analysis of Okuaizu slimhole production data and an assessment of the validity of using slimholes to predict the production characteristics of large-diameter geothermal production wells.*

Wellbore Modeling for Slimhole Reservoir Evaluation

Program Area: Slimhole Drilling Technology

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov;
Marcelo Lipman, Lawrence Berkeley National Laboratory, MS 90-1116, One Cyclotron Rd., Berkeley, CA 94720, (510) 486-5035, Fax 486-5686

Program Area Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: In order to properly analyze slimhole testing data and use it to draw proper conclusions about the viability of a geothermal reservoir, it is necessary to use an accurate model of the fluid flow in the reservoir and wellbore. Even though several wellbore simulators (e.g., WELBOR, GEM, WFS, WELLSIM) exist in the industry or in the national laboratories, all of them have shortcomings in their predictive capabilities, and none is widely used in a reservoir-coupled mode. This problem arises in part from the often large computing capabilities required and in part from the extremely wide variations in well design and reservoir properties that make some models more appropriate than others under the various conditions.

Under this project, Sandia will work with Lawrence Berkeley National Laboratory and Dr. Teklu Hadgu to: refine an existing wellbore simulator and make it robust enough for general slimhole use; couple the wellbore simulator with a reservoir simulator; and compare the predictions of the integrated code with field measurements. Sandia will focus on the wellbore simulator, Dr. Hadgu will work on coupling the wellbore simulator with the reservoir model, and LBL will concentrate on modifying the reservoir model, as needed, to make it suitable for coupling with the wellbore simulator.

The benefit of this project will be the development of a field-proven, coupled wellbore/reservoir model that can be used for analyzing slimhole testing data to determine reservoir properties and production characteristics in large-diameter geothermal wells. This model could be used directly by industry as well as serving as one module in the software toolkit for slimhole exploration that is proposed for development by Maxwell Technologies under another project described in this program plan. With a tool such as the wellbore/reservoir model available, acceptance of slimhole exploration by the industry will evolve more quickly, which could lead to a 40% reduction in exploration costs as previously noted.

Project Participants:

- Sandia National Laboratories: Refine wellbore model for slimhole production/injection; coordinate the project work; lead field tests; administer DOE funds to Hadgu; document and publish results.
- Lawrence Berkeley National Laboratory: Modify reservoir simulator as needed to accommodate coupling with wellbore simulator.

- Dr. Teklu Hadgu: Modify wellbore simulator as needed to accommodate coupling with reservoir simulator.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$225k	Sandia salary, travel; contract with Hadgu for \$85k.
DOE Geothermal - Reservoir Tech.	FY98	\$225k	Sandia salary, travel; contract with Hadgu for \$85k.
DOE Geothermal - Reservoir Tech.	FY99	\$225k	Sandia salary, travel; contract with Hadgu for \$85k.

Because of the nature of this work, we request funding for this project from the reservoir technology area of the DOE Geothermal Program. It is assumed that funding for LBL's work will be provided by DOE as part of its usual funding of reservoir technology work at LBL.

Status: This is a proposed new project, although it builds on work previously done by all the project participants. Earlier work at Sandia was directed toward comparing slimhole field data with wellbore models and toward correlating the productivities of large- and small-diameter wells (Finger *et al.*, 1994c; Finger *et al.*, 1996b). LBL's previous work includes development of the reservoir simulator TOUGH, which will be used in this project. Dr. Hadgu's previous related work includes preliminary coupling of TOUGH and the wellbore simulator WFSA.

Statement of Work: This project will be completed within three years. The objective of this work is to make an accurate, easily usable wellbore/reservoir simulator available to industry, thus encouraging exploration, especially with slimholes. There are four principal components of this work: wellbore simulation, reservoir simulation, coupling of the two models, and acquisition and analysis of field data.

Wellbore Simulation - The prediction accuracy of existing wellbore flow simulators depends on the system to which they are applied (e.g., high- or low-enthalpy fluids, single- or two-phase flow, gassy or non-gassy fluids, small- or large-diameter wellbores) and on the theory and correlations that represent fluid flow and transport within the models. Some preliminary comparative studies based on the physics of the flow rather than the customary empirical methods have been done. Other basic studies of wellbore flow have been previously carried out using flows of air-water, oil-water, and steam-water, but this work is incomplete because of the difficulties of characterizing two-phase flow and heat transfer. These methodologies need to be updated in light of new research results in this area. Extensive comparisons with field data will be made to select or develop appropriate two-phase velocity-slip correlations and frictional pressure-loss correlations for use in the wellbore simulator. The selected wellbore simulator must also be upgraded to include new features characteristic of geothermal wells, such as multiple feedzones and flows both upward and downward in the wellbore. Modeling of heat transfer between the wellbore and the reservoir must also be improved. Work on the wellbore simulator will be largely completed in FY97.

Reservoir Simulation - Current reservoir simulation practices treat the wellbore in a simplified manner. In the reservoir model TOUGH, for example, well deliverability calculations are based on assumptions of simplified feedzones and constant bottomhole pressures. The code will need at least minor modifications to properly consider wellbore transients. The adaptation of the code for execution on a personal computer in the field also needs further study. Although progress has

been made in this area, continued development is necessary to produce a product that can be utilized with ease in the field to guide drilling programs and interpret the resulting experimental observations.

Wellbore/Reservoir Model Coupling - The preliminary coupling work performed by Hadgu demonstrated that meaningful information can be obtained from the coupled simulators for realistic transient conditions. The work needs to be extended to produce a complete interfacing of the two simulators. Both simulators will require some modification to permit the coupled codes to be used with ease.

Acquisition/Analysis of Field Data - The development of a wellbore/reservoir simulator will be complemented with the collection and analysis of relevant wellbore and reservoir field data that can be used to validate the simulator. Typical field tests include flow tests, injection tests, tracer tests, and interference tests. The first two types of test are important in determining the potential energy extraction rate from a geothermal well, and all are important in characterizing the geothermal reservoir. If a sufficient data base can be established, it may also allow development of a small library of reservoir types, each of which can be represented by a simplified model. This potential simplification opens the possibility of a coupled simulator that is field-usable on a personal computer, which would provide immediate testing guidance and at least preliminary reservoir evaluation to the field engineer.

Some of the required field data may already exist. Maxwell Technologies, under contract to Sandia, has collected a large amount of data from Japanese geothermal slimholes and production-sized wells. Much of this data may be useful for this study. Additional field work required to obtain more relevant data will be identified, if necessary, and a project plan will be developed to conduct the field work. Sandia has the field expertise, logging and instrumentation vehicles, downhole and surface instruments, and experience working with the geothermal well testing industry to obtain the necessary high-quality data.

Milestones: The following milestones have been adopted for this project:

- *Complete development of an improved wellbore simulator for slimholes (6/97).*
- *Complete coupling of the slimhole wellbore simulator with approximate analytical reservoir models (8/97).*
- *Complete preliminary coupling of the slimhole wellbore simulator with the numerical reservoir simulator (8/98).*
- *Complete review and selection of existing wellbore data for validation of the coupled wellbore/reservoir simulator (9/98).*
- *Complete project plan for obtaining new wellbore data for validation of the coupled wellbore/reservoir simulator (9/98).*
- *Complete integrated coupling of the wellbore simulator and the numerical reservoir simulator (4/99).*
- *Complete field acquisition of new wellbore data for validation of the coupled wellbore/reservoir simulator (6/99).*
- *Complete validation studies of the coupled wellbore/reservoir simulator using previous and new field data (9/99).*

- *Complete final report on the development and validation of a coupled wellbore/reservoir simulator for slimhole evaluations of geothermal reservoirs (9/99).*

Deliverables: This project will result in the following deliverables:

- *A field-validated, fully-coupled wellbore/reservoir simulator for slimhole evaluations of geothermal reservoirs.*
- *Conference papers and a final report on the development and validation of the coupled wellbore/reservoir simulator.*

Software Toolkit for Slimhole Production Analysis

Program Area: Slimhole Drilling Technology

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov;
John Pritchett, Maxwell Technologies, PO Box 1620, La Jolla, CA 92038, Fax 755-0474

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The essential question facing a developer engaged in slimhole geothermal exploration can be stated as follows: Given the performance of a slimhole, what kind of completion program should be employed for future production-size holes to maximize the return (steam discharge rate) on investment (drilling cost)? The various mathematical and engineering issues that are important involve too many parameters for convenient expression in the form of design tables or algebraic formulas. Instead, the best approach would appear to be development of a mathematical toolkit that would permit appraisal of this question in the field under real-time conditions.

Under this program, Maxwell Technologies will develop such a software package. The proposed toolkit will consist of a suite of programs (operable on a PC) which may be transported to field sites. It should be noted that the various programs intended for inclusion in the toolkit either currently exist in at least a rudimentary form or may be developed based on current technology. (See, for example, the project on Wellbore Modeling for Slimhole Reservoir Evaluation.) The proposed toolkit will make these separate programs available in a convenient, user-friendly format.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Maxwell; provide technical review of work and help transfer technology to industry.
- Maxwell Technologies: Develop toolkit software; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Reservoir Tech.	FY97	\$50k	Sandia contract with Maxwell for \$50k.
DOE Geothermal - Reservoir Tech.	FY98	\$230k	Sandia salary and travel; contract with Maxwell for \$200k.
DOE Geothermal - Reservoir Tech.	FY99	\$280k	Sandia salary and travel; contract with Maxwell for \$250k.

Because of the nature of this work, we request funding for this project from the reservoir technology area of the DOE Geothermal Program.

Status: This is a proposed new project. It will build on the work currently being performed under the slimhole drilling technology program. Based on work already completed, it appears that the performance of large-diameter wells with liquid feeds may be reliably forecast using discharge and/or injection data from slimholes with liquid feeds. Work is presently under way to examine data from large-diameter and slim boreholes with two-phase feed zones. This ongoing work constitutes the essential rationale for the proposed toolkit.

Statement of Work: The proposed work will be performed by Maxwell Technologies, Inc. under a contract with Sandia Laboratories. Dr. B. J. Livesay will assist Maxwell in developing a realistic model for drilling costs in the toolkit. Dr. Jim Combs of Geo Hills Associates has been involved in the Sandia Slimhole R & D program from its inception. He will help Maxwell scientists to identify the important programs for inclusion in the toolkit.

The proposed work will be performed over a 30 month period, FY 1997 - 1999. During FY 1997, Maxwell scientists in collaboration/consultation with various interested parties (Sandia, Livesay, Combs, other geothermal companies), will develop a preliminary design for the toolkit. The bulk of the work on assembling the toolkit will be performed during FY 1998 and FY 1999. At a minimum, the toolkit is expected to include the following subprograms:

- A database management system for both the measures (*e.g.* drilling data, PTS logs, well characteristic data) and computed results.
- A graphical user interface (GUI) for the display of data/results in graphical form.
- Display tools to show PTS logs and stratigraphic information to help identify feedzones.
- Calculational model for computing downhole pressures from observed temperature and water-level data.
- Tools for estimating stable formation temperatures based on heat-up surveys.
- Display and interpretation tools for wellhead characteristics data (water and steam discharge rates as functions of wellhead pressure).
- Empirical rules for estimating "productivity index" of large-diameter wells based on measurements in slimholes.
- Mathematical tools for the initial evaluation of pressure transient data.
- Mathematical wellbore simulator for matching performance of slimholes, and for predicting the probable performance of future large-diameter wells.
- A mathematical model for estimation of well-drilling costs.

The prototype toolkit (to be completed by March 1999) will be made available to Sandia and other interested parties. Based on their comments, the toolkit will be revised as appropriate (April - August 1999). To transfer the toolkit to industry, a workshop will be held in September 1999.

Milestones: The following milestones have been adopted for this project:

- *Complete preliminary design of slimhole toolkit (9/97).*
- *Complete prototype slimhole toolkit (3/99).*
- *Complete revisions to slimhole toolkit based on industry feedback (9/99).*
- *Convene workshop on slimhole toolkit (9/99).*
- *Complete final report and release slimhole toolkit to interested users (9/99).*

Deliverables: This project will result in the following deliverables:

- *Interim and final reports on the development of the slimhole toolkit.*
- *A publicly-available software toolkit for planning and analyzing the test data from slimholes drilled for geothermal exploration and predicting the performance of large-diameter wellbores in the same reservoir.*

Geothermal Slimholes for Village Power

Program Area: Slimhole Drilling Technology

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov;

John Anderson, National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401, (303) 384-7422, Fax 384-7495

Program Area Leader: John Finger, Sandia National Labs, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Although the thrust of the slimhole drilling technology program has been to demonstrate and validate the use of slimholes for geothermal exploration, analytical work and a few actual installations indicate that there may be widespread application for small-scale power production from wells of this size. The potential for this application is emphasized by projections that the *growth* in energy consumption in developing countries (many of which have geothermal resources) between 2000 and 2010 will be greater than today's consumption in Western Europe, and that more electrical generating capacity will be built in the next 25 years than was built in the previous century. This opportunity is enhanced by an economic situation in which small geothermal plants would often be competing against diesel generators, not against grid-connected power as they do in the United States.

In this project, Sandia is initiating a study of the feasibility of using geothermal slimholes for small-scale electric power generation. This one-year project will roughly define the worldwide market for this technology, form and coordinate a Slimhole Geothermal Power Working Group from members of the geothermal community, and develop a working plan for FY98 and beyond to further develop and demonstrate the concept.

