SAND81-0380
Unlimited Release
UC-66c

MASTER

Geothermal Drilling and Completion Technology Development Program Plan

Samuel G. Varnado, James R. Kelsey, Donald L. Wesenberg

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed February 1981

Sandia National Laboratories

SF 2900-Q(3-80)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $5.00; Microfiche $3.00

SAND81-0380 Category UC-66c
Unlimited Release
Printed February 1981

Geothermal Drilling and Completion Technology Development Program Plan

Samuel G. Varnado
James R. Kelsey
Donald L. Wesenberg
Authors
Drilling Technology Division 4741
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

This document presents a long-range plan for the development of new technology that will reduce the cost of drilling and completing geothermal wells. The role of this program in relation to the total Federal Geothermal Energy Program is defined and specific program goals are identified. Then, the current status of the program, initiated in FY 1978, is presented, and research and development activities planned through 1987 are described. Budget and milestone estimates for each task are provided. The management plan for implementing the program is also discussed. The goals of this program are to develop the technology required to reduce the cost of drilling and completing geothermal wells by 25% in the near term and by 50% in the long term. Efforts under this program to date have resulted in new roller bit designs that will reduce well costs by 2% to 4%, new drag bits that have demonstrated marked increases in penetration rate, and the field verification of the effectiveness of inert drilling fluids in reducing drill pipe corrosion. Activities planned for the next six years for achieving the program goals are described. Technical activities include work in the areas of drilling hardware, drilling fluids, lost circulation control methods, completion technology, advanced drilling systems, and supporting technology.

CONTENTS

ILLUSTRATIONS

TABLES

GEOTHERMAL DRILLING AND COMPLETION TECHNOLOGY DEVELOPMENT PROGRAM PLAN

I. The Geothermal Drilling and Completion Technology Development Program

A. The Role of Drilling and Completion Technology in the Federal Geothermal Energy Program

The objective of the Federal Geothermal Energy Program is to stimulate the development of geothermal resources as reliable, operationally safe, and environmentally acceptable energy sources for the production of electricity and/or direct heat applications. To achieve this objective, the federal government is implementing research, development, and demonstration initiatives and administrative and policy initiatives. The U.S. Department of Energy has been designated the lead agency for coordinating the Federal Geothermal Energy Program.

The Inter-Agency Geothermal Coordinating Council estimates that the achievable commercial utilization of geothermal resources in the United States is 3,000 MW_e by 1985 and 25,000 MW_e by the year 2000 from hydrothermal resources alone.[1] To meet these goals, approximately 15,000 new geothermal wells will be required by the year 2000. The high cost of drilling and completing these wells (traditionally 2 to 4 times that of oil and gas wells of comparable depth) is an impediment to the timely development of geothermal energy. It has been estimated[2] that 30 to 70 percent of the cost of producing electricity from geothermal resources is associated with drilling and completing the wells, and unless the cost of the wells is reduced, it is unlikely that the estimated power-on-line will ever be achieved.

The high cost of geothermal wells is attributable, in part, to deficiencies in drilling and completion technology that arise from the formation effects, temperature effects, and erosion and corrosion effects encountered in drilling geothermal wells. Geothermal formations are typically hard and highly fractured. This results in low rates of penetration, high rates of drilling fluid loss, and difficulties in obtaining competent completions. The high temperature of geothermal formations causes rapid degradation of conventional drill bits and precludes the use of conventional drilling fluids. Due to the high temperature and the chemical composition of the downhole fluids, corrosion of drill pipe and casing is also a severe and costly problem. To reduce the cost of drilling and completing geothermal wells, therefore, it will be necessary to develop new drilling and completion equipment capable of operating in this hostile environment. Since geothermal drilling activity is so much smaller than oil and gas activity, private industry has shown little interest in developing the required technology because of the smaller market potential. Federal participation is therefore justified in trying to lower some of the technical barriers.

The Geothermal Drilling and Completion Technology Development Program was established by the Division of Geothermal Energy with the goal of reducing the cost of geothermal wells. Since drilling and completion costs account for a substantial portion of the cost of generating electricity, reductions in the cost of geothermal wells will have a major impact on accelerating the development of geothermal energy.

B. Program Definition and Implementation

1. Program Objective -- The primary objective of the Geothermal Drilling and Completion Technology Development Program is to develop

the technology required to reduce the cost of geothermal wells. This objective must be accomplished to allow geothermal energy production at costs competitive with that of conventional energy sources. The Geysers is currently the only reservoir where costs are competitive. The following specific goals have been established to support this primary objective:

(a) To develop the technology necessary to achieve a 25-percent reduction in well cost in the near term through improvements in conventional drilling and completion techniques and equipment, and

(b) To develop the technology necessary to achieve a 50-percent reduction in well cost in the long term through advanced and innovative drilling and completion methods.

Cost sensitivity analyses[3] indicate that achievement of these goals will substantially increase the probability of realizing the power-on-line estimates of the Inter-Agency Geothermal Coordinating Council.

2. Program Approach -- Areas are identified where technology development can lead to significant cost reduction; R&D contracts are then awarded on a competitive basis. Research activities at the DOE National Laboratories provide a technology base for monitoring contracts and directing the program. This approach consists of the following steps:

(a) A systems study to define the primary contributors to geothermal well costs and to identify those areas which are most amenable to cost reduction through improved technology.

(b) A systems analysis to quantify the sensitivity of well cost to technology improvement and an independent assessment of potential cost reduction by an industry-based, technology advisory panel.

(c) The implementation of well-deflued research, development, and testing activities necessary to provide the cost reduction benefit.

(d) A periodic review and critique of the program by an industrial panel.

(e) Commercialization of developed technology through industrial participation in research, development, and testing.

3. Definition of Program Elements -- In order to define areas for research and development that have high cost reduction potential, a geothermal well cost simulator has been developed. This computer model simulates the operations involved in drilling and completing geothermal wells and computes the cost associated with each operation. The model can then be used to assess the cost/benefit ratio of postulated new technology prior to initiating the development of the technology. A sample output from this model is shown in Figure 1. This plot illustrates a typical drilling and completion operation in The Geysers field. Few problems were encountered, and 45 percent of the total well cost of $1.2 million is attributable to the actual drilling operation. Using this information, the effect of improved technology on the overall well cost can be determined. As an example, the effect on the overall well cost of a new bit having increased penetration rate is shown in Figure 2. Here, the percentage reduction in well cost is plotted as a function of bit life. Two curves are shown. One assumes an increase in instantaneous penetration rate of a factor of 2; the other, of a factor of 3. If these increased rates can be achieved while maintaining bit life comparable to conventional bits, well cost reductions of between 7 and 17 percent are possible. This sample calculation indicates the procedure which is being used to define promising technology development areas and to assess the progress of the program toward meeting the stated programmatic goals.