The benefits of this project could be enormous. The use of geothermal slimholes for power production would not only enhance the position, reputation, and public awareness of geothermal power worldwide, but it would also displace less desirable forms of energy production that lead to global warming or other forms of environmental degradation. Although slimholes have in a few cases previously been used for geothermal power production and work is now under way in Mexico to develop two slimhole geothermal fields, this project will help establish a broader geographic and technical base for the concept.

Project Participants:

- Sandia National Laboratories: Coordinate the Slimhole Geothermal Power Working Group; provide funding to contractor for market assessment; write future project plan; document results.
- National Renewable Energy Laboratory: Work with Sandia to coordinate the working group; help write project plan.
- Industry/Other Members of the Slimhole Geothermal Power Working Group (TBD): participate in developing and networking the concept; guide development of project plan.

- Contractor (to be determined): Conduct market assessment; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal -drilling tech.	FY97	\$120k	Sandia salary, travel; contract with NREL for \$20k; market assessment contract for \$50k.

Because of the nature of this work, we request funding for this project from the reservoir technology area of the DOE Geothermal Program.

Status: This is a new project, but it builds on both the results of our slimhole drilling technology program and preliminary discussions with the renewable energy community regarding the slimhole village power concept.

Statement of Work: This initial scoping project will be completed in FY97. This one-year project will roughly define the worldwide market for this technology, form and coordinate a Slimhole Geothermal Power Working Group from members of the geothermal community, and develop a working plan for FY98 and beyond to further develop and demonstrate the concept.

A contract will be placed with an appropriate party to define the approximate world market for slimhole geothermal power. Three components of this contract work will be:

1. Quantify the resource--Identify areas, both in the U.S. and in developing nations, where geologic conditions are appropriate for small-scale geothermal power. In general, these will be regions which have not been, or will not be, candidates for large-scale geothermal development. Some estimate of the resource's energy content will be a necessary part of this effort.
2. Quantify the demand--In regions with adequate resource, identify areas in which electric power demand will support power sales sufficient for construction of small-scale power plants. This selection will consider extant local cost of energy and will compare that with projected power prices for small-scale geothermal.
3. Identify market barriers--Once the common resource/demand areas are defined, identify any apparent market barriers for each area, whether they are technical (fluid chemistry, infrastructure, power distribution problems, site access difficulties, etc.) or institutional (government-subsidized diesel generators, government power monopoly, necessity for local ownership, etc.).

This contract study will provide a preliminary economic basis for the concept and will identify further work necessary to refine the market survey if the project proceeds.

Sandia will also organize a Slimhole Geothermal Power Working Group consisting of members of the geothermal industry and research community. The group will meet several times during FY97 to discuss the concept and formulate a plan for developing and demonstrating it. This group will also serve in a networking capacity to publicize the idea and attract commercial interest. For this project to be successful, it is essential to involve a company or agency as soon as possible that can function as a developer in implementing the concept.

Although the plan for future work in this area will be a specific deliverable of this first-year project, it is possible to speculate on what that work may be. Further refinement of the market survey will be necessary to better define site-specific market barriers for candidate slimhole

power sites. The difficulty and cost of eliminating such barriers will be estimated and factored into the economic analysis for slimhole power. The market survey will be completed with the selection of 2-10 sites as candidates for further development.

Another probable task for future work on slimhole power is the demonstration of a working, integrated system. This task will consist of the following:

1. Relate cost of energy to resource characteristics--Using generally accepted costs for roads and site preparation, drilling, well completion, and power-plant construction, establish criteria that relate required resource characteristics to the local cost of energy.
2. Identify needed technology--Use systems analysis to identify any needed technologies that do not exist (small-diameter downhole pumps, low-pressure turbines, etc.) or that need cost reductions (better drill bits, smaller rigs, etc.). Evaluate the cost/benefit ratio for developing these technologies.
3. Pilot project--At an appropriate state of technology development, design and construct a pilot project that demonstrates reliable performance and provides operating data for further economic evaluation of the concept.

Milestones: The following milestones have been adopted for this project:

- *Place Commerce Business Daily notice for preliminary slimhole power market survey contract proposals (11/96).*
- *Convene first meeting of the Slimhole Geothermal Power Working Group (12/97).*
- *Place contract for preliminary slimhole power market survey (1/96).*
- *Complete Slimhole Geothermal Power Working Group review of preliminary market survey (6/97).*
- *Complete project plan for future slimhole geothermal power work (9/97).*

Deliverables: This project will result in the following deliverables:

- *Preliminary market survey for slimhole geothermal power worldwide.*
- *Slimhole geothermal power project plan for FY98 and beyond.*

Fort Bliss Exploratory Slimhole

Program Area: Slimhole Drilling Technology

Project Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

Program Area Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The slimhole drilling experience gained by Sandia in our program over the past several years will be used in an exploratory geothermal well at Fort Bliss, TX. Sandia will serve in an advisory role to the U.S. Army and its drilling contractor in drilling and testing the 3,000- to 4,000-ft well.

This project also contributes directly to our program objective of collecting cost and performance data on slimhole drilling. We will acquire cost and performance data on the slimhole and corresponding data from any subsequent production well that may be drilled on the army base. Sandia's participation on this hole is a Work-for-Others (WFO) project funded by the U.S. Army.

The primary benefit of this project will be the application of expertise developed with DOE funding to another U.S. government project, leading to the characterization of a potentially new geothermal reservoir in west Texas that may be developed by the U.S. Army. A second benefit, as noted, is the acquisition of additional slimhole and production well test data that could help determine the viability of slimhole drilling as a geothermal exploration tool.

Project Participants:

- Sandia National Laboratories: Advise the U.S. Army and its drilling contractor in the drilling and testing of the slimhole; provide surface and downhole logging instrumentation and support; document results.
- U.S. Army, Fort Bliss: Provide Sandia funding and overall management of the drilling and testing operations.
- Drilling Contractor (to be determined): Conduct drilling and testing operations.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
U.S. Army, Ft. Bliss	FY97	\$57.5k	Sandia salary, travel, field expenses

The above funding is actually carry-over FY96 that will be spent in FY97, after the completion of a WFO agreement. The funding level for this project is not counted in the total funding level requested from DOE Geothermal for FY97.

Status: This is an ongoing project initiated at the request of the U.S. Army. Definition of Sandia's responsibilities on this project and preparation of the WFO agreement were completed in FY96.

Statement of Work: This project will be completed in FY97. An exploratory well will be drilled by a commercial drilling contractor, with Sandia serving in an advisory role. On-site Sandia personnel will consult with the U.S. Army Project Manager as the exploratory well is drilled, make recommendations on the drilling process, use Sandia instruments to make measurements on the rig and in the wellbore, and analyze the data obtained. This project will require the near-full-time presence of a Sandia engineer at the drill site at Fort Bliss. The Army estimates that their drilling contract will be in place approximately in October, 1996, and that drilling will take 90-120 days.

Sandia personnel will perform the following tasks in support of this project:

1. Assist the U.S. Army Project Manager (APM) in planning the drilling program.
2. Assist the APM in laying out the drill site for proper operation.
3. Provide on-site consultation during drilling operations. This consultation can relate to decisions on casing points, drilling techniques, equipment choices, testing methods, and well abandonment.
4. Provide drill-rig instrumentation as applicable and available.
5. Perform wellbore measurements (e.g., temperature and pressure) during and after drilling operations.
6. Assist in preparation for permeability testing if baseline criteria indicate that the well has penetrated a potentially productive reservoir.
7. Provide analysis of permeability data.
8. Provide a written report, including narrative of drilling operations, log of wellbore measurements, test data, and analysis of test data.

Milestones: The following milestones have been adopted for this project:

- *Complete assistance in laying out drill site and initiating operations for Fort Bliss exploratory slimhole (10/96).*
- *Complete temperature/pressure logging operations at Fort Bliss exploratory slimhole (1/97).*
- *Complete assistance in planning and set-up for the Fort Bliss exploratory slimhole injection tests if the well shows potential (2/97).*
- *Complete analysis of Fort Bliss slimhole injection test data (3/97).*
- *Complete final Sandia Report on Fort Bliss slimhole drilling project (6/97).*

Deliverables: This project will result in the following deliverables:

- *Successful completion and testing of the Fort Bliss exploratory slimhole, possibly leading to a new geothermal project in west Texas.*
- *A final report on the Fort Bliss slimhole drilling and testing project.*

Long Valley Exploratory Well

Program Area: Slimhole Drilling Technology

Project Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

Program Area Leader: John Finger, Sandia National Labs, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: The Long Valley Exploratory Well near Mammoth Lakes, CA, was drilled by Sandia beginning in 1989 under DOE's Magma Energy Program. The well was rotary-drilled to 6825 ft and core-drilled to 7,588 ft in two stages in 1989 and 1991 (Finger and Jacobson, 1990c; Finger and Jacobson, 1992b). DOE cancelled the Magma Energy Program in 1990 but supported the second phase of drilling as hydrothermal exploration. All support for Long Valley ended in FY96, and DOE authorized Sandia to transfer operation of the well site to the U.S. Geological Survey. The USGS is interested in deepening the well and using it for downhole seismic monitoring in the earthquake- and potentially volcanic-active Long Valley region.

Under this project, Sandia will simultaneously complete its obligation to the DOE to relinquish responsibility for the site, demobilize the rig, and restore the site, and to cooperate in a USGS project to convert the well to another useful purpose. An agreement with the USGS for transfer of the site has been negotiated and signed. The USGS is seeking funding to deepen the well and has requested Sandia's technical assistance in planning and executing the drilling operation. If the work is funded, the rig demobilization and site restoration may be deferred until the end of the drilling operations, depending on the drilling method for the project.

The benefits of this project are two-fold: use of expertise and a valuable wellbore developed with DOE funding for another U.S. government project, leading to improved earthquake and volcanic activity monitoring and public safety in California; and restoration of the site as required by Sandia's original agreement with the leaseholder.

Project Participants:

- Sandia National Laboratories: Advise the USGS in coring operations in the Long Valley Well; coordinate and fund site restoration activities.
- USGS: Coordinate coring operations in the Long Valley Well; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$150k	Sandia salary, travel, field expenses; contracts for rig demobilization and site restoration for \$90k total.

The funding listed above is actually carry-over funding for FY96 that was allocated by DOE for site restoration at Long Valley. Funding for this project is therefore not included in the total funding request for FY97.

Status: This is an ongoing project that is the only work remaining from DOE's Magma Energy Program. The site consists of approximately 6 acres of land. The site is fenced and currently holds the drill rig, two drilling fluid sumps, an office trailer, and miscellaneous equipment. Contracts have been placed with Nabors Drilling to de-mobilize the rig and with Morrisette Construction to complete the site restoration. An agreement to transfer responsibility of the site from DOE/Sandia to the USGS was signed in September, 1996.

The USGS has applied to the California Energy Commission and the International Continental Drilling Program for funding to deepen the well. The proposal calls for continuing the coring of this well from its present depth of 7,188 ft to approximately 14,000 ft. DOE has offered the site, site restoration services, and the remaining FY96 carry-over in the form of Sandia salary and expenses as matching funds in this proposal.

Statement of Work: This project will be completed within the next one or two years, depending on the success of the USGS in obtaining funding to deepen the well. If the proposal is not funded, rig demobilization and site restoration will be completed by the end of FY97. Because of the snow and wildlife migration seasons at the site, site restoration work can only be conducted during certain times of the year, primarily in the summer. Rig demobilization consists of laying the rig down, disassembling it, loading it onto trucks, and removing it from the site. Site restoration will consist of: removing the drilling sumps, removing the chain link fence around the site, breaking up and removing most of the concrete drilling pad; removing the chip-drying pad; re-contouring the site to its original configuration, and re-seeding as directed by the U.S. Forest Service.

If the USGS proposal to deepen the well is funded, Sandia will provide technical assistance and logging support, where appropriate. The drilling operation will probably be conducted in the summer of 1997. Rig demobilization and site restoration will then follow but may not be completed until the following summer, in 1998.

Milestones: The following milestones have been adopted for this project:

- *Complete transfer of the Long Valley Exploratory Well and site to the USGS (9/96).*
- *Complete rig demobilization and site restoration (assuming well is not deepened) (9/97).*
- *Complete well deepening operations at Long Valley Exploratory Well in cooperation with USGS (10/97).*
- *Complete rig demobilization and site restoration (assuming well is deepened) (9/98).*

Deliverables: This project will result in the following deliverables:

- *Transfer of the Long Valley Exploratory Well to the USGS.*
- *A converted Long Valley Exploratory Well for use in seismic monitoring by the USGS.*
- *A restored Long Valley Exploratory Well site.*

VIII. Geothermal Drilling Organization Projects

a. Background

The Geothermal Drilling Organization (GDO) was organized in 1982 as a joint DOE-industry organization devoted to jointly developing and funding near-term technology development projects for reducing geothermal drilling costs. Sandia administers DOE funds to the private entities performing the technical work and generally provides some technical assistance in each project. The type of projects usually considered by this organization are those where the basic research and development has already been completed, and all that remains before possible commercialization is some applications development and field testing. These projects most often are used to provide assistance to technologies under development by private industry and occasionally build upon Sandia work. Equal cost-sharing between DOE and industry is a requirement for each project.

The GDO consists of the following organizations:

Baker Hughes Inteq	Boart Longyear Company	CalEnergy
Calpine Corporation	Layne Christensen Corp.	Geo Hills Associates
Halliburton Services	Los Alamos National Labs	M-I Drilling Fluids Co.
Nabors Drilling USA, Inc.	Pajarito Enterprises	Sandia National Laboratories
Santa Fe Geothermal	Smith Drilling & Completion	Thermasource
Unocal Geothermal	Tonto Drilling Services, Inc.	Weatherford Enterra

GDO projects completed since 1982 include: the high-temperature borehole televiewer (Duda, 1989), polyurethane foam tool for lost circulation (Loeppke *et al.*, 1990a), high-temperature air turbine, and high-temperature drill pipe protectors (Thomerson and Keene, 1996). The GDO remains active and has a number of ongoing and proposed projects.

b. Justification for Technology Development Effort

The GDO serves a very useful purpose in not only encouraging commercialization of emerging cost-reducing technologies but in fostering a spirit of cooperation among the various segments of the geothermal industry toward reducing drilling costs. For Sandia, the GDO also serves as a mechanism for learning of the industry's drilling problems as well as a forum for transferring the technology we develop in our program.

c. Geothermal Drilling Organization Projects

There are currently six GDO projects under way. Two of these, Expert System for Lost Circulation Control and Field Evaluation of Cementitious LCM, are described under the lost circulation technology program area. The four remaining ongoing projects are described below; Sandia has only minimal involvement in these. One new proposed project in which Sandia will be heavily involved is also described.

Ongoing GDO Projects

Program Area: Geothermal Drilling Technology Projects

Project Leader: Alan Sattler, Sandia National Laboratories, Mail Stop 0706, Albuquerque, NM 87185, (505) 844-1019, Fax 844-0240, arsattl@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: There are several ongoing GDO projects in which Sandia has only minimal involvement., including the positive-displacement air motor, the retrievable whipstock, rotating-head rubbers, and the percussive mud hammer. In all of these projects, the technology was developed by industry and does *not* fit within one of Sandia's technology development program areas. We are involved in these projects by providing DOE's portion of the funding to the appropriate parties and assisting in field evaluation of the technology where appropriate.

Project Participants:

- Sandia National Laboratories: Administer DOE funding; provide technical assistance where appropriate.
- Baker Hughes Inteq: Develop and test positive-displacement air motor; document results.
- Smith International: Develop and test retrievable whipstock and rotating head rubbers; document results.
- Novatek: Develop and test percussive mud hammer; document results.
- Unocal Geothermal: Participate in field testing of positive-displacement air motor, retrievable whipstock, and percussive mud hammer.
- CalEnergy: Participate in field testing of percussive mud hammer.
- Amoco Production Research: Participate in field testing of percussive mud hammer.

Requested Funding: The following funding is required for these projects:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$80k	Sandia salary, travel; Novatek contract for \$165k (\$10k to be spent in FY97); Amoco contract for \$40k
DOE Geothermal - Drilling Tech.	FY98	\$70k	Sandia salary, travel; CalEnergy contract for \$40k.

Note that most DOE funding for these projects has been expended, except for the percussive mud hammer. Industry funding for these projects in FY97 is expected to be: \$100k for percussive mud hammer development and testing; \$20k for positive-displacement air motor field testing; and \$20k for retrievable whipstock field testing. Industry funding for FY98 is expected to be: \$120k for percussive mud hammer development and testing.

Status: These projects are all *ongoing*, and all but one are essentially complete. The following narrative provides the status of each project.

Positive Displacement Air Motor for High Temperatures

Two prototype 8-inch air motor assemblies for high-temperature drilling have been developed by Baker Hughes Inteq. These motors should be useful in directional drilling operations in the reservoir section of the wellbore, where air is often used as the drilling fluid. Being able to directional drill in that section would allow the wellbore to be turned in the proper direction to intersect more fractures, even after the production zone has been reached. This would improve the productivity of each well and reduce the number of wells needed for a given geothermal project, thus reducing overall drilling costs.

Prior to final assembly, sections of the air motor assemblies underwent extensive laboratory and bench-scale testing at Inteq's facilities in Houston, TX, and Celle, Germany. One unit was tested in The Geysers in December, 1994. During the test, the motor was first used to ream a section of hole for about 8 hours, after it had already been in the hole tripping for 10.5 hours. When the motor reached the bottom of the hole, it was no longer capable of drilling. The injected air temperature was 58°F, and the returning air temperature was 199°F. Although the temperature in these strata in this part of The Geysers would not have exceeded 450°F, a heat tab in the motor indicated a temperature of 550°F, suggesting a possible downhole fire in the motor.

Upon disassembly, it was found that the stator elastomer probably overheated. The majority of the elastomer was missing. Air injection probably caused a local burn to spread to the remaining stator elastomer. The location where the fire tab was located is approximately 10 ft from the bottom of the stator, so the actual stator temperature was probably much higher than 550°F. It is possible that insufficient mist/water was injected during the test. This could cause high frictional temperatures. The possibility of rust and scale causing high frictional temperatures has also not been ruled out.

The positive-displacement air motor is currently awaiting another field testing opportunity, where more careful attention will be paid to providing proper operating conditions.

Retrievable Whipstock for Geothermal Wells

A prototype 13-3/8 inch diameter retrievable anchor stock (whipstock) assembly has been developed by AZ Grant International, now a part of Smith International. This combination anchor and whipstock provides a means of sidetracking in a cased hole. Portions of this assembly have undergone extensive testing in the Smith International facilities in Tulsa and Houston. The prototype has been shipped to Healdsburg, CA, where it is awaiting arrangements for a field test. The 13-3/8 inch size is primarily used for geothermal drilling. Because there is little domestic geothermal drilling under way, and there is no oilfield drilling of this size, difficulty has been encountered in securing a test opportunity for this unit.

Rotating-Head Rubbers for High-Temperature Fluids

AZ Grant International, now a part of Smith International, has optimized rubber compounds for rotating heads, which seal against the rotating drill pipe where it enters the wellhead. Previously tested compounds proved to be too short-lived, or they leaked.

Percussive Mud Hammer

Novatek is developing a percussive mud hammer for high-temperature, hard-rock applications. This would make available to mud drilling applications at least part of the penetration-rate improvements achievable with percussive hammers in air-filled holes. Novatek has developed a patented percussive mud hammer design with parallel mud streams such that only a portion of the drilling fluid passes through the valving mechanism. This makes it less subject to plugging and hence more reliable. It would also allow conventional rotary drilling to continue if the percussive hammer quits working downhole, until such time that the hammer can be replaced during the next bit change. This makes the design attractive from a risk standpoint. Under this project, Novatek is modifying the design for high temperatures and will be building a mud hammer for 12-1/4 inch holes. Unocal, CalEnergy, and Amoco Production Research are all participating in the field evaluation of the tool.

Statement of Work: All of these ongoing GDO projects are expected to be completed in FY97. Additional field testing opportunities will be sought for the positive-displacement air motor and the retrievable whipstock. Final reports will then be written on the projects, along with recommendations for any further work needed.

The percussive mud hammer will be tested in the field at Amoco's Catoosa Test Facility in Oklahoma. This will allow the performance of the hammer to be compared with previous data obtained with conventional drilling in a variety of rock types beneath the facility. The penetration rate improvement achieved with the 7-3/4 inch tool will be measured and documented. These tests were originally planned for a Unocal oil and gas well in west Texas; however, it was learned that Unocal has very few wells of a size compatible with the existing Novatek tool. Amoco researchers offered the use of the Catoosa Test Facility, and it was agreed by all concerned that this was a good substitute.

If the Catoosa field tests continue to show promise for the tool, a hammer will be designed and built for a high-temperature, 12-1/4 inch hole based on the design principles developed for the 7-3/4 inch tool. This hammer will be tested in a geothermal well in cooperation with CalEnergy. The current schedule calls for the field test of the larger tool to be completed before the end of FY97, but that will depend on the availability of a field testing opportunity.

Milestones: The following milestones have been adopted for this project:

- *Complete field test of percussive mud hammer at Catoosa Test Facility (12/96).*
- *Complete design of percussive mud hammer for 12-1/4 inch hole (2/97).*
- *Complete fabrication and bench-testing of percussive hammer for 12-1/4 inch hole (5/97).*
- *Complete second field test of the positive-displacement air motor (6/97).*
- *Complete field test of retrievable whipstock (6/97).*
- *Complete final report on positive-displacement air motor project (9/97).*

- *Complete final report on retrievable whipstock project (9/97).*
- *Complete final report on rotating-head rubber project (9/97).*
- *Complete field test of percussive hammer in 12-1/4 inch geothermal well (9/97).*

Deliverables: This project will result in the following deliverables:

- *A positive-displacement air motor for directional drilling using air as the drilling fluid.*
- *A retrievable whipstock for sidetracking in high-temperature, cased wellbores.*
- *Improved high-temperature rotating head rubbers for drilling fluid control in geothermal drilling.*
- *A commercially available percussive mud hammer for geothermal drilling.*

Insulated Drill Pipe

Program Area: Geothermal Drilling Organization Projects

Project Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

Program Area Leader: Alan Sattler, Sandia National Laboratories, Mail Stop 0706, Albuquerque, NM 87185, (505) 844-1019, Fax 844-0240, arsattl@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: High downhole fluid temperatures are a significant problem in geothermal drilling, leading to degradation of drilling fluids, reduction of bit life, increased drillstring corrosion, and complexities with downhole electronics. The temperature of the drilling fluid is the highest in the annulus, about 10% above the bottom of the hole; this is because the drill pipe is an excellent counterflow heat exchanger. Fluid flowing up the annulus between the wellbore and the drill pipe picks up heat from the wellbore wall. As the fluid heats up, it transfers some of its heat through the drill pipe wall to the cooler fluid flowing down the center of the drill pipe. The fluid flowing down the pipe is thereby continually heated as it flows downhole, reaching a maximum near the bottom of the hole (Duda, 1984; Goodman, 1981).

The key to minimizing the downhole fluid temperature is, therefore, to reduce the conduction of heat through the drill pipe wall. The net effect would be that the drilling fluid exiting the wellbore would be hotter than it otherwise would be, but the heat can be removed at the surface with heat exchangers (Geo-Coolers). More heat would thus be removed from the wellbore, making it a much cooler drilling environment. This cooler environment would preserve the drilling fluid, enhance bit life, reduce corrosion, and permit the use of downhole motors, logging tools, and instrumentation such as MWD systems that are now unusable in geothermal wells because of high temperatures.

In this proposed project, Sandia and the GDO will assist Drill-Cool System (DCS) in completing the development and testing of insulated drill pipe (IDP). The immediate objective is to refine and test the design, build a string of IDP, and validate both the design and the benefits of the IDP in a series of field tests. The goal is the commercial availability of insulated drill pipe that can be leased or purchased for high-temperature applications.

The benefit of this project could be significant. Reduction in drilling fluid conditioning costs could amount to several thousand dollars per well, saving perhaps 1/2% of the total well cost. A 25% improvement in bit life would reduce geothermal drilling costs by about 3%. Other benefits of cooler downhole drilling fluid temperatures are more difficult to quantify but could be significant. Overall, a 5% potential reduction in drilling costs is anticipated with the successful development of insulated drill pipe.

Project Participants:

- Sandia National Laboratories: Administer DOE funding; conduct thermal and mechanical analyses of design; recommend insulation material; coordinate field instrumentation and testing; help document and publish results.

- Drill-Cool Systems: Design and fabricate prototype IDP; conduct thermal testing; participate in field testing; help document and publish results.
- Other GDO Member (to be determined): Participate in field testing.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$200k	Sandia salary, travel; DCS contract for \$150k.
DOE Geothermal - Drilling Tech.	FY98	\$265k	Sandia salary, travel, field expenses; DCS contract for \$200k.

Industry funding for this project is expected to match or exceed the above DOE funding levels.

Status: This is a new project, although Sandia did work on the IDP concept in the early 1980s in support of the Magma Energy Program and placed design and feasibility-study contracts with two companies (Finger, 1986). The concept has since lain dormant at Sandia, but Drill-Cool System (DCS), a subsidiary of Kern Steel Fabrication in Bakersfield, CA, recently became interested in pursuing IDP as a business line. They have built five joints of prototype IDP, have performed preliminary evaluation of the pipe's effective thermal conductivity, and have run these joints in field operations, including both drilling and workover.

The idea of initiating a GDO project on insulated drill pipe has been discussed and greeted with enthusiasm by the membership. In FY97, a proposal for this project will be submitted for the GDO's endorsement. It will first be necessary to secure the involvement of another GDO member, such as a geothermal operator, who is willing to participate in field testing the IDP.

Statement of Work: This is a proposed two-year project to develop IDP in a basic configuration of conventional drill pipe with a liner sleeve inside it and insulation in the annulus between the inner and outer tubes. There are two major goals for the first year's work: develop a prototype design, and verify its performance. In general, Sandia will perform thermal and mechanical analyses on the proposed IDP design, investigate insulation materials, and coordinate test planning and instrumentation with DCS, who will build, lab-test, and field-test the prototype IDP.