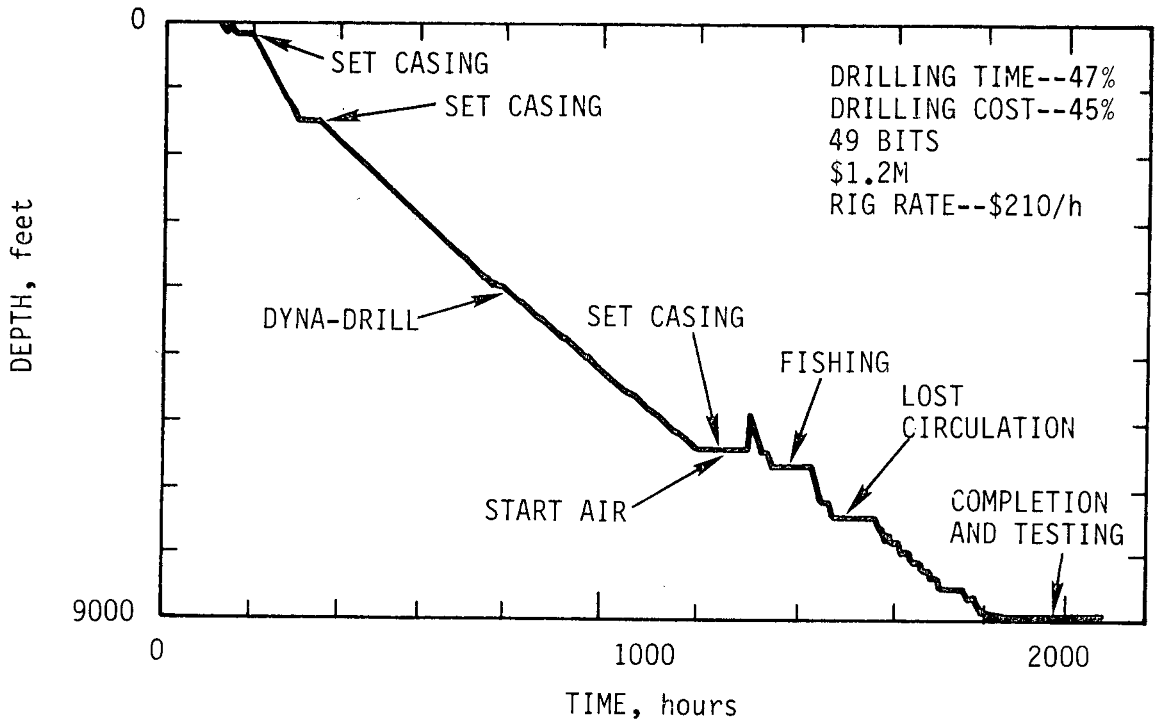

Figure 1. Depth versus Time Plot for a Geysers, CA, Well--1978

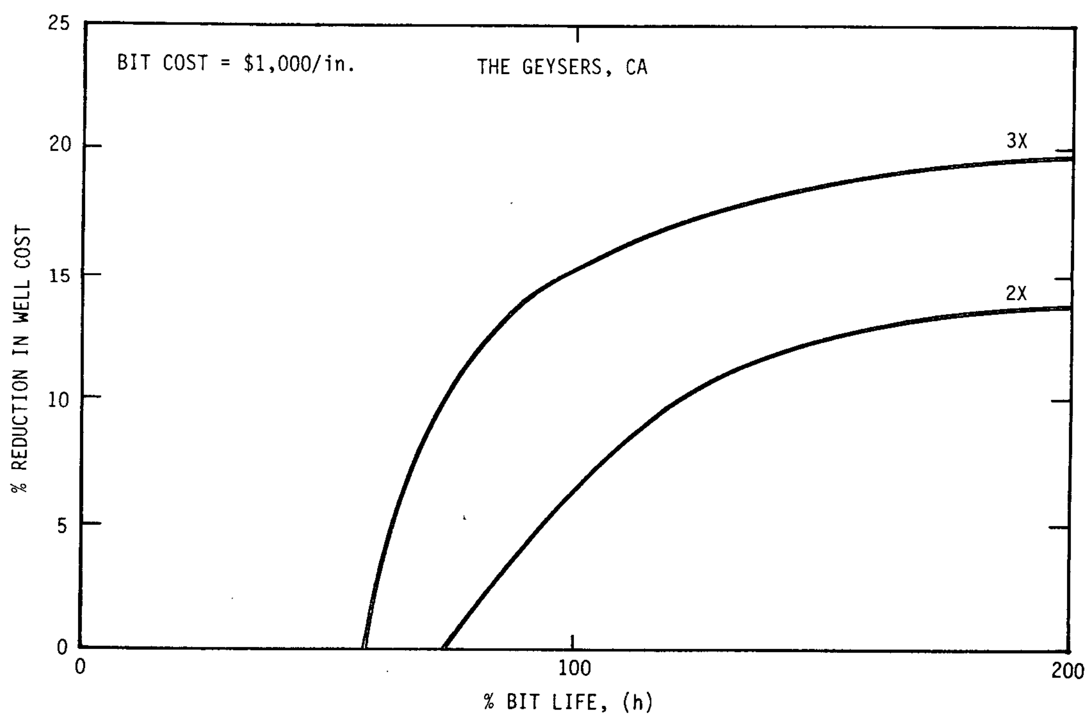

Figure 2. Effect of Increased Penetration Rate on Well Cost

A second example, shown in Figure 3, serves to illustrate the variety of problems which are encountered in geothermal drilling. This well, drilled in Utah, encountered severe problems, particularly with lost circulation. This resulted in a high well cost, and only 29 percent of the total cost of the well is attributable to the actual drilling operation. The results of an investigation of the effect of increased penetration rate in this well have shown that very little benefit is realized (1- to 2-percent reduction), but that improved methods of preventing lost circulation could significantly impact well cost.

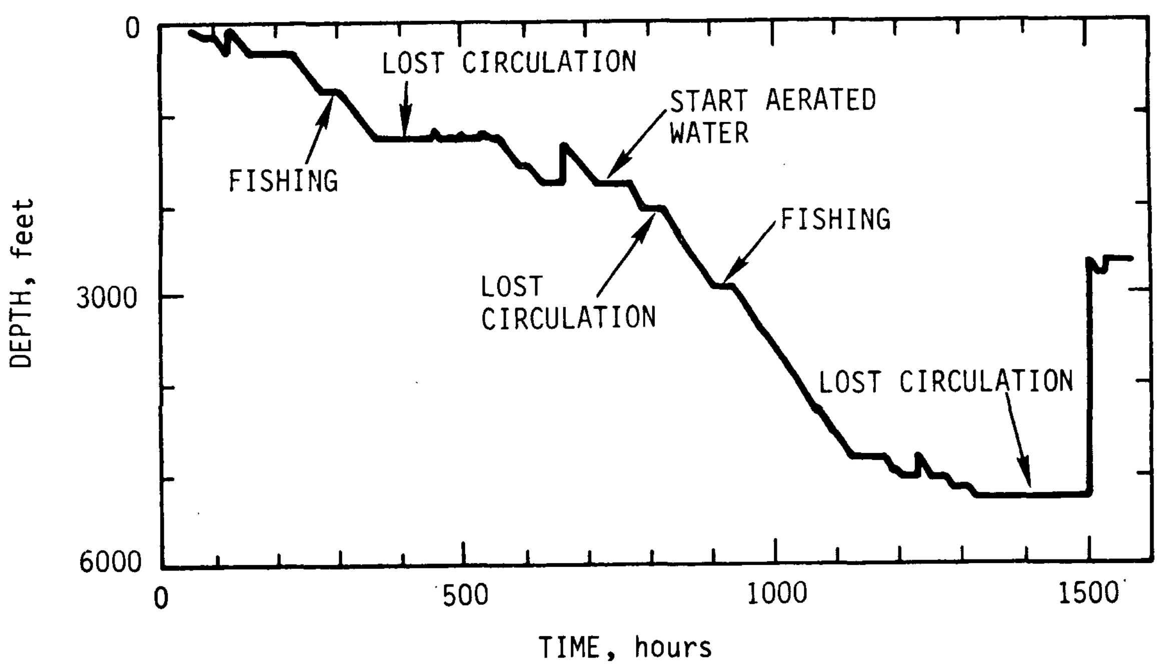

Figure 3. Depth versus Time Plot for a Cove Fort-Sulphurdale, UT, Well--1978

These two examples indicate the varying aspects of improved well technology that will impact well cost. Based on analyses of this type, technical areas requiring research and development have been identified as follows:

- Drilling Hardware
- Drilling Fluids

- Completion Technology
- Lost Circulation Control Methods
- Advanced Drilling Systems
- Supporting Technology

This program plan presents a detailed description of the work to be conducted under each of these major headings. The first four elements are directed primarily at improving conventional rotary drilling technology. The advanced drilling system development is directed at the long-term, 50-percent cost reduction goal. Cost analyses indicate that it will be necessary to achieve the 25-percent cost reduction goal through improved bits, fluids, completion techniques, and lost circulation methods before the 50-percent cost reduction goal can be realized. Therefore, the current emphasis in the program is directed at the near-term goal. This emphasis will change to the development of advanced systems as time progresses and the near-term goals are met.

(a) Drilling Hardware. Drilling bits and reamers with improved penetration rates and lifetimes are required to reduce well drilling costs. The DGE program includes research in improved bit materials, improved high-temperature bit seals and lubricants, wear mechanisms of polycrystalline diamond compact (PDC) cutters, and the effects of drilling fluids on the required cutting force, wear mechanisms, and wear rates of PDC cutters; the development of a prototype, downhole replaceable drill bit; the development of drag bits using PDC cutters; and joint industry-DOE field tests to verify the performance of the improved hardware and to assist in the transfer of this technology to industry. To date, an improved, unsealed roller cone bit has been developed that could lead to well cost reductions of 2% to 4% in air-drilled wells; new bit seals and lubricants capable of 100 hours of life under geothermal conditions have been developed and are commercially available; the downhole replaceable, continuous chain drill has been field tested; and two experimental PDC drag bits have been field tested indicating increased rates of penetration over conventional roller cone bits.

(b) Drilling Fluids. The corrosive conditions, high temperatures, and fractured formations typical of geothermal resource areas impose severe operating requirements on drilling fluids. Under geothermal conditions, the physical and chemical behavior of drilling fluids is not well understood; thus, basic investigations are required in order to formulate more cost-effective fluids. The approach to developing improved drilling fluids includes applied research into the morphology of clay particles, the development of foam drilling fluids, and the measurement of the rheological properties of drilling fluids at high temperature and pressure. Field evaluations of the corrosion reduction potential of inert gas drilling fluids (nitrogen), and the development and field testing of high-temperature drilling muds are also included. To date, a new high-temperature drilling mud has been formulated, successfully field tested, and is being used by industry. Several surfactants for generating foams that can be used in high-temperature applications have been identified; laboratory equipment for determining the viscoelastic properties of drilling muds under simulated downhole conditions has been developed; and a field test of nitrogen as a noncorrosive drilling fluid has been completed.

(c) Completion Technology. The completion of a geothermal well includes lining the borehole with casing and cement and providing for flow and control of the geothermal fluids. Because of the high thermal stresses induced in the casing when the well is placed on production, it is important to achieve proper cement placement and bonding to avoid casing collapse, buckling, and corrosion. In addition, problems of scale buildup and damage to producing formations from drilling fluids can reduce well productivity and result in increased energy cost.

Projects to extend well life and increase productivity are being conducted with the objectives of (1) establishing needs and defining requirements for downhole primary cementing tools, (2) identifying critical failure modes of a geothermal well completion, (3) designing and demonstrating a system using a controlled cavitation technique for downhole geothermal well cleaning and scale removal, and (4) investigating fluid/formation interactions to define damage mechanisms.

(d) Lost Circulation Control Methods. The loss of drilling fluid circulation during drilling results in insufficient cooling of the bit, inadequate removal of drilled solids, increased cost for fluids, the requirement for transportation of additional fluid additives to the drilling site, and costly time delays. Lost circulation problems, in general, are not well defined nor readily understood; consequently, procedures to control lost circulation problems are even more ill defined. The current program is to characterize and define in detail the operational and technical parameters of the problem by:

(1) Determining the geological characteristics of lost circulation zones,

(2) Collecting, collating, and analyzing industry experience, and

(3) Defining the causes, prevention techniques, and remedies of lost circulation in geothermal environments.

Subsequent activities will include formulation of R&D tasks to solve these problems.

(e) Advanced Drilling Systems. Advanced drilling systems (different than conventional rotary systems) will be required to meet the long-term well cost reduction goal of 50 percent. To meet this goal, penetration rate must be increased by a factor of 5 to 10 over that of conventional systems. In addition, the advanced system should have the capability to accurately drill high-angle, directional wells so that near-vertical fractures can be intersected. Achieving these objectives may require the development of new approaches to rock fracturing, new rig equipment, and improved techniques for surveying wellbores and steering the bit.

To guide the development of the required technology, an industry-wide workshop was held to review past efforts and to identify areas of needed emphasis.[4] As a result of this workshop, three candidate systems are currently under investigation -- high-speed downhole motors and bits, high-pressure water-jet drilling systems, and percussion drilling systems. Laboratory and field tests coupled with systems analyses will be used to select the most promising candidates for full-scale development.

(f) Supporting Technology. The proper design of improved and new drilling and completion systems requires an understanding of the unique requirements of the geothermal environment. The objective of the supporting technology element is to provide the information necessary to develop hardware required to meet program goals. Currently, projects are under way to expand capabilities to predict wellbore fluid temperatures during drilling, circulating, injection, and production in geothermal wells; to determine optimal number, size, and placement of nozzles used for bit cooling and cleaning purposes; to optimize the design of PDC geothermal bits by study of the stress buildup and chip formation processes of rock-cutting tools utilizing PDC cutters; and to study the metallurgical composition of conventional drill stem and make compositional changes in the drill stem material to maximize its chemical resistance to H_2S environments without large sacrifices in its mechanical properties or cost.