Much of the analysis to predict IDP thermal performance will use GEOTEMP2, a finite-element code previously developed with Sandia support that calculates the temperature of the drilling fluid and the formation surrounding the wellbore (Mondy and Duda, 1984). Sandia and DCS will collaborate on the IDP design. The following tasks are required to meet the objectives:

1. Define a list of candidate insulation materials and evaluate their thermal and mechanical properties. Recommend material(s) for a prototype IDP that not only has adequate insulating values but also adequate compressive strength to support internal pressure in the drill pipe.
2. Create a prototype method for joining inner and outer IDP tubes and perform mechanical analysis of this prototype method.
3. Build one to three sections of IDP, possibly with more than one design for the prototype joining method.

4. Modify the existing DCS test chamber and, using the prototype IDP built in the previous task, measure the thermal conductivity of the IDP body.
5. Field test the prototype IDP in drilling or workover operations to assess the joint's ruggedness.
6. Perform a GEOTEMP2 parametric study on the thermal effects of combining conventional drill pipe and IDP in the same string.
7. Evaluate the effects, at least analytically and experimentally if possible, of insulated and non-insulated connections in the drill string.
8. Based on analysis and field experience, continue iterations of IDP designs to produce a second-generation prototype.
9. Field test the new prototype in drilling or workover operations to assess the joint's ruggedness.
10. Validate the GEOTEMP2 calculations by performing temperature logs in field drilling operations and comparing measurements with calculations. Modify the code, if necessary.
11. Write a comprehensive technical report on the development and testing of IDP, including an assessment of its benefits in geothermal drilling.

Milestones: The following milestones have been adopted for this project:

- *Submit insulated drill pipe proposal to GDO and gain GDO endorsement (10/96).*
- *Place contract with DCS for DOE-sponsored portion of the IDP project (12/96).*
- *Complete definition and evaluation of insulation candidates (12/96).*
- *Complete development of prototype joining methods for insulated drill pipe (3/97).*
- *Complete fabrication of prototype insulated drill pipe (6/97).*
- *Complete measurement of thermal properties of the prototype insulated drill pipe (7/97).*
- *Complete the first field test of the prototype insulated drill pipe (11/97).*
- *Complete GEOTEMP2 parametric study of insulated drill pipe design and use (11/97).*
- *Complete design iteration and fabrication of prototype second-generation insulated drill pipe (4/98).*
- *Complete first field test of prototype second-generation insulated drill pipe (7/98).*
- *Complete validation and modification of GEOTEMP2 for use with insulated drill pipes (8/98).*
- *Complete final report on the development and testing of insulated drill pipe (9/98).*

Deliverables: This project will result in the following deliverables:

- *An assessment of the benefits of insulated drill pipe in geothermal drilling.*
- *Commercially available insulated drill pipe that can be leased or purchased for geothermal drilling.*
- *Conference papers and a final report on the development and testing of insulated drill pipe.*

IX. Geothermal Heat Pump Technology

a. Background

Geothermal heat pumps (GHPs), also known as ground-source or ground-coupled heat pumps, are more efficient than conventional heat pumps. They exchange heat with a more moderate-temperature source, the earth, rather than with the outside air. In appropriate climates, geothermal heat pumps can pay for themselves within 3-7 years, because of reduced energy consumption.

Sandia's program on GHPs began in the early 90s as a very broad-based activity that included installation demonstrations, performance measurement programs, limited marketing efforts, and R&D on in-ground heat exchangers. This program was funded by both the DOE Office of Geothermal Technologies and the Department of Defense Strategic Environmental Research and Development Program (SERDP). Some of the accomplishments of this program include:

- Establishment of several long- and short-term field data acquisition and demonstration projects measuring the response of installed GHP systems throughout the country. Examples include projects at Stockton College (NJ), Fort Polk (LA), Fort Hood (TX), Selfridge Air National Guard Base (MI), and Patuxent River Naval Air Station (MD). The data acquired and analyzed from these sites have illuminated operational and design problems, provided a basis for confirming design tool accuracy, and provided credible marketing data for the GHP community.
- Design, completion, and documentation of experiments on vertical loop and GeoBag heat exchangers. These experiments identified several important issues regarding these heat exchangers, such as grout instability in vertical boreholes and excessive volume changes in GeoBags.
- Agreement by Sandia plant engineering to install a 15-ton GHP system on one of its new buildings in Albuquerque. The 18-loop vertical ground heat exchanger for this building also serves as a test facility for evaluating new and innovative grout and completion technologies and testing the validity of design tools used to size loop fields. This experiment was jointly designed by Sandia, South Dakota State, and Loop Tech International. The field has been comprehensively instrumented to measure relative heat transfer for each well. Early results indicate that the completions have a significant effect on overall loop heat transfer.
- Implementation of the first GHP drilling technology workshop, which gathered prominent loop installers to discuss future R&D needs aimed at reducing the costs and risks associated with vertical loop installation and completion. The crux of Sandia's FY97 R&D program is based on suggestions from this workshop.
- Creation of a reputation for Sandia as a valuable contributor advancing the understanding and improving the state of technology for GHP systems. Sandia is a frequent contributor at workshops, fora, and symposia on GHPs. Sandia has also provided objective technical consulting services to a wide range of potential GHP customers and practitioners.

Two important changes occurred in FY95-96 that affected the Sandia GHP program. The Geothermal Heat Pump Consortium (GHPC) was launched, and their plans included a major thrust in joint industry/GHPC projects, including GHP demonstrations and data acquisition projects. Also, the SERDP program was realigned toward technologies other than GHPs. As a result of these changes, the Sandia program, starting in FY96, sharpened its focus toward R&D aimed at reducing the costs of ground heat exchanger installations, particularly vertical, drilled

installations. This change was designed to conserve the reduced funding available to Sandia by focusing its R&D effort toward projects connected to its established expertise in drilling technology. This re-focusing effort is reflected in this program plan.

b. Justification for Technology Development Effort

The DOE and GHPC have adopted a goal of attaining 400,000 GHP installations per year in the U.S. by the year 2002. This is a significant increase from 40,000 installations per year in 1996. The GHPC program includes both marketing and R&D as major components of their effort to achieve the goal. The DOE is providing partial funding to the GHPC, which in turn is funding the technology development program at Sandia.

c. Geothermal Heat Pump Technology Projects

There are currently four GHP technology projects under way. Two new projects are proposed for FY97. All of these projects are described below.

GHP Loop Installation Systems Study

Program Area: Geothermal Heat Pump Technology

Project Leader: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

Program Area Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: One of the GHP system components targeted for cost reduction is loop installation, particularly for the vertical- and horizontal-well configurations. Borehole drilling, loop insertion, and grouting account for about 40% of the cost of GHP systems that use one of these configurations. In order to reduce the cost of these operations, improved technology and/or methods must be developed.

As yet, it is not readily apparent how to reduce costs in these operations. The GHP drilling industry consists mostly of current or former water well drillers for whom cost is a constant concern. These bright and clever people have already eliminated unnecessary costs wherever possible. In most cases, GHP boreholes are already drilled much more cheaply than water wells emplaced to the same depth.

In order to identify possible cost-saving measures that could be developed for GHP loop installation, a systematic investigation of the problems and a quantitative understanding of individual cost components and their relationships are needed. Such a systems study is under way in this project. For this study, we are: observing loop drilling, insertion, and grouting activities at a number of sites across the country; collecting data on the time, material, and cost required to perform various tasks in the process; developing a spreadsheet-based economic model that will allow cost sensitivities to be studied; and identifying any high-cost components where technology or methodology improvements would reduce costs.

The benefits resulting from this project will be two-fold: it will provide information that members of the GHP drilling community can immediately use to examine their own operations; and it will help GHPC, DOE, and Sandia maximize the impact of research and development activities for reducing loop installation costs.

Project Participants:

- Sandia National Laboratories: Conduct site visits; collect and analyze data; develop economic model; conduct sensitivity study; document and publish results.
- Bertram Drilling: Provide access to loop installation operations and data for study.
- Ewbank and Associates: Provide access to loop installation operations and data for study.
- Loop Tech International: Provide access to loop installation operations and data for study.

- Mill Pond, Inc.: Provide access to loop installation operations and data for study.
- Viera Artesian Wells: Provide access to loop installation operations and data for study.
- Winslow Pump and Well, Inc.: Provide access to loop installation operations and data for study.
- Other Contractors (to be determined): Provide access to loop installation operations and data for study.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - GHP Tech.	FY97	\$110k	Sandia salary, travel.
DOE Geothermal - GHP Tech.	FY98	\$30k	Sandia salary, travel.

Part (\$80k) of the FY97 funding shown is actually the remaining FY96 carry-over funding (\$150k) that was allocated to this project by the GHPC and DOE; this carry-over amount will thus not be counted in the total FY97 funding request. The remaining \$30k requested new funding for FY97 is to maintain an ongoing study of loop installation operations, as noted below.

Status: This is an ongoing project that was initiated in April, 1996. To date, site visits have been made to observe the loop drilling, insertion, and grouting operations of six different contractors. The sites were selected to sample wide ranges of geology types, drilling methods, and geographic locations. Sandia engineers highly experienced in a variety of drilling activities performed the work. Data were collected at each site on time, materials, and costs for various components of the process. Common installation methods were noted as well as some innovative variations in equipment and technique used by some of the drillers.

Work was also partially completed on developing a loop installation cost model. The model is based on an EXCEL spreadsheet that lists the time, material, and costs required to complete each part of a multi-loop installation. There is a distinction between distributed costs, which are spread over the entire project, and per-loop costs. Any individual cost component can be easily changed to evaluate its effect on the total project cost.

Cost drivers that have been identified to date include: rate of penetration, environmental/site cleanup, loop insertion/unsuccessful holes, inexact field design, variation in heat transfer from loops, equipment cost and reliability, regulatory differences, logistics, and variability in sites and formations.

Preliminary results of this project were presented at an IGSHPA conference in September, 1996. The work will be completed in early FY97, but a continuing low-level effort is proposed, as noted below.

Statement of Work: This work will be substantially completed in the early part of FY97. Horizontal boring and trenching operations will be observed and data collected as with the vertical bores. Cost models for all three types of loop installations will then be completed. A sensitivity study will be conducted to determine the effects of operational variables on the total project cost. The factors that have the greatest effects on project costs will be identified, and

potential technology development projects will be defined. The study will be documented and published in reports and conference papers.

Although the above tasks will be completed in FY97, we propose maintaining a much lower, but continuous, level of effort surveying drilling operations. This is because the nature of the business varies so much from site to site as geology changes, so no single study can hope to cover all possible drilling operations and technologies. This would also provide an important vehicle to keep Sandia's research effort connected with actual drilling operations, and it would provide us with ready contacts who will cooperate in testing the technology we develop.

As part of an ongoing systems study, Sandia's drilling team can also be made available as pre-paid consultants to aid GHP drillers encountering severe drilling problems at their sites. This will keep Sandia connected to "real-world" drilling problems, and our experience could contribute toward effective solutions. To help with these problems, Sandia can use its in-house expertise, enlist the support of experienced GHP drillers in the area, and arrange for help by service companies in other segments of the drilling industry with which we work.

To maintain the ongoing systems study described above, we estimate required funding to be \$30k per year.

Milestones: The following milestones have been adopted for this project:

- *Complete first site visit to horizontal boring operations (10/96).*
- *Complete first site visit to horizontal trenching operations (11/96).*
- *Complete cost models for vertical drilling, horizontal boring, and horizontal trenching loop installation methods (2/97).*
- *Complete parametric cost sensitivity study for GHP loop installation (3/97).*
- *Complete Sandia Report on GHP loop installation systems study (4/97).*
- *Present conference paper on GHP loop installation system study at IGSHPA conference (5/97).*

Deliverables: This project will result in the following deliverables:

- *Final report and conference papers on the GHP loop installation systems study.*
- *Recommendations for cost-effective R&D projects to reduce GHP loop installation costs.*

Low-Cost, Replaceable-Cutter PDC Bit for GHP Drilling

Program Area: Geothermal Heat Pump Technology

Project Leader: David Raymond, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8026, Fax 844-3952; Tom Dennis, Dennis Tool Company, 2020 Rankin Rd, Houston, TX 77073, (713) 821-9495, Fax 821-4171

Program Area Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: GHP drilling occurs in a wide variety of geologies. Soft sand and clay can be efficiently drilled with wing-type, tungsten carbide-tipped drag bits. If the compressive rock strength exceeds about 5,000 to 10,000 psi, this type of bit wears or breaks excessively, so roller-cone bits or pneumatic hammers become the preferred drilling method. Roller bits have relatively low penetration rates compared to drag bits, and pneumatic hammers are noisy and costly to operate. Consequently, an alternative, cost-effective drilling method for moderate-strength rocks, 10,000-20,000 psi compressive strength, would be welcomed by the GHP drilling industry.

Polycrystalline diamond compact (PDC) drill bits are extensively used in the oil and gas drilling industry in rock formations with compressive strengths less than 20,000 psi. Because of their rapid rock penetration and long life in appropriate formations, PDC bits save millions each year in drilling costs worldwide. Cost savings of over \$100,000 *per bit run* have been reported in the literature.

Currently, PDC bits cost about \$1000 per inch of bit diameter because of the quality necessary to ensure reliability in high-cost drilling applications. To extend the use of PDC bits to GHP applications, a significant reduction in bit cost would be necessary. PDC bits are reportedly already used for GHP applications in a few isolated cases, so reductions in bit cost could lead to a significant increase in such use.