4. Procedure for Defining R&D Tasks -- As outlined previously, there are several areas in which technological improvement will yield reduced geothermal well cost. Analytical models are used to evaluate the relative merits of alternative proposals and designs. In addition, industrial participation in the identification of research tasks

is an important part of the program strategy. Inputs are solicited from the Geothermal Drilling and Completion Advisory Panel which is composed of representatives from drilling equipment manufacturers, drilling contractors, service companies, operating companies, and national laboratories. This panel was formed to provide guidance to Sandia and is convened semiannually to review the elements of the program, to suggest areas where further research is needed, and to advise on program priorities. This combination of technology-based, cost-sensitivity models and the input from the advisory panel provides the decision framework for allocating resources among the various program tasks. An attempt is made to analyze each research topic from the standpoint of cost/benefit ratio to insure that all funded tasks will contribute to programmatic goals.

5. Program Implementation -- DOE/DGE assigned the program management responsibilities for the Geothermal Drilling and Completion Technology Development Program to Sandia National Laboratories at the start of FY 1978. Implementation of the required research tasks is primarily through contracts with private industry and universities. However, supporting in-house research, as appropriate, is conducted by Sandia, with DOE/DGE approval.

Contracts are usually awarded on a competitive basis, and activities involving joint funding by government and industry are encouraged. Past experience indicates that any new technology developed can be quickly commercialized when one or more companies are intimately involved in the development. When a university is the contractor, Sandia National Laboratories provides the interface between the university and industry to assure that the results are made available to the industry in a timely manner. Contractual arrangements which allow private industry to participate in joint research programs while not compromising their competitive positions are, and will continue to be, sought. This strategy is designed to involve industry to the fullest extent in technology development so that commercialization is promoted early in the development process.

Industry acceptance of new technology requires proven reliability and economic benefit from the technology. It is necessary, therefore, to thoroughly demonstrate the technical and economic reliability of new concepts. Toward this end, laboratory and field testing programs are an integral part of the Drilling and Completion Technology Development Program. New concepts are usually tested first under laboratory conditions; industrial involvement in following field tests is then encouraged. Operating companies, drilling contractors, equipment manufacturers, and service companies are invited to observe, participate, evaluate, and comment on these tests. In addition, test results and major program developments are made available through publication in the open literature and presentation at technical meetings.

6. Summary of Technical Accomplishments -- This list presents a brief summary of past technical accomplishments in the program. Additional descriptions of the current program status are given in Appendix A of this report and References 5 through 10.

(a) Drilling Hardware

- Developed, tested, and commercialized an improved unsealed geothermal roller cone bit that yields projected well cost reductions of 2 to 4 percent.

- Identified a new high-temperature lubricant for sealed bits -- now available commercially as Geobond.

- Fabricated and tested a new bit seal/lubricant combination that ran for 100 hours at 150°C (302°F) in laboratory testing.

- Designed, fabricated, and tested a new polycrystalline diamond compact drag bit that demonstrated a 400-percent increase in penetration rate in actual field testing.

- Developed and conducted three field tests of the continuous chain bit.

(b) Drilling Fluids

- Completed design and fabrication of a high-temperature, high-pressure mud test loop.
- Identified six high-temperature surfactants for use in formulating foam drilling fluids.
- Completed laboratory testing and evaluation of a diesel exhaust conversion scheme for generating inert drilling fluids.

(c) Completion Technology

- Identified geothermal well casing failure modes.
- Demonstrated a cavitating-jet scale removal system.

(d) Advanced Drilling Systems

- Identified three candidates for development.
- Designed, fabricated, and tested new seal designs for downhole motors that survived 45 hours at 125°C (257°F).
- Established that cavitating jets could be utilized with drilling muds and under wellbore pressure.
- Established high-temperature failure modes of existing percussion hammers.

(e) Supporting Technology

- Developed and commercialized a computer model for predicting the temperature of wellbore fluids.

- Completed development of a well cost sensitivity model.

- Constructed a facility for drill bit hydraulics studies.

- Developed the capability for modeling the drag cutter/rock interaction.

7. Milestone Schedule and Budget -- The program emphasis in the period FY 1981 through FY 1983 will be on the near-term cost reduction goal of 25 percent. Beginning in FY 1984 increased emphasis will be placed on the development of advanced drilling systems that will provide an additional 25-percent cost reduction. The combination of improved conventional technology and advanced systems will be required to achieve the 50-percent cost reduction goal. The program milestone schedule is depicted in Figure 4.

The budget required to meet the stated program goals is shown in Table 1. Funding levels lower than those required will preclude the achievement of the stated program goals, and schedule slippages will occur.

Most of the activities in Program Elements 1, 2, 3, and 4, Table 1, will be completed by the end of FY 1983; however, some funding for these elements will be needed in FY 1984 to complete testing, reporting, and commercialization activities.

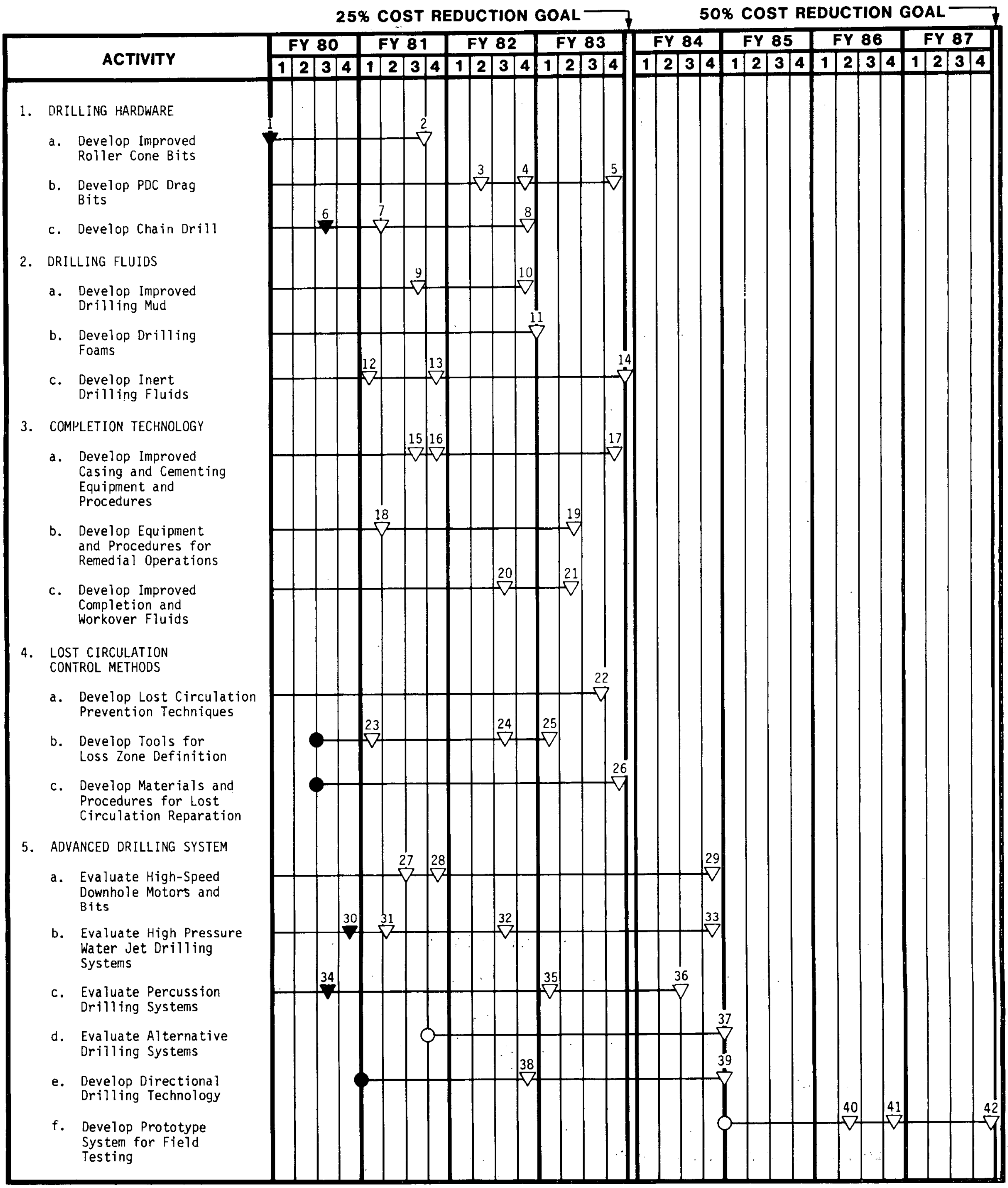

Figure 4. Geothermal Drilling and Completion Technology Development Program Milestones

Figure 4 (Continued)

Geothermal Drilling and Completion Technology
Development Program Milestone Descriptions

No.	Description
1.	Complete development of unsealed geothermal bit.
2.	Complete development of sealed geothermal bit.
3.	Complete definition of wear mechanisms for PDC bits.
4.	Complete development of computer optimization methods for PDC cutter placement on bit.
5.	Complete development and field testing of optimized PDC bit design.
6.	Complete field test of second prototype of continuous chain drill.
7.	Initiate commercialization activities for chain drill.
8.	Complete field testing of all-PDC chain bit.
9.	Complete mud test loop - University of Oklahoma. Complete high temperature test facility - NL Baroid.
10.	Formulate and field test stable, noncorrosive, high-temperature drilling muds.
11.	Complete formulation and field test of stable, noncorrosive foam.
12.	Field test nitrogen as a drilling fluid.

Figure 4 (Continued)

Geothermal Drilling and Completion Technology
Development Program Milestone Descriptions

No.	Description
13.	Complete cost/benefit assessment of nitrogen as an inert drilling fluid.
14.	Complete development of a full-scale, portable nitrogen unit.
15.	Complete casing stress analysis.
16.	Complete fabrication of cement test facility.
17.	Complete development of criteria and techniques for reliable geothermal completions.
18.	Complete field testing of cavitating jet descaling system.
19.	Complete development of remedial equipment.
20.	Complete investigation of damage effects in fractured formations.
21.	Complete development of improved fluids.
22.	Complete fabrication and testing of prevention techniques.
23.	Identify tools for defining loss zones.
24.	Complete fabrication of prototype tools for mapping loss zones.
25.	Field test tool for mapping loss zones.
26.	Complete field test of placement tool and new materials.

Figure 4 (Continued)

Geothermal Drilling and Completion Technology
Development Program Milestone Descriptions

No.	Description
27.	Complete laboratory testing of first prototype high-speed bit design.
28.	Complete development of bearing/seal package with 200-hour lifetime at 125°C (257°F).
29.	Complete field test of the final high-speed bit design.
30.	Complete data compilation of high-pressure, erosion drilling systems.
31.	Complete optimization of standard Cavijet™ nozzle.
32.	Complete optimization of advanced Cavijet™ nozzle.
33.	Complete field testing of the Cavijet™ and pulsating nozzles and decide on future development.
34.	Complete air hammer high-temperature failure mode identification.
35.	Complete field tests of first prototype air hammers.
36.	Complete field tests of mud hammers.
37.	Complete evaluation of alternative drilling systems.
38.	Complete field test of first prototype of borehole navigator.
39.	Complete high-temperature upgrade for borehole navigator.

Figure 4 (Continued)

Geothermal Drilling and Completion Technology
Development Program Milestone Descriptions

No.	Description
40.	Complete fabrication of prototype advanced system components.
41.	Complete first field test of first prototype system.
42.	Complete second field test of the first prototype system.

Table 1

Budget Requirements in Thousands of Dollars

	PROGRAM ELEMENTS	FY 81	FY 82	FY 83	FY 84	FY 85	FY 86	FY 87
1.	Drilling Hardware	905	830	700	1100	800	0	0
2.	Drilling Fluids	1000	1100	1300	500	0	0	0
3.	Completion Technology	1455	1700	1900	600	0	0	0
4.	Lost Circulation Control Methods	590	1200	1400	500	0	0	0
5.	Advanced Drilling Systems	2000	2010	2340	4420	6275	6500	5410
6.	Supporting Technology	1200	1400	1550	1500	1425	1300	1090
7.	Program Management	600	650	750	740	700	650	600
8.	Program Support	500	610	660	640	600	550	400
	TOTAL :	8250	9500	10600	10000	9800	9000	7500

Of the three candidate advanced systems currently being investigated, it is anticipated that one or two will be selected for full-scale development. FY 1984 will be the pivotal decision year and funding in the advanced systems area will be needed in FY 1984 to perform thorough evaluations of the competing technologies. In FY 1985 through FY 1987, the selected system or systems will be developed, fabricated, and tested.

8. Relationship to Other Programs -- The Geothermal Drilling and Completion Technology Program is chartered to provide new technology that will be applicable to a broad range of reservoirs. This requires an awareness of the drilling and completion problems arising in each resource area. This requirement is being met through the use of an industry-based advisory panel that includes members from major geothermal producers who provide guidance on industry needs. In addition, the DOE/DGE sponsored Hot Dry Rock (HDR) Program experiences unique drilling problems and close liaison is maintained between the HDR Program and the Drilling and Completion Technology Program. As a specific example, support from the Drilling and Completion Program has recently been provided to the HDR Program in the form of geothermal turbodrills and experimental bits.

The DOE/DGE Geochemical Engineering and Materials (GEM) Program is currently funding the development of high-temperature cements, elastomers, and bit materials. The Drilling and Completion Program works closely with the GEM Program in identifying needs for materials development and in providing testing for new materials that are developed. In particular, the Drilling and Completion Program provides a representative on the API task group that is helping guide the development of high-temperature cements. Joint programs between Brookhaven and Sandia National Laboratories on cement testing and evaluation are planned. New elastomers developed under the GEM Program have been tested in bit seals, downhole motor seals, and as packer elements by the Drilling and Completion Program.

A program directed at developing high-temperature instrumentation for geothermal well logging is being conducted by Sandia. Close liaison is maintained between the Drilling and Completion Program and the Logging Instrumentation Development Program to insure that needs and technology are interchanged. For example, directional survey tools and casing inspection tools are needed for geothermal drilling and completions. Joint development programs are anticipated in areas such as these.

The DOE/Office of Oil, Gas, and Shale Technology (OGST) conducts a Drilling and Offshore Technology Development Program that is developing technology to support the frontier areas in oil and gas drilling. These areas include deep land drilling for gas as well as deep water drilling on the continental shelf. Some of the problems are similar to those found in geothermal drilling. For example, temperatures in deep gas drilling are often comparable to those found in geothermal wells. Developments in high-temperature technology in the Geothermal Drilling and Completion Program can thus be directly applied to deep gas drilling.

In addition, unconventional resource recovery, such as methane from coal, will require the development of specialized drilling methods and equipment. Some work is currently being supported by OGST in these areas. To maximize the effectiveness of drilling research efforts, these programs must be tightly coupled to prevent duplication of effort and to assure that the research sponsored in these programs is complementary.

The DOE/Office of Mining Research is supporting the development of improved cutting and drilling technology for mining applications. Developments in high-pressure jet drilling and PDC drag bits under the Geothermal Drilling and Completion Program are directly applicable to the mining application. Coordination between these two programs is necessary and is being carried out.

Finally, a program to assess the scientific feasibility of extracting energy from magma bodies is being conducted by Sandia National Laboratories under funding from the DOE/Office of Basic Energy Sciences. To realize energy recovery from this resource, it will be necessary to penetrate extremely hot formations. This will require the development of new, high-temperature drilling systems. The current Geothermal Drilling and Completion Program will provide the technology base for extending drilling system performance to the required temperatures.

Sandia National Laboratories participates in research and development activities in all the above mentioned programs. All of Sandia's activities are centered in the Geoenergy Technology Department II. This organizational structure provides a clearinghouse for drilling technology, insures that information is freely exchanged among programs, and minimizes the possibility of duplication of effort.

II. Technical Plan

A. Introduction

This section presents detailed descriptions of the technical tasks currently planned for the Geothermal Drilling and Completion Technology Development Program. Modifications to this plan may be dictated as time progresses, and yearly updating is planned.

B. Program Elements

1. Drilling Hardware

(a) Objective. Drilling in hard, fractured, hot formations that are typical of geothermal reservoirs results in low penetration rates, short bit lives, rapid loss of hole gage, and difficulties in directional drilling. These factors combine to increase well costs. The objective of the drilling hardware development projects is to develop, in conjunction with the drilling industry, improved downhole drilling equipment that will lead to higher penetration rates, longer bit lives, better control of hole gage, and improved directional drilling techniques.

(b) Technical Approach. The approach to achieving the objective of this program element is to focus effort on understanding the primary factors affecting drilling rate and bit life and to apply improved technology to these factors to increase performance. Efforts to improve directional drilling techniques will be conducted under the advanced drilling systems program element. The required activities include the design, fabrication, and testing of prototype hardware and any additional improvements necessary to commercialize the new technology. Based on cost sensitivity analyses, this task has been divided into five subtasks as follows:

(1) Identification and utilization of new materials in unsealed roller cone bits.

(2) Design, development, and testing of high-temperature seals and lubricants for sealed roller cone bits.

(3) Design, development, and testing of new bit designs utilizing polycrystalline diamond compact (PDC) cutters.

(4) Design, fabrication, and testing of a prototype downhole-replaceable chain bit.

(5) Design, fabrication, and testing of a reamer utilizing PDC cutters.

(c) Development Activity by Subtask. Four of the above subtasks are currently being pursued; one has been completed. Some will continue into future years. New subtasks will be initiated as existing activities are completed and commercialized and new needs are identified. The drilling hardware subtask milestone schedules are shown in Figure 5.

- Subtask 1 -- Design, Development, and Testing of Improved Unsealed Roller Cone Bits

  The objective of this subtask is to improve the lifetime and gage maintenance properties of unsealed roller cone bits that are typically used in air drilling. To accomplish this, materials with improved hardness and toughness at high temperature have been identified and bits using these materials in critical wear areas have been

COMPLETED AND NEAR TERM MILESTONES

DRILLING HARDWARE

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - UNSEALED ROLLER-CONE BITS												
Development and Field Test of New Geothermal Roller-Cone Bits Completed in FY79												
SUBTASK 2 - SEALED ROLLER-CONE BITS												
Development of New Bit Seals and Lubricants with Seal Life of Over 100 Hours at 150°C Completed		▼										
Development of High Temperature Bit Grease Completed		▼										
Fabrication and Test of Full-Scale Sealed Bits Complete								▽				
Technology Transfer Complete								▽				
SUBTASK 3 - PDC DRAG BITS												
Field Test of First Prototype Designs Completed	▼											
Field Test of Second Prototype Designs Completed				▼								
Modeling of Cutter Heat Buildup Due To Frictional Heat Input Complete								▽				
Single Cutter Laboratory Tests Complete									▽			
Definition of Wear Mechanisms, Investigation of the Effects of Drilling Fluids on Wear Rates, and the Development of Empirical Models Complete										▽		
Development of Computer Optimization Methods for Cutter Placement Complete												▽

Figure 5. Drilling Hardware Milestones

COMPLETED AND NEAR TERM MILESTONES

DRILLING HARDWARE (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 3 - PDC DRAG BITS (Continued)												
Development and Field Testing of Optimized Bit Design Complete by the End of FY83												
SUBTASK 4 - CONTINUOUS CHAIN BIT												
Field Tests of First Prototype Completed in FY79												
Field Tests of Second Prototype Completed				▼								
Commercialization Activities Initiated						▽						
Fabrication and Laboratory Testing of First Prototype of All-PDC Chain Links Complete								▽				
Field Testing of Full-Scale Bit using All-PDC Cutters Complete												▽
SUBTASK 5 - PDC REAMER												
Design, Fabrication, and Field Testing Complete								▽				

Figure 5 (Continued). Drilling Hardware Milestones

fabricated. Six of these experimental bits were tested in a geothermal well at The Geysers along with seven conventional bits. Lifetime and gage maintenance improvements were demonstrated, and the use of these bits in The Geysers is projected to result in a 2- to 4-percent reduction in well costs.[5] The research and development activities on this project have been completed and several bit manufacturers are evaluating this new technology for commercialization.

- Subtask 2 -- Design, Development, and Testing of Improved Sealed Roller Cone Bits

The objective of this subtask is to improve the lifetime of sealed roller cone bits by developing high-temperature seal designs, materials, and lubricants. A seal tester and a lubricant tester have been fabricated to simulate downhole conditions -- 300°C (572°F) and 20.7 MPa (3,000 psi). A new high-temperature grease called Geobond was developed by Pacer Industries in support of this program and is currently being evaluated. In addition, a new high-temperature elastomer, Utex HTCR, has been developed and is commercially available. Seals made using the new elastomer and the new grease have been tested for more than 100 hours at a temperature of 150°C (302°F) after soaking at 288°C (550°F) for two hours. Bits incorporating these new materials will be constructed for laboratory testing. Commercialization activities will be initiated following successful laboratory testing.

In addition to the work on elastomeric seals, activities directed at developing metal-to-metal face seals will be conducted in an attempt to extend seal life and/or allow operation at higher temperature. New seal designs will be formulated, fabricated, and tested using the existing seal test facility. Bits using the most promising face seal designs will be fabricated for field testing if the laboratory tests are encouraging.