Under this project, a low-cost, replaceable-cutter PDC bit design is being developed in cooperation with Dennis Tool Company. Dennis Tool reclaims over one-half the used PDC bits in the oil and gas industry, tests and re-certifies the cutters, and markets them to the PDC bit industry. They have a large inventory of used PDC cutters that are not suitable for deep, expensive drilling but that could be used effectively in low-cost drilling operations, where the risk of cutter breakage would not be so important. Sandia has devised a method of mechanically holding such cutters on a bit body, thereby making them field-replaceable. If we can jointly develop a replaceable-cutter PDC bit using reclaimed PDC cutters, Dennis Tool believes it may be able to sell such a bit for a few hundred dollars each.

The benefits of this project could be significant. The use of PDC bits could easily double the penetration rate achieved in some GHP applications and could eliminate the need for a pneumatic hammer and air compressor in others. We do not currently have the information necessary to estimate the cost savings that would result. A cost model of the process is under development in the GHP loop insertion systems study. The predictions of that model will be used when it becomes available to estimate the cost benefits of the PDC bit project.

Project Participants:

- Sandia National Laboratories: Design PDC cutter holder; design PDC cutter layout; conduct laboratory testing and coordinate field testing of prototype PDC bit; document and publish results.
- Dennis Tool Company: Design PDC bit structure; fabricate PDC bit; participate in lab and field testing.
- Ewbank and Associates: Provide rig time for field testing PDC bit.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - GHP Tech.	FY97	\$30k	Sandia salary, travel; contract with Dennis Tool for \$25k (\$18k to be spent in FY97).

Part (\$20k) of the FY97 funding shown above is actually the remaining FY96 carry-over funding (\$30k) that was allocated to this project by the GHPC and DOE; this carry-over amount will thus not be counted in the total FY97 funding request. The remaining \$10k requested new funding for FY97 is for conducting more extensive lab and field testing than was originally contemplated, as noted below.

Status: This is an ongoing project. It began in May, 1996, with discussions and placement of a contract with Dennis Tool for cooperative development of the bit. Bit specifications were developed by Sandia based on discussions with GHP drillers. A 3-3/4 inch bit diameter was chosen based on the size typically drilled by Ewbank and Associates, who has offered to help field test the bit. Dennis Tool Co. developed proposed cutter layouts, and Sandia analyzed the layouts using our PDCWEAR code (Glowka, 1987). An optimal layout was fine-tuned to achieve a balanced bit design. Dennis Tool Co. is currently studying the proposed layout to incorporate it into the design of the bit.

Statement of Work: This work will be completed in early FY97. The bit design will be finalized and fabricated by Dennis Tool. Sandia will then test the bit in our Cutter Wear Test Facility to measure the penetration rate response and cutter wear of the bit. A comparative test will be run with a roller-cone bit of the same size. Any design problems noted will be corrected, then the bit will be tested in the field. Ewbank and Associates will participate in the test by providing rig time to run both the test bit and a conventional bit in several locations with both soft and moderate-strength rock.

Milestones: The following milestones have been adopted for this project:

- Complete cutter layout for PDC bit for GHP applications (9/96).
- Complete design of PDC bit for GHP applications (10/96).
- Complete fabrication of PDC bit for GHP applications (10/96).
- Complete Cutter Wear Test Facility testing of the PDC bit for GHP applications (11/96).
- Complete first field test of PDC bit for GHP applications (12/96).

- *Complete Sandia Report on the development and testing of the PDC bit for GHP applications (2/97).*

Deliverables: This project will result in the following deliverables:

- *Commercially-available, low-cost, replaceable-cutter, PDC bit for GHP drilling applications.*
- *Final report and conference paper on the development and testing of a PDC bit for GHP applications.*

Annual Vertical Loop Installation Workshop

Program Area: Geothermal Heat Pump Technology

Project Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Sandia sponsored a loop installation workshop in January, 1996, to discuss the R&D needs and problems facing the GHP drilling community. This meeting provided a valuable forum for drillers to express their opinions and give researchers feedback on the relevance of their work.

We propose to make this workshop an annual meeting. It will focus on the presentation of ongoing research results, demonstrations and presentation of new drilling technologies, and acquisition of feedback from the drilling community. Meetings like this are essential to help keep communication flowing between production drillers and researchers. The first meeting was held in Albuquerque. The next meeting will be held in another location to encourage drillers from other parts of the country to attend.

This workshop, with the support of IGSHPA, GHPC, and NWGA, could evolve to include on-site training curricula for drillers learning the art of loop installation.

Project Participants:

- Sandia National Laboratories: Plan, develop, arrange, and conduct annual workshop; provide partial travel support to attendees.
- Department of Energy: Participate in workshop planning and implementation.
- Geothermal Heat Pump Consortium: Participate in workshop planning and implementation.
- Drilling Contractors (to be determined): Participate in workshop.
- Other Researchers (to be determined): Participate in workshop.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal	FY97	\$40k	Sandia salary, travel; partial travel reimbursement for attendees.
DOE Geothermal	every	\$40k	Sandia salary, travel; partial travel reimbursement for attendees

Status: This is an ongoing project. The first workshop was held at Sandia in January, 1996. It was instrumental in directing the Sandia GHP program for the remainder of FY96. The GHP loop installation systems study and the PDC bit development project for GHP drilling are both outcomes of that workshop.

Statement of Work: As an annual workshop held in January, work would need to begin each year in November to plan and coordinate the event. A tentative agenda for the workshop will first be developed and distributed to the GHP drilling community together with an announcement of the workshop date and location. Workshop attendees would be registered and arrangements made for the meeting location.

We will try to hold the workshop in a location where demonstrations of GHP drilling technology or techniques can be provided. The intent will be to provide a mix of presentations, discussions, and demonstrations at the workshop. Workshop proceedings will be copied and distributed to interested parties.

Milestones: The following milestones have been adopted for this project:

- *Mail announcement of 1997 Annual Vertical Loop Installation Workshop (11/96).*
- *Convene 1997 Annual Vertical Loop Installation Workshop (1/97).*

Deliverables: This project will result in the following deliverables:

- *An annual gathering of GHP drillers and researchers to discuss GHP drilling problems, technology needs, and solutions.*

PSSL Loop Field Testing and Analysis

Program Area: Geothermal Heat Pump Technology

Project Leaders: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov;

Chuck Remund, South Dakota State University

Program Area Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: A large part of the potential market for GHPs is in locations with dry soils, which are common throughout the West. The performance of GHPs is significantly affected by the thermal coupling between the in-ground heat exchanger and the surrounding earth. If the surrounding earth is dry, the thermal coupling is relatively poor, thereby reducing the effectiveness of GHP systems. Development of heat exchanger installation and grouting methods to enhance thermal coupling in dry soils is, therefore, of significant importance.

The Photovoltaic Systems Science Laboratory (PSSL) is a new building at Sandia that is fitted with an 18-loop vertical field. The loop field was designed with six different completions consisting of IGSHA standard grout, two grades of thermally enhanced grouts developed by South Dakota State University, cuttings backfill, and grout with a bore liner designed to reduced water loss. The 250-ft bores at the PSSL are well above the water table and are thus appropriate for studying the short- and long-term suitability of grouts in dry soil.

In this project, Sandia will work with South Dakota State University to measure and compare the short- and long-term performance of the six loop installation and grouting methods. The most effective methods for dry soils will thereby be identified.

The benefits resulting from this project will include improvements in heat exchanger performance and reliability in dry soils. These improvements could conceivably yield reductions in total loop length of 20% through increased heat transfer and reduced contingencies.

Project Participants:

- Sandia National Laboratories: Lead PSSL data acquisition and analysis; document and publish results.
- South Dakota State University: Participate in PSSL data acquisition and analysis; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - GHP Tech.	FY97	\$215k	Sandia salary, travel; contract to SDSU for \$20k.
DOE Geothermal - GHP Tech	FY98	\$200k	Sandia salary, travel contract to SDSU for \$20k.

It is assumed that South Dakota State University will also be funded directly by the GHPC to partially cover its expenses on this project.

Status: This is an ongoing project. The PSSSL, its GHP system, and most of the loop field's instrumentation was installed in FY96. The test program has a broad set of objectives. Precision instruments permit measurement of heat transfer for each of the six loop completions. This allows a quantitative comparison of the loops' effectiveness. We expect that the relative loop performance will vary with time due to changes in the thermal state of the field with continued loading and physical changes in the backfill. The seasonal variations in overall loop temperature may be compared with the analytical models used by the GHP community to give insight into the accuracy of these tools. Finally, the overall energy use performance of the building will be measured to assess the energy efficiency of the heat pumps and other energy-saving measures that are part of the PSSSL.

Statement of Work: This project will be completed within the next two years, although longer-term monitoring may continue beyond that time if the results continue to be of significant interest. The focus of the work will be data acquisition, design and completion of special tests, and reporting of results. Special tests include imposing extended periods of high heating and cooling loads to test the response of the loop field.

Part of this effort will be jointly conducted with Prof. Chuck Remund of South Dakota State University. He has proposed locating one of his graduate students in Albuquerque to participate in the design, implementation, and interpretation of this test program.

Milestones: The following milestones have been adopted for this project:

- *Complete PSSSL loop instrumentation (10/96).*
- *Complete design of special PSSSL tests (3/97).*
- *Complete analysis of PSSSL performance data for first year of PSSSL performance (9/97).*
- *Complete all special PSSSL tests (7/98).*
- *Complete analysis of PSSSL performance data for second year of PSSSL performance (9/98).*
- *Complete Sandia Report on PSSSL performance measurement program, data analysis, and recommendations on dry-soil loop installation and grouting methods (9/98).*

Deliverables: This project will result in the following deliverables:

- *Short- and long-term performance data for six different GHP loop installation and grouting techniques in dry soils.*
- *Recommendations for efficient dry-soil GHP loop installation and grouting techniques.*

Grout Stability in Dry Soils

Program Area: Geothermal Heat Pump Technology

Project Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov;

Chuck Remund, South Dakota State University

Program Area Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: There have been questions raised by Sandia and South Dakota State University about the long-term stability of bentonite grout materials placed in dry soils. The issue is dehydration of the grout due to water migration to the dry formation. If this migration occurs, there will be substantial reduction of overall grout volume, possibly leading to the creation of major voids in the grout matrix and significant reduction in thermal coupling between the heat exchanger and the earth.

The PSSSL loop field is designed to measure the overall consequences for heat transfer from a variety of effects, including degradation from dehydration, but direct measurement and observation of the dehydration process is not possible because the loops are buried.

In this proposed project, we will work with South Dakota State University to design and perform a series of tests in Sandia's Engineered-Lithology Test Facility (ELTF). This facility, designed and built for the study of lost circulation problems in geothermal drilling, can be used to study test bores installed in an engineered "dry" formation. These bores may be backfilled with a variety of grouts and/or liners and mined back at a later date to determine the grout status. Loops may even be installed in the bores to apply heat to accelerate the dehydration process.

The benefits resulting from this project will include improvements in heat exchanger performance and reliability in dry soils. These improvements could conceivably yield reductions in total loop length of 20% through increased heat transfer and reduced contingencies.

Project Participants:

- Sandia National Laboratories: Cooperate with SDSU in designing and conducting grout stability tests; document and publish results.
- South Dakota State University: Cooperate with Sandia in designing and conducting grout stability tests; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal	FY97	\$55k	Sandia salary, travel; contract to SDSU for \$10k.
DOE Geothermal	FY98	\$100k	Sandia salary, travel; contract to SDSU for \$20k.

It is assumed that South Dakota State University will also be funded directly through the GHPC to partially cover its expenses on this project.

Status: This is a proposed new project that will be completed within two years. The project will use an existing Sandia facility, the ELTF, and SDSU expertise in grout testing to study grout stability in dry soils.

Statement of Work: In FY97, Sandia and SDSU will design and plan a grout stability test series. It is envisioned that such a test will require a minimum of six months to reasonably establish measurable, long-term trends. Because the ELTF will not be available for such an extended period until early FY98, testing for this project will actually be deferred until then.

Because of the long-term aspect of the test and the large scale of the ELTF, it will be important to simultaneously test a number of bores, and the parameters to be varied must be carefully selected. Instrumentation techniques will need to be devised to measure levels of dehydration and grout recession throughout the test period. Test chamber excavation procedures must be designed to maximize the visual evidence obtainable from the tests. A test plan will be written by the end of FY97 that contains these details.

Beginning early in FY98, the test plan will be implemented. The ELTF will be filled with selected materials, compacted as necessary, with instrumentation emplaced according to the test plan. Test bores will be drilled from the top of the emplaced material, in-hole instrumentation and heat transfer loops will be installed in the selected manners, then the selected grouts will be placed in the test bores. Operation of any heated loops will be conducted for approximately six months while monitoring emplaced instrumentation. As the conclusion of the test period, the earthen material will be carefully excavated from the facility to expose the downhole grout material, identify any cracking or void development, and measure shrinkage.

The results of the test will be evaluated, and recommendations will be made for optimal loop installation techniques and grouting materials for dry-soil installations. A final report and conference papers will be written to make the results widely available.

Milestones: The following milestones have been adopted for this project:

- *Complete selection of grouting materials/techniques to be tested in the ELTF (2/97).*
- *Complete design of grout stability tests in the ELTF (8/97).*
- *Complete grout stability test plan for the ELTF (9/97).*
- *Complete ELTF material and instrumentation emplacement for grout stability tests (12/97).*
- *Complete test bore, loop, borehole instrumentation, and grout installation in the ELTF for grout stability tests (1/98).*

- *Complete excavation of ELTF to conclude grout stability tests (8/98).*
- *Complete final Sandia Report on grout stability tests (9/98).*

Deliverables: This project will result in the following deliverables:

- *Final report and conference papers on the grout stability tests.*
- *Recommendations for efficient GHP loop installation and grouting techniques.*

Percussive Mud Hammer for GHP Drilling

Program Area: Geothermal Heat Pump Technology

Project Leader: Bill Sullivan, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3354, Fax 844-3952, wnsulli@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: Downhole pneumatic (air) hammers are currently used in the harder-rock applications of GHP drilling. Percussive drilling is an efficient method of breaking rocks with compressive strengths greater than 10,000 psi. There are significant disadvantages to the use of air hammers, however, including: the need for a heavy, noisy air compressor; the noise of the hammer itself; large quantities of rock dust generated when drilling above the water table; and reduced effectiveness and large quantities of water that can be produced when drilling below the water table.

Under this project, we will work with Novatek, Inc., to investigate the feasibility of developing a percussive mud hammer for GHP applications. The motivation for this project was two-fold: a percussive mud hammer was identified by members of the GHP drilling community as a tool they would very much like to have available; and we are currently funding Novatek to develop a percussive mud hammer for larger-diameter wellbores, 7-3/4 to 12-1/3 inches. The design approach used for the large-diameter tools will be employed by Novatek in this project to determine the feasibility of designing a tool for 3-6 inch diameter holes.

The benefits of this project could be significant. The use of a percussive mud hammer could eliminate the need for pneumatic hammers and air compressors in many applications. We do not currently have the information necessary to estimate the cost savings that would result. A cost model of the process is under development in the GHP loop insertion systems study. Predictions of that model will be determined when it becomes available to estimate the cost benefits of the percussive mud hammer project.

Project Participants:

- Sandia National Laboratories: Define design specifications for the percussive mud hammer; provide funding to Novatek; develop program plan for further development; document and publish results.
- Novatek, Inc.: Conduct design feasibility study of the percussive mud hammer concept for GHP drilling; help construct program plan for further development; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal	FY97	\$60k	Sandia salary, travel; contract with Novatek for \$45k.

Status: This is a proposed new project. It was enthusiastically supported by members of the GHP drilling community who attended the first annual Vertical Loop Installation Workshop at Sandia in January, 1996.

Novatek is currently developing large-diameter percussive mud hammers for geothermal drilling under a Geothermal Drilling Organization project. Novatek has developed a patented design with parallel mud streams such that only a portion of the drilling fluid passes through the valving mechanism. This makes it less subject to plugging and hence more reliable. Novatek's expertise and design tools will be used in this project to determine whether or not a small-diameter tool can be built according to their design principles.

Statement of Work: This work will be completed in early FY97. If the concept proves feasible, a project plan will be developed for FY98 and beyond to develop such a tool.

Sandia will develop design specifications for the percussive mud hammer based on discussions with members of the GHP drilling community. Novatek will then use these specifications to design a tool. The design procedures they have developed for their large-diameter tools will be employed to determine whether or not sufficient impact energy can be imparted to the rock in the small hole size required for GHP installations. If the concept passes that basic test, a conceptual design for the tool will be developed, and any design or fabrication issues will be identified. The feasibility of the small-diameter tool will be assessed, and if feasible, a plan will be developed jointly by Sandia and Novatek to begin development of the tool. This plan will be completed by the middle of FY97.

Milestones: The following milestones have been adopted for this project:

- *Place contract with Novatek for feasibility study of a percussive mud hammer for GHP applications (12/96).*
- *Complete development of specifications for the percussive mud hammer for GHP applications (12/96).*
- *Complete final Sandia Report assessing the feasibility of a percussive mud hammer for GHP applications (4/96).*
- *Complete project plan for developing a percussive mud hammer for GHP applications (5/96).*

Deliverables: This project will result in the following deliverables:

- *Feasibility assessment for a percussive mud hammer for GHP applications.*

X. Program Management, Development, and System Studies

a. Background

Program management, development, and system study projects are those that apply to the entire R&D program or pertain to a management function. While these projects do not directly develop any cost-reducing technology, they do provide a programmatic structure whereby technology development projects can be conceived and carried out in an efficient manner.

Program management pertains to the programmatic and administrative services provided to the technical members of the program. Program development is the formal forward-looking function of the program, whereby new projects and new industry partners are sought in a deliberate manner. System studies provide a solid technical and economic basis for initiating technology development projects.

b. Justification for Technology Development Effort

A diverse, comprehensive technology development program requires a significant program management, development, and system studies component. The advantages of an arrangement with these functions centralized and distinct from individual projects are: it provides for coordination of the program as a whole; it is more efficient; and it relieves the technical staff of the burden of administrative work, allowing them to concentrate on technical work.

c. Program Management, Development, and System Study Projects

Five projects are planned in this area. Three projects are ongoing, and the other two are proposed new projects. The projects are described in the following pages.

Geothermal Technology Program Management

Program Area: Program Management, Development, and System Studies

Project Leaders: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: This project includes program planning, program administration, interaction with DOE and industry, financial management, personnel management, and reporting. This is an essential project, needed to ensure coherence in the overall program.

This project involves and funds the program manager, the office administrative assistant, and the management assistant. The program manager is responsible for the overall program. The office administrative assistant provides administrative services such as travel arrangements, meeting arrangements, timekeeping, secretarial services, and publication services. The management assistant provides financial and contract management for the program.

This project also funds the department's computer network needs (hardware, software, and system management) and the cost of our field vehicles (logging trucks, boom trucks, instrumentation vans, and pickups).

Project Participants:

- Sandia National Laboratories: Manage the Geothermal Drilling R&D Program for DOE.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$670k	Sandia salary, travel, supplies.

Because of the nature of this work, we request funding for this project from the drilling technology area of the DOE Geothermal Program.

Status: This is an ongoing, continuous project that is required throughout the duration of the program.

Statement of Work: In FY97, the following activities will be conducted under this project:

- Provide program planning and administration.
- Track and maintain an updated list of milestones for all projects in the program; provide weekly program highlights to DOE together with a summary of milestone status.

- Track project costs and maintain program accounting; submit a monthly financial statement to DOE.
- Provide technical oversight on work performed under all projects in the program.
- Publish a quarterly newsletter on program activities and accomplishments for DOE and industry review.
- Publish an annual report of program activities and accomplishments.
- Convene a Program Review by the Industry Review Panel.
- Undertake program development activities such as discussions with operating companies and other geothermal companies on ways we can work together to reduce drilling costs.

Milestones: The following milestones have been adopted for this project:

- *Finalize and publish the FY97 Geothermal R&D Program Plan (10/96).*
- *Publish first Geothermal Drilling R&D Newsletter (12/96).*
- *Complete FY96 Annual Report and submit to DOE (12/96).*
- *Convene Industry Review Panel to review the Geothermal Drilling R&D Program (5/97).*

Deliverables: This project will result in the following deliverables:

- *Accountable, effective management of the Geothermal Drilling R&D Program at Sandia.*

Systems Analysis of Novel Wellbore-Lining Methods

Program Area: Program Management, Development, and System Studies

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: About half of the cost of a geothermal well is due to the cost of casing and lining the wellbore. The need to case the hole in a prescribed manner with conventional technology also dictates the size of hole that must be drilled at the surface, which has a large effect on the drilling costs. Alternative wellbore casing and lining techniques are needed if these costs are to be reduced. Techniques that could line the hole as it is drilled would be particularly attractive because they could solve or mitigate problems caused by lost circulation, stuck pipe, wellbore instability, and faulty cement jobs around conventional steel casing. Many wells would require fewer casing strings, and the casing would be of smaller diameter, accruing additional cost savings.

Under this project, Sandia National Laboratories and Livesay Consultants are working cooperatively to perform a system analysis of novel wellbore-lining techniques. This study is being funded by the National Advanced Drilling and Excavation Technology (NADET) Institute. The objective of the study is to identify one or more alternative wellbore-lining techniques that meet the functional requirements of a wellbore liner and reduce drilling, installation, and/or operating costs. The study will also define the work necessary to develop and test such techniques.

The primary benefit of this project is the possibility that it will lead to an alternative wellbore casing/lining technique. Without knowing which concepts may be identified and selected for development, it is not possible to accurately estimate the potential cost savings resulting from this project. It is not unreasonable to assume that a 20% overall cost savings in drilling and casing costs could result from the successful development of an alternative wellbore lining method for geothermal wells.

Project Participants:

- Sandia National Laboratories: Administer NADET funding to Livesay Consultants; work with Livesay to conduct the study; document and publish results.
- Livesay Consultants: Work with Sandia to conduct the study; document and publish results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
NADET Institute	FY97	\$150k	Sandia salary, travel; contract with Livesay for \$75k.

This project was selected by the NADET Institute as one of its seven funded projects in FY97. The funding for this project will thus not be counted in the FY97 total funding requested from DOE Geothermal.

Status: This is an ongoing project that has recently received funding from NADET.

Statement of Work: This project will be completed in FY97. If it is successful in identifying an alternative wellbore-lining technique that should be developed, a project plan will be drafted and appropriate funding sought.

There are eight principal tasks in this project:

1. *Review literature and patents, interview past/present researchers to define the state-of-the-art.* This effort will concentrate on identification of past and present researchers involved with wellbore-lining systems (WLS). As many as possible of these researchers will be contacted for information.
2. *Define situations or application in which the wellbore-lining system could be used.* There are many possible situations in which a WLS could be used. For the limited scope of this study, it will be necessary to select the relatively few cases that are most appropriate for application to geothermal drilling and completions.
3. *From the application scenarios, define functions that the wellbore lining system must perform.* Given that the application scenarios will probably involve lost circulation and well control, the specific functions that the WLS must perform will be defined. Some examples of possible design criteria are the following: the specific level of internal and/or external pressure that must be sustained; whether to line the wellbore while drilling or afterwards; whether to operate in drilling mud or air; and whether the lining must be permanent or can be temporary.
4. *Based on the functional requirements, define two or more conceptual systems.* It should be noted that a particular system may not perform all functions. Develop two or more conceptual systems, each of which can satisfy at least a significant portion of the functional requirements embodied in the design criteria.
5. *Develop functional and cost criteria for selection of a conceptual design.* Based on the conceptual designs, develop tradeoff criteria between increased performance and increased cost, considering both capital and operating costs.
6. *Identify critical system information.* A distinction will be made between currently available data and that which is needed for the conceptual design. As the conceptual designs emerge, it will become clear that specific items of design data are critical to completion of the designs. In some cases, those critical data items will not exist and will require limited laboratory testing. The need for testing or for extensive data search will be evaluated by sensitivity analysis.

7. *Develop conceptual layouts of the two most promising systems.* When the critical design data items have been acquired, generate concept-level layouts of the two most promising wellbore-lining systems.

8. *Document the study.* A final report will be written that includes drawings or diagrams of the most promising systems, rationale for the selection process, strengths and weaknesses of each system, estimates of development and operational cost for each system, and a project plan for continued development.

Milestones: The following milestones have been adopted for this project:

- *Complete review of literature, review of patents, and interviews with past/present researchers to define the state-of-the-art in wellbore lining (2/97).*
- *Complete definition of conceptual alternative wellbore lining systems (6/97).*
- *Complete definition of functional and cost criteria for selection of a conceptual design and identification of the critical system information needed for each conceptual design (6/97).*
- *Select two most promising alternative wellbore-lining systems for conceptual design (7/97).*
- *Complete final report for alternative wellbore-lining system study (9/97).*
- *Complete project plan for future development of an alternative wellbore-lining system (9/97).*

Deliverables: This project will result in the following deliverables:

- *A feasibility study of alternative wellbore-lining systems and a project plan for further development.*

Hydrothermal Drilling Cost Study

Program Area: Program Management, Development, and System Studies

Project Leaders: John Finger, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-8089, Fax 844-3952, jtfinge@sandia.gov

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Justification: A fully documented well and trouble cost model is a basic tool for performance evaluation of technology developments and for evaluating the reduction of ordinary drilling and trouble costs. The Carson-Lin-Livesay cost study (Carson *et al.*, 1983) was completed in 1981. Since then, there have been at least five further analyses of geothermal resource development that have used some form of the results of that study.

The time has come for an update and expansion of the previous study. In this proposed project, an adaptable, modular well costing code will be developed and used for sensitivity analysis, trade-off studies, case studies, and life-cycle analysis of selected geothermal projects. These analyses will use the code to develop information needed by DOE, the industry, and the geothermal research community in focusing on high pay-off research and development with the greatest potential impact on the industry.

The benefits that will result from this project will be two-fold: technologies or technical solutions that could have the greatest effects on the cost of geothermal energy will be identified and the effects quantified; and the industry will have a comprehensive, flexible tool for independently conducting drilling, completion, and well life-cycle cost studies.