- Subtask 3 -- Design, Development and Testing of Polycrystalline Diamond Compact (PDC) Drag Bits

The objective of this task is to develop and demonstrate the performance of a new type of drag bit that utilizes high-pressure sintered polycrystalline diamond compact (PDC) cutters. Several bit designs have been developed under this program. The most recent designs have demonstrated increases in penetration rates of from 50 to 400 percent over those obtained with conventional roller bits in drilling geothermal formations.[8] Additional development and testing is required to quantify and maximize bit lifetime and to optimize the bit design.

Activities required to achieve these results include: (1) laboratory testing of single cutters; (2) laboratory and field testing of full-scale bits; (3) definition of wear mechanisms and empirical models to predict wear rate; (4) calculations and measurements of temperatures generated in the cutters due to frictional heat input during drilling; (5) determination of the effects of different drilling fluids on wear rate; (6) development of models for cutter/rock interaction studies; and (7) development of computer optimization codes for locating the cutters on the bit body to maximize performance.

The Drill Bit Hydraulics Studies and the Rock/Cutter Interaction Studies being conducted under the Supporting Technology Program element directly support this task. Both these supporting tasks will assist in optimizing the bit design.

It is anticipated that several iterations on bit design and field testing will be required before the PDC bit technology is ready for commercialization for geothermal drilling.

- Subtask 4 -- Design, Development, and Testing of a Prototype Downhole Replaceable Drill Bit

The objective of this task is to demonstrate a prototype version of a bit in which the cutting surface can be changed while the bit is still in the hole.

Successful completion of this subtask will provide the drilling industry with a bit that can be replaced in a very short time, thereby reducing drilling costs by reducing the time required for tripping to replace worn bits. The current prototype design developed by Sandia National Laboratories utilizes both natural and PDC cutters mounted on the links of a continuous chain. The chain is stationary while drilling, but can be cycled from the surface to bring new cutters into the drilling position. As many as 15 replacement cutting structures can be carried in the current design.

Field tests of this bit have recently been conducted, and the ability to reliably cycle the bit downhole has been demonstrated. A meeting with industry representatives will be conducted to explain the design and to identify one or more industry partners who would be interested in a joint program to commercialize the product. Assistance to industry partners will be provided by Sandia.

In parallel with commercialization activities on the current design, new cutting surfaces will be investigated. In particular, a chain using only PDC cutters will be developed. Cutter positioning, hydraulics considerations, and the use of a casting to make the chain links will be studied. A successful PDC design would allow use of the chain drill concept in a wider range of formations and would significantly improve the penetration rate of the bit.

- Subtask 5 -- Design, Development, and Testing of Improved Reamers

  Loss of gage while drilling is a common problem in geothermal drilling because of the hard formations encountered. This adds to the cost of drilling because it becomes necessary to ream to return the bit to bottom when resuming drilling after a bit run. The objective of this subtask is to develop the technology required to minimize loss of gage in geothermal drilling.

  This subtask will design, develop, and test new reamers using PDC cutters. New designs have already been generated, but fabrication and testing of these designs remain to be accomplished. The new designs use conventional roller reamers augmented by PDC cutters. New reamers will be fabricated, tested, modified, and retested to develop a design suitable for commercialization.

2. Drilling Fluids

(a) Objective. The objective of this program element is to develop drilling fluids that have desirable rheological properties, are stable, and are noncorrosive at high temperature and in the presence of geothermal brines.

(b) Technical Approach. Because of the high temperature, fractured, underpressured nature of geothermal formations, conventional drilling fluids are in many cases not suitable for use in geothermal drilling. The lack of suitable fluids increases the direct costs associated with fluids, corrosion inhibitors, and surface equipment required in geothermal drilling; and the indirect costs associated with field related problems such as pipe sticking, corrosion-induced pipe failures, time lost due to lost circulation, slow drilling because of poor solids control, borehole instability, and formation damage.

Fluids used in geothermal drilling include water-based muds, water, air, and foam. Because of the obvious simplicity and lower cost, drilling is done with water or air whenever practical, but when high formation pressures are encountered, a weighted fluid is required for well control. In some cases of drilling in highly permeable or fractured formations, it is even difficult to use water because of high rates of fluid loss. Air drilling can be used, but it is limited by such factors as insufficient bit cooling, high corrosion rates, hole sloughing, reduced ability to lift cuttings to the surface in deep holes, lack of control of water influx, and erosion of the drill string from high-velocity particles.

Work previously sponsored by this program has shown that some of today's high-temperature muds degrade badly at geothermal temperatures. They often become corrosive due to chemical decomposition and can permanently damage the producing formation by excess fluid loss and filter cake buildup. Viscoelastic properties are altered by temperature, and increased gel strength leads to increased circulating pressures which can cause formation breakdown.

Drilling foams have high lifting capacity and, therefore, low annular velocities are required for cuttings removal. However, existing foams become unstable and/or corrosive at high temperature, are not easily broken down after use, and present difficulties in separating fine cuttings from the fluid. Foams can, however, fill the need for noncontaminating, nondamaging fluid and can also allow increases in rate of penetration. If formation pressure is not a problem, industry spokesmen have estimated that a significant fraction of geothermal wells would be foam drilled if a high temperature foam were available.

In order to address the problems cited above, it will be necessary to develop new drilling fluids for geothermal applications. Thus, this program element has been divided into the three following subtasks:

(1) Development of improved drilling muds for drilling in high-temperature formations where a weighted fluid is needed.

(2) Development of drilling foams for use in underpressured formations.

(3) Development of inert gas drilling fluids to reduce the corrosion rates in formations where gas drilling is desirable.

(c) Development Activity by Subtask. The drilling fluids subtask milestone schedules are shown in Figure 6.

- Subtask 1 -- Development of Improved Drilling Muds

  The objectives of this subtask are to develop a fundamental understanding of the high-temperature behavior of various clays used in drilling muds and to use this understanding to formulate a mud that will be usable in geothermal drilling. To meet these objectives, it is necessary to continue the development of laboratory instrumentation for measuring the viscoelastic properties of muds at high temperature and pressure; to study the high-temperature morphology of bentonite, attapulgite, sepiolite, and other clays; and to define candidate mud formulations for laboratory and field testing.

  Previous activities under this program have led to the construction of a mud flow test loop[5] at the University of Oklahoma capable of subjecting drilling muds to simulated downhole conditions of up to 288°C (550°F) and

COMPLETED AND NEAR TERM MILESTONES

DRILLING FLUIDS

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - DRILLING MUDS												
Development of Mud Flow Test Loop at the University of Oklahoma Completed		▼										
Development of High-Pressure Mud Test Facility at NL Baroid Complete						▽						
Studies of Temperature and Chemical Effects on Clay Morphology at Texas Tech University Complete								▽				
Formulation and Field Testing of Improved Geothermal Drilling Mud Complete											▽	
SUBTASK 2 - DRILLING FOAMS												
Identification of High-Temperature Surfactants Completed		▼										
Screening of Surfactants at Simulated Downhole Conditions Complete						▽						
Testing of Promising Foams in Borehole Simulator Complete								▽				
Formulation and Field Testing of Stable, Non-corrosive Foam Complete												▽
SUBTASK 3 - INERT DRILLING FLUIDS												
Field Test of Nitrogen as a Drilling Fluid Complete					▽							
Determination of Corrosion Rates and Potential Costs of Inert Drilling Fluids Complete							▽					

Figure 6. Drilling Fluids Milestones

COMPLETED AND NEAR TERM MILESTONES

DRILLING FLUIDS (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 3 - INERT DRILLING FLUIDS (CONTINUED)												
Laboratory Testing of Portable Nitrogen Generation System Complete						▽						
Cost/Benefit Assessment of Nitrogen as a Drilling Fluid Complete								▽				
Development of Full Scale Nitrogen Generation Unit Complete by the End of FY83												

Figure 6 (Continued). Drilling Fluids Milestones

20.6 MPa (3,000 psi). Viscoelastic properties and corrosivity can be measured while the mud is circulating in this loop. This loop will be made available for use by private industry following a few final tests. A new test facility that will extend the test conditions to 371°C (700°F) and 138 MPa (20,000 psi) is currently under construction at NL Baroid. Completion of this facility will provide the ability to determine rheological properties of fluids under all postulated downhole environments.

The formulation of an optimum geothermal mud requires an understanding of clay morphology as a function of temperature and chemical environment. To develop this understanding, several clays are currently being analyzed after exposure to temperature and various chemical environments. Both scanning transmission electron microscope (STEM) and X-ray diffraction techniques are being used to determine the morphological changes occurring in the clays. Temperatures to 350°C (662°F) are being used. A test matrix of clays, temperatures, exposure times, and chemical additives has been defined. Following these tests, recommendations will be made concerning the best mud formulation to be used in specific reservoir types. These formulations will be tested using the high-temperature/high-pressure instrumentation developed previously and their performance compared with that of muds currently used in geothermal drilling. Promising candidates will be field tested.

In parallel with the clay morphology study, additional laboratory and field tests on currently used geothermal drilling fluids will be conducted. For example, sepiolite is a clay that has shown good high-temperature characteristics when used with thinning agents. Laboratory tests on a mud formulation (HTM-1)[5] using this clay were encouraging, and a successful field test was recently conducted. Other formulations have been suggested for laboratory and field testing. Continuation of this activity is planned to provide comparative data for any new muds developed in this program.

- <u>Subtask 2 -- Development of Drilling Foams</u>

The development of a stable, noncorrosive drilling foam for high-temperature use will proceed with the identification of promising chemical systems by screening commercially available surfactants under high-temperature conditions, to 310°C (590°F). Measurements of foam drainage time, foam density, cell structure, and pH are being performed both before and after exposure to 260°C (500°F) temperatures for periods of two hours. Fifty-six surfactants have already been screened, and twelve (primarily sulfonates) have been identified for further testing at higher temperatures and pressures [310°C (590°F), 3.4 MPa (500 psi)]. In addition, comparisons between foams generated with deionized water and with simulated brines will be made to determine the effect on foam performance of wellbore fluids that might be expected to contact the foam under actual drilling conditions. Those surfactants passing this more severe screening procedure will be identified for testing in a simulated wellbore. This testing will involve the use of Sandia's Long Tube Heat Exchanger Facility and will include measurements of the heat transfer coefficients of the foams under flowing conditions. Tests conducted in this facility will provide the data needed to predict the performance of the foams under actual field conditions.

Those foams identified as suitable for field testing will be formulated and tested. This field testing will result in an identification of the costs and benefits associated with using foams in geothermal drilling.

Those surfactants identified in preliminary screening as being suitable for field testing will also be investigated as to the ease or difficulty of disposal. The disposal procedure will probably require a surfactant that can be broken down by chemical or mechanical treatment. Most of the surfactants considered to date are biodegradable, but continued attention to the problem of disposal is required.