Project Participants:

- Sandia National Laboratories: Administer DOE funding to Livesay and Ballew; work with consultants to conduct the study; document and publish results.
- Livesay Consultants: Work with Sandia to conduct the study; document and publish results.
- Ballew Tool Company: Conduct ROP-sensitivity study as input to the well-cost study; document results.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$280k	Sandia salary, travel; contract with Livesay for \$100k; contract with Ballew for \$30k
DOE Geothermal - Drilling Tech.	FY97	\$250k	Sandia salary, travel; contract with Livesay for \$100k.
DOE Geothermal - Drilling Tech.	FY97	\$250k	Sandia salary, travel; contract with Livesay for \$100k.

A portion of the FY97 funding, \$30k, is already in hand, allocated in FY96 by the reservoir technology area of DOE's Geothermal Research Program for the Ballew contract work. Consequently, a funding request of only \$250k for this project is included in the total FY97 funding requested from DOE Geothermal.

Status: This is a proposed new project. It was conceived and endorsed by a Geothermal Energy Association (GEA) industry panel in July, 1995.

There have been several well cost studies by Sandia and others in the past. The most significant effort was the work by Carson, Lin, and Livesay previously mentioned. Resource Technology, Inc., developed a spreadsheet costing template based on Lotus 123. Spreadsheet programs are also used by some of the geothermal operators. Maurer Engineering completed a cost study of deep gas drilling in order to help the Gas Research Institute determine what research should be done. That study was based on well records and did not develop a well cost code or model for subsequent use.

The IM-GEO study, the HDR power cost study, and the Advanced Drilling Systems Study (Pierce *et al*, 1996), all done by Sandia for DOE, used various versions of well cost modeling. Other costs were integrated with the well cost models for the specific needs of the analysis. All of these efforts will be valuable input as a starting point for a more useful cost model and the studies that it will enable us to do now. The detailed development notes from Sandia's past studies are in hand and should help shorten the effort to prepare timelines and to estimate the cost of goods and services in drilling.

The work to be done under this project will differ from the past studies in the type of model developed and its scope. The following section describes the model in some detail.

Statement of Work: This is a three-year project. It will build on the past work, which will also be used to assess the level of detail and characteristics needed in the new code. Prior models and spreadsheets have demonstrated a lack of adaptability and required a high level of experience with the data. The new code should be useful to others, and changes to the code should be as simple as possible. The modular nature of the proposed code should satisfy these requirements.

There are regional considerations that will affect the modeling effort. The drilling environment for various geothermal regions will be considered and factored into the cost program. Differences in rock type, bit life, tool life, lost circulation severity, casing problems, cementing problems, and temperature-related problems and depth will be incorporated into the model.

It will also be necessary to estimate appropriate rental rates for newly developed equipment. As was done in the Advanced Drilling Systems Study, the capital cost for new equipment will be estimated and, using standard business logic, a break-even rental rate can be estimated. This will

allow us to put the cost of new equipment on a normalized basis with rental rates for the conventional equipment to be replaced.

The specific tasks to be completed under this project include:

1. *Development of a new well-cost code.* We propose developing an entirely new code in a modular fashion so that modifications can be easily made by the user. Each cost module would be accessed through a call routine or a separate spreadsheet as new or different information that reflects cost changes and technology changes is obtained. Most technology changes will require new modules that use performance algorithms appropriate to the technology. This adaptability is important for ease of use by others.
2. *Sensitivity studies.* The code will be exercised to perform sensitivity studies on the various components and processes used in drilling and completing a geothermal well. The most critical cost parameters will be identified.
3. *Trade-off analyses.* Trade-off analyses of site development, drilling options, and completion practices and materials will be performed to illustrate the use of the code as well as to illustrate the need for proper technical and financial choices in planning and developing a geothermal well field. An attempt will be made to quantify risk within the trade-off analyses.
4. *Trouble-cost analysis.* Trouble costs will first be determined by studying the frequency of occurrence through interviews and records as available, then by estimating the time and material costs required to correct the problems. Various degrees of severity will be included in the frequency and cost determination.
5. *General life-cycle cost analysis.* Life-cycle costs for well repairs and workovers will be defined in such a way that they can be used in determining the cost profile and life of a geothermal project. The cost of the well field will be determined over the entire life of the project. The life-cycle cost module will include analysis for cash flow and discounted cash flow information as it applies to reservoir testing, analysis and management. Guidelines will be established for making decisions regarding workovers and replacement wells.
6. *Case Studies.* Case studies will be performed to give the costing code credibility and to document project cost patterns. Of interest is how the trade-off studies might reduce well cost and workover expenses for the well throughout its life.

A penetration-rate sensitivity analysis will also be conducted at the beginning of the study by Ballew Tool Co. This analysis will use existing data bases supplied by geothermal operators to examine the sensitivity of drilling costs to the observed rock penetration rates. The effects of increased penetration rates in the specific wells studied will also be estimated. This analysis will be used for two purposes: 1) to provide an early assessment of the quantity and characteristics of drilling cost data available from the geothermal operators; and 2) to provide specific case-history data and analysis that can be compared with the predictions obtained with the cost code developed under this project.

Milestones: The following milestones have been adopted for this project:

- *Complete development of detailed task list for well-cost study (10/96).*
- *Complete design of well-cost code (1/97).*
- *Complete ROP-sensitivity study (6/97).*

- *Complete development of well-cost code (3/98).*
- *Complete sensitivity analysis for well-cost study (10/98).*
- *Complete trade-off studies for well-cost study (10/98).*
- *Complete life-cycle analysis for well-cost study (10/99).*
- *Complete case studies for well-cost study (10/99).*
- *Complete final Sandia Report on well-cost study (10/99).*

Deliverables: This project will result in the following deliverables:

- *A well-documented study of geothermal well drilling, completion, and life-cycle costs and their components.*
- *Identification of geothermal drilling research areas with the largest potential benefit in reducing costs.*
- *A well-cost code that can be used by DOE, the industry, and other researchers to evaluate well costs and the impacts of various technology or economic changes on those costs.*

Compact Rig Survey

Program Area: Program Management, Development, and System Studies

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Program Manager: Dave Glowka, Dept. 6111 Manager, Sandia National Laboratories, Mail Stop 1033, Albuquerque, NM 87185, (505) 844-3601, Fax 844-3952, daglowk@sandia.gov

Justification: As demonstrated in the slimhole drilling technology program, drilling costs can be significantly reduced by reducing the size of the drill rig necessary for drilling exploratory geothermal wells. The same would also be true of production wells. If the size of the rig used to drill large-diameter, production-sized wellbores could be reduced from the mammoth size of today's rigs, significant reductions in production well field costs would result. Smaller rigs reduce mobilization costs, site-preparation costs, and site disturbance, and they require fewer rig hands and less fuel, thereby further reducing costs.

In this project, Geothermal Management Co. is conducting a survey of drill rig manufacturers to determine the availability of compact rigs capable of drilling production-sized holes in geothermal environments. Existing rig designs that best fit the requirements will be examined, and any required changes will be identified. The cost of an ideal compact rig will be estimated, and recommendations will be made on further work required to make this technology widely available to the geothermal drilling industry.

This project could lead to a greater use of smaller rigs for geothermal development. The benefit of such a development would be two-fold: reduced well costs and reduced site impact of a proposed project. Data being acquired in this project are needed to accurately estimate the cost savings that could result, but experience with slimhole drilling, where a 40% cost reduction is typical, suggests that at least a 5% reduction in production-sized well costs might be expected with smaller rigs.

Project Participants:

- Sandia National Laboratories: Administer funding to Geothermal Management Company; document and publish results.
- Geothermal Management Company: Define geothermal well rig requirements; conduct compact rig survey; document and publish results.
- Rig Manufacturer(s) (to be determined): Provide rig specifications, drawings; participate in design discussions.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$30k	Sandia salary; contract with Geothermal Mgmt. for \$25k (\$20k remaining in FY97).

Because of the nature of this project, funding is requested from the drilling technology area of DOE's Geothermal Research Program.

Status: This is an ongoing project. It was conceived and endorsed by a Geothermal Energy Association (GEA) industry panel in July, 1995.

The study began in FY96 with a survey of available rigs from U.S. manufacturers. Optimal compact rig specifications were developed via interviews with geothermal industry drill rig users, and site visits to rig manufacturers were conducted by Geothermal Management Co. The size, cost, operating characteristics, and other important information were gathered on rigs that met the important specifications. The information will be documented and published as a Sandia Report.

The second phase of the study was initiated in July, 1996. Using the results of Phase 1, Geothermal Management Co. has defined multiple criteria for the desirable hardware and software components on an ideal compact rig. The remaining contract work will focus on further defining and estimating the cost of an ideal compact rig for geothermal drilling applications.

Statement of Work: This project will be completed in FY97. Using the defined hardware and software criteria, Geothermal Management Co. will prepare specifications for an ideal compact drill rig, including selection of components and rig layout. The specs will be submitted to one or more drill rig manufacturers, who will conduct preliminary cost estimates. These estimates will be used by Geothermal Management Co. to perform cost-benefit analyses associated with the use of the compact rig in various geothermal applications.

Milestones: The following milestones have been adopted for this project:

- *Complete definition of hardware and software components on an ideal compact rig for geothermal drilling (9/96).*
- *Complete compact rig cost estimates (3/97).*
- *Complete cost-benefit analyses for use of compact rig in geothermal drilling applications (4/97).*
- *Complete final report on study of compact rigs for geothermal drilling (5/97).*

Deliverables: This project will result in the following deliverables:

- *A conceptual design and cost estimate for an ideal compact rig for geothermal drilling applications.*
- *A cost-benefit analysis that demonstrates the cost savings resulting from the use of optimized compact drill rigs for geothermal drilling.*

Development of Joint DOE-NEDO Drilling Research Project

Program Area: Program Management, Development, and System Studies

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Justification: DOE/Sandia and the New Energy and Industrial Technology Development Organization (NEDO) in Japan are working on many of the same aspects of geothermal drilling technology. Nevertheless, the timing of the emphasis on different elements of the two R&D programs is not in phase. Some of the drilling problems addressed in past Sandia projects are now being initiated by NEDO. Similarly, it appears that some of the recent research efforts initiated by Sandia have been studied for years by NEDO. Both the U.S. and Japanese geothermal drilling programs are supported with limited funding. There are probably many areas of drilling research that would be adaptable to joint DOE and NEDO cost-shared efforts. It is apparent that there is a need for better communication between the two programs. Better cooperation and communication will make it possible to share ideas and financial resources to develop new technologies for geothermal drilling cost reduction in the U.S., Japan, and throughout the world.

Project Participants:

- Sandia National Laboratories: Hold discussions with NEDO and develop one or more joint projects; administer DOE funding to Geo Hills Associates.
- Geo Hills Associates: Act as liaison between Sandia and NEDO on initial discussions.
- New Energy and Industrial Technology Development Organization (NEDO): Hold discussions with Sandia and develop one or more joint projects.

Requested Funding: The following funding is required for this project:

<u>Funding Source</u>	<u>Year</u>	<u>Funding Level</u>	<u>Description</u>
DOE Geothermal - Drilling Tech.	FY97	\$165k	Sandia travel; contract with Geo Hills for \$120k.

Sandia salary for this project is already included under the program management project in this plan.

Status: This is a proposed new project. It is based on encouraging discussions between Geo Hills Associates and NEDO officials in June, 1996, in which NEDO expressed an interest in developing joint projects with DOE and Sandia.

Statement of Work: This project will be completed in FY97, although if it is successful, it will identify one or more joint projects that will be initiated in FY98.

The initial effort under this project will consist of an exchange of information between NEDO and Sandia. The Sandia program manager and a Geo Hills representative will confer with NEDO in a series of meetings at NEDO headquarters in Tokyo, Japan. The Sandia program manager will make a number of formal presentations on the Sandia program, and NEDO staff will make presentations and provide on-site examination of several of their ongoing geothermal drilling R&D projects.

Sandia will then host NEDO officials on a visit to Sandia, in which Sandia's ongoing projects and test facilities are shown in more detail. Discussions will be conducted on areas of mutual interest and the possibility of conducting a joint project. A draft list of possible joint projects will be developed for further consideration by both parties.

Further trips between Japan and Sandia will be made if necessary, but it is anticipated that a joint program plan can be drafted based on the site visits to that point. The draft will be reviewed by Sandia, DOE, and NEDO and finalized by the end of FY97.

As joint cost-shared geothermal drilling R&D projects are defined and initiated, there will be a need for ongoing travel and communications among the multiple participants in each of the projects. Additionally, the joint DOE-NEDO projects would be reviewed twice yearly, perhaps in specific sessions convened in association with the annual Geothermal Resources Council technical conference and the annual Stanford Geothermal Reservoir Engineering Workshop.

Milestones: The following milestones have been adopted for this project:

- *Complete initial site visit to NEDO to exchange drilling program R&D information (2/97).*
- *Complete site visit of NEDO officials to Sandia (4/97).*
- *Complete draft project plan for first DOE-NEDO joint project (7/97).*

Deliverables: This project will result in the following deliverables:

- *One or more joint project plans for DOE and NEDO cooperative research and development in geothermal drilling.*

XI. Requested Funding Summary

The FY97 requested funding for each project is compiled in Table 2 along with a listing of the budgeted cost components (Sandia salary, contracts, travel, hardware/miscellaneous). This table includes all the geothermal-related projects planned for the Geothermal Research Department in FY97, including ongoing and proposed new projects, projects for which funding is requested from DOE, and projects for which funding is already in hand.