- Subtask 3 -- Development of Inert Gas Drilling Fluids

The objectives of this subtask are to determine the cost/benefit of using nitrogen rather than air as a drilling fluid in geothermal drilling and to develop field portable nitrogen generation systems, if appropriate. The use of air for geothermal drilling has many advantages, but one major disadvantage exists, namely, increased drill pipe corrosion. This increase in corrosion is attributed primarily to the presence of oxygen in the air. Oxygen scavengers are usually effective in reducing the corrosion rate; however, they are expensive. Another approach is to use an inert gas, such as nitrogen, rather than air. This subtask will first determine the amount of drill pipe corrosion occurring with air as the drilling fluid, then with nitrogen as the drilling fluid. This determination will allow an assessment of the well cost reduction potential of drilling with nitrogen. Both systems analysis procedures and actual field tests will be used to perform this assessment. Field tests will be conducted as required and on wells of opportunity, but primary emphasis will be given initially to hydrothermal reservoirs, such as the Baca location in New Mexico.

It is unlikely that a cost savings can be realized if the nitrogen has to be trucked to the drilling location as a liquid. Therefore, techniques for generating nitrogen at the rig location will be investigated. A determination of the unit cost of generating nitrogen with each technique will be made. This cost can then be used in systems analysis procedures to determine the overall cost/benefit ratio.

Two techniques for generating nitrogen at the rig site have been identified. The first involves the conversion of diesel exhaust gas into a gas having low oxygen content by burning the exhaust with excess diesel fuel in the presence of a catalyst. The assessment of the feasibility of this technique involves laboratory studies using small diesel engines to determine the chemical composition of the product gas. These experiments will indicate what techniques are required to clean the gas before it can be passed through the compressor (e.g., it may be necessary to provide for sulfur removal). Once the downstream cleanup processes have been identified, an assessment of the cost of the nitrogen produced by this method will be made before a scale-up of the unit to field test proportions is attempted. If the cost/benefit calculations are encouraging, a full-size catalytic convertor will be constructed for field testing.

The second technique for nitrogen generation involves cryogenic separation of nitrogen from air by successive cooling. This technique is commonly used by manufacturers who supply liquid nitrogen; however, the distillation columns used are very large and generally not portable. Recently a supplier of a new, portable separator has been identified. A small unit has been constructed under private funding. This unit will be leased for field testing so that the cost of nitrogen produced by the unit can be determined. If the field tests are encouraging, a large unit capable of supplying sufficient quantities of nitrogen for drilling will be constructed and field tested.

3. Completion Technology

(a) Objective. The objective of the completion technology development program is to minimize the life cycle cost of the completion of both production and injection wells.

(b) Technical Approach. The approach to meeting the stated objective is to develop the technology that will extend the useful life of the completion, increase productivity and/or injectivity, increase the reliability of the completion, and decrease both workover frequency and costs. Meeting these objectives will reduce the number of new wells required to meet production and injection requirements. The initial cost of the improved completion may not be substantially reduced, but the increased reliability of the completion should substantially reduce the total life cycle cost of the well.

Poor cement placement is known to be the primary cause of most casing failures. Failure to completely displace all of the drilling fluid by the cement will lead to the formation of mud pockets in the cement which have essentially no bonding strength; hence, the casing will be unsupported in these sections. When a geothermal well is placed on production, casing expansion is resisted by the cement emplaced behind the casing. In those areas where the casing is unsupported, the resistance to longitudinal expansion may cause buckling to occur. The entrapped drilling fluid may also expand and tend to collapse the casing with external pressure. Water flows external to the casing may lead to extensive corrosion damage in these uncemented areas. Proper cement placement will alleviate all of the above failure modes; therefore, methods of improving the cement placement operation will be identified and developed.

The technology development activities are broken into four broad categories:

(1) Development of casing and cementing equipment and procedures.

(2) Development of equipment and procedures for remedial and production enhancement operations.

(3) Development of completion and workover fluids.

(4) Analysis of life cycle cost of geothermal well completion.

In the first three activities listed above, the general approach followed is to perform a limited state-of-the-art study in which needs are assessed. Next, requirements for new equipment or operating procedures are formulated. Subsequently, the new equipment or procedures will be developed, tested in the laboratory, and, finally, tested in the field.

The life cycle cost model will be used to define the areas where development effort will net the greatest return and to assess the magnitude of cost reductions resulting from improved completion techniques.

(c) Activities by Subtask. The completion technology subtask milestone schedules are shown in Figure 7.

- Subtask 1 -- Development of Casing and Cementing Equipment and Procedures

  The goal of this subtask is to develop improved casing and cementing tools as well as improved cementing procedures. To accomplish this, a laboratory cement testing facility will be established. This laboratory will allow circulation of mud and cement between casing and a simulated borehole under simulated downhole conditions. The facility will allow determination of the cement flow rates that will provide for optimal displacement of mud by cement, and will allow the measurement of the rheological properties of the cement under simulated downhole conditions. Based on the results of these tests, tools for properly placing cement may need to be developed.

COMPLETED AND NEAR TERM MILESTONES

COMPLETION TECHNOLOGY

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - CASING AND CEMENTING EQUIPMENT AND PROCEDURES												
Background Studies of Casing Failure Completed				▼								
Analysis of Casing Failures and Recommendations for Remedies Complete							▽					
Identification of Limitations of Primary Cementing Tools and Recommendations for Modification Completed				▼								
State-of-the-Art Study of Auxiliary Completion Equipment Complete								▽				
Design and Fabrication of Cement Test Facility Complete								▽				
Preliminary Laboratory Tests of Materials and Displacement Procedures Complete												▽
SUBTASK 2 - EQUIPMENT AND PROCEDURES FOR REMEDIAL AND ENHANCEMENT OPERATIONS												
Preliminary Study of Water-Jet Underreamer Completed				▼								
Screening of High-Temperature Explosives for Perforation Completed				▼								
Development of High-Temperature Perforator Complete								▽				
Design, Fabrication, and Field Test of Prototype Water-Jet Descaler Completed				▼								
Definition of Further Development Efforts for Remedial Equipment Complete								▽				
Development of Required Equipment Complete by the End of FY83												

Figure 7. Completion Technology Milestones

COMPLETED AND NEAR TERM MILESTONES

COMPLETION TECHNOLOGY (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 3 - COMPLETION AND WORKOVER FLUIDS												
Initial Fluid/Formation Laboratory Tests Completed				▼								
Investigation of Chemical and Particulate Damage Effects on Permeable Formations Complete							▽					
Investigation of Damage Effects on Fractured Formations Complete											▽	
Development of Improved Fluids Complete by the End of FY83												
SUBTASK 4 - LIFE CYCLE COST ANALYSIS												
Data Gathering for Completion Model Complete							▽					
Computer Code Operational								▽				

Figure 7 (Continued). Completion Technology Milestones

Certain sections of casing may never be adequately protected. Analytical techniques that will define the maximum unsupported pipe length that can be tolerated will be developed. This activity will assist in establishing casing design criteria.

- Subtask 2 -- Development of Equipment and Procedures for Remedial and Production Enhancement Operations

  In addition to the primary completion equipment associated with the casing and cementing equipment and operations, there are many other completion operations which influence the productive life of a well. In this subtask, these operations will be evaluated and, where appropriate, development efforts will be initiated. Completion development activities which may be included are the following: improve sand control with gravel packing procedures; improve productivity using bottomhole underreaming to remove shallow damage collars and skin impairment; and improve productivity through the development of more reliable high-temperature perforators. Equipment development needs in the areas of open hole packers and surface wellhead and well control equipment will be evaluated. Workover operations of scale removal and casing and tubing repair techniques will be defined and evaluated. Inflow control techniques to limit the influx of cold water into producing wells will be defined. Initial well test criteria will be defined so that the best way to bring a geothermal well on-line is determined. Further development efforts in the above areas are awaiting technical definition and analysis of economic benefit.

- Subtask 3 -- Completion and Workover Fluid Development

  Typical drilling and completion fluids can cause damage to the producing formation. It has been observed that near-wellbore permeability impairment may result from several mechanisms. These mechanisms include the transport of drilling fluid solids into the formation and the deposition of solids at the wellbore interface, the swelling of in situ clays upon contact with drilling fluid filtrate and their subsequent reduction of free space in the rock or migration in the rock, and in situ chemical reactions including clay transformation reactions, polymer degradation, and simple exchange reactions. Work is in progress to define the importance of these mechanisms and to suggest specific measures to protect both matrix-dominated and fracture-dominated reservoirs. It may be necessary to develop new drilling and completion fluids that minimize the probability of formation damage.

- <u>Subtask 4 -- Life Cycle Cost Analysis of Geothermal Well Completion</u>

  Since there are many aspects to a geothermal well completion, the program to reduce the cost of a geothermal well completion has many diverse avenues of approach. The pursuit of all of the possible programs is not the most cost effective route to follow. In this task, a life cycle cost analysis of a geothermal well will be performed in sufficient detail so that each aspect of the well completion may be evaluated independently. This analysis will be useful not only as a management tool, but also, as a means of measuring the progress of the program.

4. <u>Lost Circulation Control Technology</u>

(a) <u>Objective</u>. The objective of this program element is to develop materials, hardware, and methodology which will reduce the cost impact of lost circulation in geothermal drilling and completion, addressing both preventive and corrective means.

(b) Technical Approach. Geothermal reservoirs are typically characterized by high-temperature, highly fractured formations. These characteristics tend to make ineffective many of the conventional (oil and gas drilling) lost circulation materials and techniques.

The first goal in the project is to gain a thorough understanding of the lost circulation phenomenon and the current methods used in attacking the problem. Both analytical and experimental efforts will be made to solve three general problems: prevention of lost circulation, definition of the loss zone, and reparation of the zone to reestablish fluid circulation.

The lost circulation program has been divided into four major subtasks:

(1) Assessment of problem and solution methods.

(2) Development of materials and hardware for the prevention of lost circulation.

(3) Development of tools for the definition/location of loss zones.

(4) Development of materials and techniques for the reparation of lost circulation zones.

(c) Development of Activities by Subtask. The lost circulation control technology milestone schedules are shown in Figure 8.

- Subtask 1 -- Assessment of Problem and Solution Methods

  This effort will gather information which will be used to direct the specific efforts involved in the remaining three subtasks. This background information will include:

COMPLETED AND NEAR TERM MILESTONES

LOST CIRCULATION CONTROL TECHNOLOGY

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - PROBLEM/SOLUTION ASSESSMENT												
Study of Problem and Existing Solutions Completed				▼								
Characterize Geology of Lost Circulation Zones:												
Background Studies Completed				▼								
Field Experiments Complete								▽				
SUBTASK 2 - LOST CIRCULATION PREVENTION												
Survey of Existing Techniques Complete							▽					
Definition of Hardware Necessary for Lost Circulation Prevention Complete											▽	
Fabrication and Test of Prevention Hardware Complete by the End of FY83												
SUBTASK 3 - LOSS ZONE DEFINITION												
Identification of Tools for Defining Loss Zones								▽				
Design and Laboratory Testing of Tool for Defining Loss Zones Complete											▽	
Field Test of Tool for Defining Loss Zone Complete by the End of FY83												
SUBTASK 4 - LOST CIRCULATION REPARATION												
Design and Fabrication of Test Facility for Lost Circulation Materials Complete								▽				

Figure 8. Lost Circulation Control Technology Milestones

COMPLETED AND NEAR TERM MILESTONES

LOST CIRCULATION CONTROL TECHNOLOGY (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 4 - LOST CIRCULATION REPARATION (Continued)												
Preliminary Tests of Lost Circulation Materials at Geothermal Conditions Complete												▽
Design and Test of Method for Spanning Vugular Formations Complete									▽			
Design and Test of Tool for Placement of Lost Circulation Materials Complete									▽			
Field Test of Placement Tool and Best Candidate Lost Circulation Material Complete by the End of FY83												

Figure 8 (Continued). Lost Circulation Control Technology Milestones

(1) Methods currently used to resume circulation when a loss zone is encountered.

(2) Geological characteristics of lost circulation zones, including fracture size, temperature and pressure of zone, and depth of occurrence.

(3) Methods that can be used to determine the extent and the location of loss zones.

(4) Hardware and techniques which either prevent or circumvent lost circulation.

(5) An evaluation of existing facilities for testing lost circulation control materials and hardware.

Activities in support of items (1) and (5) have been completed. A survey of available information indicates that a field experiment will be required to complete item (2). Items (3) and (4) will be initiated in FY 1981.

- <u>Subtask 2 -- Development of Materials and Hardware for the Prevention of Lost Circulation</u>

This subtask includes the development of materials and hardware to prevent or circumvent lost circulation. Methods such as concentric drill pipe, parasite strings (for fluid aeration), and low-density drilling fluids (foam, mist, air) will be studied to determine their economic benefit, if any.

While one or more of these methods may prove to be economically viable for the drilling operation, each must be considered in conjunction with the completion operation. Lost circulation zones that are bypassed in the drilling operation are likely to break down during cementing and lead to casing failure. This subtask must therefore be coordinated with the Completion Technology project. Also, the study of low-density drilling fluids will be coordinated with the Drilling Fluids Technology project.

Specific efforts to be made include:

(1) An economic evaluation of the several prevention methods and, if justified,

(2) Fabrication of hardware for test and evaluation.

More detailed definition of efforts within this subtask must await the background studies noted in Subtask 1.

- Subtask 3 -- Definition/Location of Loss Zones

Repairing a lost circulation zone would be facilitated by knowledge of the location and size of the zone. This subtask is aimed at developing a tool that could be used to secure this information.

Since additional costs would be incurred in using such a tool, the information gained must be economically justified. This justification will necessarily be dependent on the method used to repair the zone. For example, the use of a mechanical patch requires specific size and location data, while a plugging material may require only approximate zone definition.

Specific efforts within this subtask will include:

(1) Definition of a tool or method to map the loss zone.

(2) Economic evaluation of the tool/method in conjunction with various repair techniques.

(3) If justified, fabrication of hardware for test and evaluation.

- Subtask 4 -- Development of Materials and Techniques for Repair of Lost Circulation Zones

This subtask is the major element in the lost circulation program. Geothermal lost circulation zones are thought to be dominated by two types of formations: fractured and vugular. Fractured formations may be repaired by a plugging material, whereas vugular formations will likely require some sort of mechanical patch. This subtask is aimed at developing both of these repair techniques.

Specific efforts to be pursued under this subtask are:

(1) Development of test facilities which simulate the fractured, lost circulation zones in geothermal wells.

(2) Laboratory testing aimed at developing fracture plugging materials.

(3) Development of a downhole tool for placing the plugging materials.

(4) Development and testing of a method for patching vugular loss zones.

Development of both the plugging material and the patching method will involve screening tests, verification tests and, finally, field tests. In addition to the experimental efforts, analytical support will be used to guide the development within this subtask.

5. Advanced Systems Development

(a) Objective. Achievement of the 50-percent cost reduction goal will require the development of a drilling system capable of extremely high rates of penetration. It is unlikely that the required rates can be achieved by incremental improvements in conventional rotary technology. The objective of this project is to evaluate candidate advanced drilling systems and to develop one or more of these systems. This objective will be met by examining fundamental performance characteristics of candidate systems and by testing components of these systems.

(b) Technical Approach. The three leading candidates for advanced drilling systems are water-jet drilling, percussion drilling, and downhole drilling motors, either turbine or positive displacement. To choose among them, it is necessary to estimate the drilling performance of each system as well as the cost to develop and operate it. Performance estimates will be compiled from laboratory and field tests of presently available hardware, laboratory and field tests of prototype advanced components, and extrapolations from supporting technology research in such areas as rock mechanics, bit hydraulics, and material development. Economic analysis of each system will be closely tied to the well cost model developed as part of the Supporting Technology project. Once the evaluations are complete on these three systems, and any other promising candidates, one or more systems will be selected to be developed, field tested, and transferred to industry.

(c) Research Activity by Subtask. This task has been divided into seven subtasks as follows:

(1) Evaluation of high-pressure fluid jet drilling systems.

(2) Evaluation of percussion drilling systems.

(3) Evaluation of high-speed downhole motors and bits.

(4) Development of unconventional drill string and surface equipment.

(5) Development of improved directional drilling equipment.

(6) Evaluation of alternative systems.

(7) Development of advanced drilling systems.

The advanced drilling systems subtask milestone schedules are shown in Figure 9, and the activities in each subtask are described below.

- Subtask 1 -- Evaluation of High-Pressure Fluid Jet Drilling Systems

  Use of high-pressure fluid jets, either alone or as augmentation for conventional drilling, will be investigated. Collection and organization of data on existing jet drilling systems will allow comparison of cost effectiveness and will identify system elements requiring concentrated development. Once technical and economic feasibility are established, prototype components can be designed and tested to verify predicted performance.

  Nozzle design will receive special attention because it is critical in determining system performance and because nozzles operating at reduced pressure offer the possibility of augmenting conventional rotary drilling with no other equipment changes. Cavitating nozzles will be designed and tested in the laboratory; if successful, they will be incorporated into conventional rotary bits and tested in comparison with the same bits and conventional jets.

COMPLETED AND NEAR TERM MILESTONES

ADVANCED DRILLING SYSTEMS

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - HIGH PRESSURE JET DRILLING FLUID SYSTEMS												
Study of the Potential of Cavitating Jets Completed in FY79												
Optimization of Standard Cavijet™ Nozzle Complete						▽						
Optimization of Advanced Cavijet™ Nozzle Complete											▽	
Laboratory Testing of first Prototype Pulsating Nozzle Complete						▽						
Optimization of Pulsating Nozzle Complete									▽			
Compilation of Data and Characterization of High Pressure Erosion Drilling Systems Complete					▽							
SUBTASK 2 - DEVELOPMENT OF PERCUSSION DRILLING SYSTEM												
Testing of Percussion Hammers to Identify High Temperature Failure Modes Completed			▼									
Laboratory Testing of First Prototype, High-Temperature, Air Hammer System Complete						▽						
Bit Design Change Requirements Complete							▽					
Mud Hammer Design Requirements Complete								▽				
Field Test of First Prototype Air Hammer Complete												▽
SUBTASK 3 - HIGH-SPEED DOWNHOLE MOTORS AND BITS												
Design and Fabrication of Prototype Bearing and Seal Package with 200-Hour Life at a Circulating Temperature of 125°C Complete								▽				
Testing of Candidate Seals Complete								▽				

Figure 9. Advanced Drilling Systems Milestones

COMPLETED AND NEAR TERM MILESTONES

ADVANCED DRILLING SYSTEMS (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 3 - HIGH-SPEED DOWNHOLE MOTORS AND BITS (Continued)												
Laboratory Testing of First Prototype High-Speed Bits Complete						▽						
Laboratory Testing of Second Prototype High-Speed Bits Complete											▽	
SUBTASK 4 - DEVELOPMENT OF UNCONVENTIONAL DRILL STRING AND SURFACE EQUIPMENT												
Testing of Candidate High-Temperature Polymers with a Flexible Pipe System at High Temperature and Pressure Complete								▽				
Two Conceptual Designs of a High-Pressure, Geothermal Fluid-Jet Drilling System Complete								▽				
SUBTASK 5 - DIRECTIONAL DRILLING HARDWARE												
First Proof-of-Principle Test for Wellbore Inertial Navigation System Complete							▽					
Field Test of First Prototype of Inertial Navigation System Complete												▽
Development of Equipment for Kicking-off in Hard Rock Initiated												▽
SUBTASK 6 - EVALUATION OF ALTERNATIVE SYSTEMS												
Cost and Penetration Rate Data for Various Systems Complete											▽	
Initiate Trade-Off Studies												▽
SUBTASK 7 - DEVELOPMENT OF ADVANCED DRILLING SYSTEMS												
Start in FY85												

Figure 9 (Continued). Advanced Drilling Systems Milestones

Research and development activities will be directed toward providing information for making a decision regarding the development of a prototype jet drilling system.

- Subtask 2 -- Evaluation of Percussion Drilling Systems

Since percussion drilling does not represent a radical departure from conventional drilling practice, the evaluation of percussion drilling will focus on the verification of hammer operation at high temperature, the quantification of the economic benefits of percussion system operation, and the estimation of the geothermal resource appropriate for hammer use. Commercially available, air-powered percussion hammers will be modified for and tested at high temperature. Prototype liquid-powered hammers will be investigated for high-temperature use and, if necessary, will be modified and tested. Solid head bits for hammers will be redesigned to improve their gage maintenance. These hardware-oriented activities, which provide a measure of performance improvement, will be complemented by an economic analysis and a survey to estimate how much potential geothermal drilling could be done using the percussion technique. Using these inputs, it will then be possible to establish whether the advantages of percussion drilling can be realized at reasonable cost.