Project funding requests are further delineated in Tables 2 and 3. Ongoing projects for which DOE Geothermal funding is requested are listed in Table 3. The DOE funding request is delineated into three categories: drilling technology, reservoir technology, and geothermal heat pump technology. Also shown in Table 3 are the costs for projects that have already received funding from other sources (DOE Office of Fossil Energy, the NADET Institute, and DoD).

New projects for which DOE funding is requested are listed in Table 4. The DOE funding request is again delineated according to drilling, reservoir, and GHP technologies. Also shown in Table 4 are the projects for which FY96 carry-over funding is available.

The funding requests from Tables 2-4 are summarized in Table 1 below. (Note that the totals may not match Tables 2-4 exactly because of round-off error.)

TABLE 1
PROJECT FUNDING REQUEST SUMMARY

<u>Total Funding...</u>	<u>Ongoing Projects</u>	<u>New Projects</u>
Requested from DOE Office of Geothermal Technologies, Drilling Technology	\$3,071k	\$2,294k
Requested from DOE Office of Geothermal Technologies, Reservoir Technology	\$253k	\$394k
Requested from DOE Office of Geothermal Technologies, Geothermal Heat Pump Technology	\$292k	\$116k
In-hand from other sources (DOE Fossil, NADET, DoD)	\$542k	\$0k
In-hand from FY96 carry-over	<u>\$346k</u>	<u>\$0k</u>
Totals	\$4,504k	\$2,804k

It should be noted that this program plan is structured assuming that all the requested funding for ongoing and proposed new projects is received; thus the Sandia staff time has been distributed across all the projects. This was necessary in order to ensure that we can perform the described work if it is all funded. On the other hand, it is recognized that full funding as requested is not likely, given the probable overall geothermal budget for DOE. When the final FY97 funding level for Sandia's program is established, the projects that will be conducted will then be selected, and the Sandia staff time will be distributed over those projects. This approach is necessary to ensure that all the staff time is fully funded and utilized.

Table 2-Budgeted Project Costs

Project	Sandia Salary	Contracts	Travel	Hardware/Misc.	Total FY97 Project Costs
Lost Circulation Projects					
Rolling Float Meter for Outflow Rate Measurement	120	0	15	20	155
Doppler Flow Meter for Inflow Rate Measurement	51	0	15	15	81
Expert System for Lost Circulation Control	27	27	1	1	56
Automated Mud Monitoring System	57	12	2	10	81
Drillable Straddle Packer	304	10	10	65	389
Field Evaluation of Cementitious LCM	36	53	10	5	104
Advanced Lost Circulation Materials	27	0	3	10	40
Encapsulated-Accelerator Cements	15	100	2	0	117
Hard-Rock Drill Bit Projects					
Claw Cutter Optimization	136	23	1	15	175
Track-Set Bit Optimization	182	50	1	5	238
TSP Bit Optimization	52	26	0	3	81
Microwave Brazing of TSP Cutters	12	0	1	7	20
Impregnated-Diamond Bit Optimization	0	25	0	0	25
Self-Induced PDC Bit Vibrations	20	40	0	6	66
Advanced Numerical Modeling of Drag Cutting	349	0	2	25	376
Mechanics of Percussive Rock Drilling	0	250	0	0	250
Mudjet-Augmented PDC Bit	30	117	3	0	150
Downhole Pump for Ultra-High-Pressure Drilling	0	300	0	0	300
Explosively Compacted Drag Cutters	2	30	0	0	32
High Temp. Instrumentation Projects					
Temperature/Pressure Memory Tool	57	10	5	20	92
Downhole Steam Sampler	93	0	5	5	103
Spectral Gamma Tool	85	5	3	65	158
Core-Tube Data Logger	133	5	15	20	173
Downhole Flow Tool	20	20	2	5	47
High-Temp. Silicon-On-Insulator Evaluation	104	0	2	15	121
High-Temperature Slimhole Televiewer	22	0	3	0	25
High Data-Rate Drilling Telemetry System	226	50	4	20	300
Acoustic Technology Projects					
Core-Tube Latching Detector	104	0	10	10	124
Alignment System for Line-Shaft Pumps	118	0	4	20	142
Wireless Telemetry for Production Monitoring	104	0	20	41	165
Slimhole Drilling Technology Projects					
Geothermal Slimhole Handbook	103	20	2	0	125
Analysis of Kirishima, Japan, Slimhole Data	5	248	0	0	253
Analysis of Okuaizu, Japan, Slimhole Data	0	75	0	0	75
Wellbore/Reservoir Modeling for Slimholes	126	85	2	10	223
Software Toolkit for Slimholes	0	50	0	0	50
Geothermal Slimholes for Village Power	38	70	10	0	118
Fort Bliss Exploratory Slimhole	41	0	17	0	57.5
Long Valley Exploratory Well	50	90	10	0	150

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Table 3-Ongoing Projects

Project	Total FY97 Cost	DOE-OGT/Drilling Funding Request(1)	DOE-OGT/Reservoir Funding Request(3)	DOE-OGT/GHP Funding Request(5)	Funding In-Hand Other Sources(7)
Lost Circulation Projects					
Rolling Float Meter for Outflow Measurement (1)	155	155			
Doppler Flow Meter for Inflow Measurement (1)	81	81			
Expert System for Lost Circulation Control (1)	56	56			
Automated Mud Monitoring System (1)	81	81			
Drillable Straddle Packer (1)	389	389			
Field Evaluation of Cementitious LCM (1)	104	104			
Advanced Lost Circulation Materials (2)	40				
Encapsulated-Accelerator Cements (2)	117				
Hard-Rock Drill Bit Projects					
Claw Cutter Optimization (1)	175	175			
Track-Set Bit Optimization (1)	238	238			
TSP Bit Optimization (1)	81	81			
Microwave Brazing of TSP Cutters (7)	20				20
Impregnated-Diamond Bit Optimization (1)	25	25			
Self-Induced PDC Bit Vibrations (8)	66				
Advanced Numerical Modeling of Drag Cutting (2)	376				
Mechanics of Percussive Rock Drilling (2)	250				
Mudjet-Augmented PDC Bit (7)	150				150
Downhole Pump for UHP Drilling (2)	300				
Explosively Compacted Drag Cutters (2)	32				
High Temp. Instrumentation Projects					
Temperature/Pressure Memory Tool (1)	92	92			
Downhole Steam Sampler (1)	103	103			
Spectral Gamma Tool (1)	158	158			
Core-Tube Data Logger (1)	173	173			
Downhole Flow Tool (4)	47				
High-Temp. Silicon-On-Insulator Evaluation (2)	121				
High-Temperature Slimhole Televiewer (4)	25				
High Data-Rate Drilling Telemetry System (2)	300				
Acoustic Technology Projects					
Core-Tube Latching Detector (1)	124	124			
Alignment System for Line-Shaft Pumps (1)	142	142			
Wireless Telemetry for Prod. Monitoring (7)	165				165
Slimhole Drilling Technology Projects					
Geothermal Slimhole Handbook (1)	125	125			
Analysis of Kirishima, Japan, Slimhole Data (3)	253		253		
Analysis of Okuaizu, Japan, Slimhole Data (4)	75				
Wellbore/Reservoir Modeling for Slimholes (4)	223				
Software Toolkit for Slimholes (4)	50				
Geothermal Slimholes for Village Power (2)	118				
Fort Bliss Exploratory Slimhole (7)	57.5				57.5
Long Valley Exploratory Well (8)	150				

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Table 3-Ongoing Projects

Geothermal Drilling Organization Projects					
Ongoing GDO Projects (1)	80	80			
Insulated Drill Pipe (2)	200				
Geothermal Heat Pump Projects					
GHP Loop Installation Systems Study (5)	108			28	
Low-Cost, Replaceable-Cutter PDC Bit (5)	29			9	
Annual Vertical Loop Installation Workshop (5)	41			41	
PSSL Loop Field Testing and Analysis (5)	214			214	
Grout Stability in Dry Soils (6)	54				
Percussive Mud Hammer for GHP Drilling (6)	62				
Program Mgmt., Dev., and Systems Studies					
Geothermal Technology Program Management (1)	669	669			
Systems Analysis of Wellbore-Lining Methods (7)	150				150
Hydrothermal Drilling Cost Study (2,8)	281				
Compact Rig Study (1)	20	20			
Development of Joint DOE-NEDO Project (2)	165				
TOTALS	7309	3071	253	292	542
Notes:					
1 = Ongoing project; funding requested from DOE/OGT-Drilling Technology					
2 = New project; funding requested from DOE/OGT-Drilling Technology					
3 = Ongoing project; funding requested from DOE/OGT-Reservoir Technology					
4 = New project; funding requested from DOE/OGT-Reservoir Technology					
5 = Ongoing project; funding requested from DOE/OGT-GHP Tech. & GHPC					
6 = New project; funding requested from DOE/OGT-GHP Tech. & GHPC					
7 = Ongoing project; funding in hand from other sources					
8 = Ongoing project; funding in hand from FY96 carry-over					

Table 4-Proposed New Projects

Project	Total FY97 Cost	DOE-OGT/Drilling Funding Request(2)	DOE-OGT/Reservoir Funding Request(4)	DOE-OGT/GHP Funding Request(6)	Funding in-Hand FY96 C.O. (8)
Lost Circulation Projects					
Rolling Float Meter for Outflow Measurement (1)	155				
Doppler Flow Meter for Inflow Measurement (1)	81				
Expert System for Lost Circulation Control (1)	56				
Automated Mud Monitoring System (1)	81				
Drillable Straddle Packer (1)	389				
Field Evaluation of Cementitious LCM (1)	104				
Advanced Lost Circulation Materials (2)	40	40			
Encapsulated-Accelerator Cements (2)	117	117			
Hard-Rock Drill Bit Projects					
Claw Cutter Optimization (1)	175				
Track-Set Bit Optimization (1)	238				
TSP Bit Optimization (1)	81				
Microwave Brazing of TSP Cutters (7)	20				
Impregnated-Diamond Bit Optimization (1)	25				
Self-Induced PDC Bit Vibrations (8)	66				66
Advanced Numerical Modeling of Drag Cutting (2)	376	376			
Mechanics of Percussive Rock Drilling (2)	250	250			
Mudjet-Augmented PDC Bit (7)	150				
Downhole Pump for UHP Drilling (2)	300	300			
Explosively Compacted Drag Cutters (2)	32	32			
High Temp. Instrumentation Projects					
Temperature/Pressure Memory Tool (1)	92				
Downhole Steam Sampler (1)	103				
Spectral Gamma Tool (1)	158				
Core-Tube Data Logger (1)	173				
Downhole Flow Tool (4)	47		47		
High-Temp. Silicon-On-Insulator Evaluation (2)	121	121			
High-Temperature Slimhole Televiewer (4)	25	25			
High Data-Rate Drilling Telemetry System (2)	300	300			
Acoustic Technology Projects					
Core-Tube Latching Detector (1)	124				
Alignment System for Line-Shaft Pumps (1)	142				
Wireless Telemetry for Prod. Monitoring (7)	165				
Slimhole Drilling Technology Projects					
Geothermal Slimhole Handbook (1)	125				
Analysis of Kirishima, Japan, Slimhole Data (3)	253				
Analysis of Okuaizu, Japan, Slimhole Data (4)	75		75		
Wellbore/Reservoir Modeling for Slimholes (4)	223		223		
Software Toolkit for Slimholes (4)	50		50		
Geothermal Slimholes for Village Power (2)	118	118			
Fort Bliss Exploratory Slimhole (7)	57.5				
Long Valley Exploratory Well (8)	150				150

Table 4-Proposed New Projects

Geothermal Drilling Organization Projects					
Ongoing GDO Projects (1)	80				
Insulated Drill Pipe (2)	200	200			
Geothermal Heat Pump Projects					
GHP Loop Installation Systems Study (5)	108				80
Low-Cost, Replaceable-Cutter PDC Bit (5)	29				20
Annual Vertical Loop Installation Workshop (5)	41				
PSSL Loop Field Testing and Analysis (5)	214				
Grout Stability in Dry Soils (6)	54			54	
Percussive Mud Hammer for GHP Drilling (6)	62			62	
Program Mgmt., Dev., and Systems Studies					
Geothermal Technology Program Management (1)	669				
Systems Analysis of Wellbore-Lining Methods (7)	150				
Hydrothermal Drilling Cost Study (2,8)	281	246			30
Compact Rig Study (1)	20				
Development of Joint DOE-NEDO Project (2)	165	165			
TOTALS	7309	2289	394	116	346
Notes:					
1 = Ongoing project; funding requested from DOE/OGT-Drilling Technology					
2 = New project; funding requested from DOE/OGT-Drilling Technology					
3 = Ongoing project; funding requested from DOE/OGT-Reservoir Technology					
4 = New project; funding requested from DOE/OGT-Reservoir Technology					
5 = Ongoing project; funding requested from DOE/OGT-GHP Tech. & GHPC					
6 = New project; funding requested from DOE/OGT-GHP Tech. & GHPC					
7 = Ongoing project; funding in hand from other sources					
8 = Ongoing project; funding in hand from FY96 carry-over					

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