- Subtask 3 -- Evaluation of High-Speed Downhole Motors and Bits

The use of downhole drilling motors operating at high rotary speeds has the potential for greatly increasing penetration rates. Positive displacement motors are currently used extensively in oil and gas drilling. Unfortunately, they use elastomeric materials for both the motor stator and the seal in the bearing package. These motors are unsuitable for use in high-temperature applications because of the failure of the elastomeric materials. Turbodrills, on the other hand, utilize blades that are capable of withstanding high temperatures, but they still encounter the problems associated with sealed bearings used at high temperature. In addition, turbodrills typically operate at rotary speeds that are too high to be compatible with conventional bits. Nevertheless, a determination has been made[4] that turbodrills have a high potential for use in geothermal applications; therefore, the objective of this subtask is to evaluate the use of turbodrills in the geothermal environment.

The first phase of this evaluation involves the testing of seals, lubricants, and bearings to determine the expected bearing lifetime under simulated downhole conditions. A seal tester, a lubricant tester, and a bearing and seal package tester have been fabricated at the Drilling Research Laboratory.[5] These testers simulate downhole conditions. Most existing seals and lubricants have been tested and found to be inadequate. The critical element that must be developed is, therefore, a bearing/seal package capable of operating at the required temperatures. The feasibility of developing the required components must first be assessed before system assessments can be reliably performed. New seals and lubricants will be developed and unsealed bearing packages will be fabricated and tested with a goal of achieving a 200-hour operating lifetime at a circulating temperature of 125°C (257°F).

The second phase of the evaluation involves the fabrication, testing, and further development of bits capable of operating at high rotary speeds. PDC bits appear to be suited for this application and will be the first bit types evaluated under this program.

To complete this evaluation of downhole motors, it will be necessary to determine the feasibility of developing a motor that could be powered by a low-density, compressible fluid such as air or foam because many geothermal reservoirs are drilled with such fluids.

Completion of these component evaluations will provide the basis for making decisions regarding full-scale system development.

- <u>Subtask 4 -- Development of Unconventional Drill String and Downhole Equipment</u>

Tripping and connection times associated with conventional rotary drilling have been identified as major contributors to overall drilling costs. Continuous, flexible drill pipe can be reeled into and out of a hole and can greatly simplify the tripping process. Development of a flexpipe system for oil and gas drilling has been under way for some time in Europe, but has not been tested at geothermal temperatures. Short sections of flexpipe with couplings will be pressurized and flexed at high temperature to identify any new failure modes. The application of new elastomers may be required to upgrade the pipe to higher temperature. The feasibility of developing a high-temperature, flexible pipe system will be assessed.

An assessment of the feasibility of developing a downhole pressure intensifier, which may be necessary for the proper performance of jet drilling nozzles and for operation of some types of downhole rotary motors, will be performed. Such an intensifier could also assist the water-jet descaling project. This system, if developed, would reduce the need for high-pressure pumps and swivels on the rig. Development will follow the assessment, if appropriate.

• Subtask 5 -- Development of Improved Directional Drilling Equipment

Directional drilling in geothermal wells is currently difficult because of the destructive influences of high temperature on downhole motors, bearings and seals, downhole tools, and surveying instruments. Specifically, the need for a high-accuracy survey tool has been identified, and work has been initiated to adapt an inertial navigation system to a geometry that is compatible with the borehole dimensions. The tool is expected to operate only at low temperatures, 100°C (212°F), at first, but if successful testing is accomplished, a prototype capable of operating at high temperatures will be developed.

In addition, new techniques for kicking-off a well in hot, hard formations are needed. Development of these new techniques will be initiated in FY 1982.

• Subtask 6 -- Evaluation of Alternative Systems

Near-term activity in this subtask will integrate test and study results into a systems analysis model. By using the same model to evaluate all drilling systems, additional data requirements can be identified and new tasks can be started. This evaluation will account for both the technical risk associated with hardware development and the economic benefit to be derived from such systems.

• Subtask 7 -- Development of Advanced Drilling Systems

Following the completion of subtasks 1 through 6, a decision will be made to develop one or more of the advanced drilling systems into the prototype stage for field testing.

6. Supporting Technology

(a) Objective. The objective of the Supporting Technology projects is to provide the necessary analytical and experimental support for the drilling and completion hardware development programs.

(b) Technical Approach. Analytical and experimental techniques required to support the development of improved technology will be defined by the respective technology programs and initiated on an as-needed basis.

(c) Research Activities by Subtask. The Supporting Technology program element is currently divided into six subtasks. These are:

(1) Wellbore thermal model

(2) Systems analysis

(3) Drill pipe corrosion studies

(4) Drill bit hydraulics

(5) Rock/cutter interaction studies

(6) Drill string dynamics studies

The Supporting Technology subtask milestone schedules are shown in Figure 10.

- Subtask 1 -- Wellbore Thermal Model

  The objective of this subtask is to develop the capability for calculating the temperature of wellbore fluids during drilling, cementing, production, and injection operations. This predictive capability is needed to allow proper formulation of drilling fluids and cements

COMPLETED AND NEAR TERM MILESTONES

SUPPORTING TECHNOLOGY

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 1 - WELLBORE THERMAL MODEL												
Single Phase Flow Model Completed in FY79												
GEOTEMP Available and Used Successfully by Industry	▼											
Variable Cross-Section and Wellbore Deviation Options Completed			▼									
Compressible Flow Model Complete					▽							
SUBTASK 2 - SYSTEMS ANALYSIS												
Well-Cost Model Completed			▼									
Generic Well Described and Well Troubles Quantified							▽					
Survey of Future Drilling Requirements Complete						▽						
Initial Assessment of Program Elements as to Their Progress Toward Program Goals Complete							▽					
Updated Assessment of Progress Toward Goals Complete												▽
SUBTASK 3 - DRILL PIPE CORROSION STUDIES												
Formulation and Fabrication of New Corrosion-Resistant Steel Completed				▼								
Fatigue Testing of Steel and Transfer of Information to Industry Complete								▽				

Figure 10. Supporting Technology Milestones

COMPLETED AND NEAR TERM MILESTONES

SUPPORTING TECHNOLOGY (CONTINUED)

MILESTONE	FY 1980				FY 1981				FY 1982			
	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK 4 - DRILL BIT HYDRAULICS												
Fabrication of Bit Hydraulics Test Facility Completed				▼								
Preliminary Hydraulic Studies of PDC Bits Complete												▽
SUBTASK 5 - ROCK/CUTTER INTERACTION												
Numerical Model of Forces on Drag Cutter and Fractures in Rock Completed	▼											
Drag Cutter Heat Transfer Model Completed			▼									
Experimental Measurements of Drag Cutter Forces and Temperatures Complete												▽
SUBTASK 6 - DRILL STRING DYNAMICS STUDIES												
Feasibility Study and Formulation of the Bit-Formation Interaction Problem Complete						▽						
Solution of both the Drill String and the Downhole Assembly Equations Complete												▽

Figure 10 (Continued). Supporting Technology Milestones

in geothermal operations. In addition, the information is useful in predicting injection well performance and in determining temperature profiles in producing wells. A single-phase, heat-transfer, wellbore fluid flow code, GEOTEMP, has been developed, verified, and commercialized. Temperatures are computed as a function of time in a flowing stream, both in the wellbore and in the surrounding medium. Further activities will include modification of this code to include the following elements:

(1) The ability to analyze wellbores having variable cross-sectional geometry and hole deviation.

(2) The ability to analyze single- and multi-component, compressible flow and two-phase flow in the wellbore.

- Subtask 2 -- Systems Analysis

The objectives of this subtask are as follows:

(1) To evaluate the progress of the Geothermal Drilling and Completion Technology Development Program toward achieving its stated cost reduction goals.

(2) To define the costs of various drilling operations as functions of well size and depth, casing size, and cement type.

(3) To identify general categories of geothermal wells that will be drilled in the foreseeable future and to construct well plans for a typical well in each category.

(4) To identify technology development areas that have the highest impact on well cost through cost/benefit analyses so that selection of development programs is closely tied to program goals.

A well-cost simulation model that provides the capability for analyzing the costs of drilling and completing geothermal wells has been developed. Each of the systems analysis objectives will provide information which is required for the well-cost model. The model will be used to analyze and assess cost reductions that can be made through improvements in drilling technology and to evaluate the associated costs. The model also requires detailed well plans in addition to cost estimates for drilling operations and equipment. The coupling of the model with the well plans will allow an assessment of progress toward goals as well as an identification of technology development projects.

- <u>Subtask 3 -- Drill Pipe Corrosion Studies</u>

Drill pipe corrosion can be a minor problem, or a very serious one, depending on the geothermal environment. In general, about 75 to 85 percent of drill pipe loss is attributed to corrosion and, currently, the primary effort in reducing corrosion is the addition of corrosion inhibitors to the drilling fluid. These chemicals are very expensive and, in some locations, comprise a significant fraction of the drilling cost. This subtask will assess alternative methods for reducing corrosion in drill pipe.

The following tasks will be pursued:

(1) Characterize the corrosion fatigue susceptibility of both current and recently developed drill pipe steels.

(2) Assess the reduction of corrosion of drill pipe steels through the use of inert drilling fluids.

(3) Characterize the effects of individual corrosive elements in addition to defining their synergistic effects.

(4) Evaluate the use of dual-phase steel alloys as drill pipe material in the geothermal environment.

These tasks will be accomplished through the use of a corrosion fatigue test apparatus. Specimens of the various steels will be prepared and subjected to cyclic loading in the presence of H_2S and geothermal brines. The growth rate of stress-induced cracks will be measured and compared for each sample.

- Subtask 4 -- Drill Bit Hydraulics Studies

The objectives of this subtask are to provide an understanding of drill bit hydraulics, particularly for polycrystalline diamond compact bits, and to optimize the hydraulics of experimental drill bits through analytical and experimental studies.

In order to assess the performance of different hydraulic designs, the flow field across the bit face and in the near-bit annular region will be studied experimentally. A bit hydraulics test facility has been built which dynamically simulates the downhole flow field and allows visual observation and electronic measurement of the flow field characteristics. Qualitative and quantitative measurements of these characteristics can thus be correlated with different hydraulic designs to determine optimum nozzle configurations for each bit and range of operating conditions.

In addition to flow visualization studies, convective heat transfer coefficients on the cutter surfaces can be measured, as well as the pressure distribution on the bottom of the hole.

The results of the experiments will be a performance ranking of each hydraulic design for each particular test. Since the design selected for downhole operation must perform all of the required functions well, the results must be further analyzed in order to select the optimum configuration. It is quite likely that different tests will rate the hydraulic designs differently. In that case, the characteristics of the superior designs for each test must be identified and a compromise reached among competing factors. Such a process would result in a hydraulic design which combines the characteristics of several different designs to achieve optimum performance of all hydraulic functions.

- <u>Subtask 5 -- Rock/Cutter Interaction Studies</u>

The rock/cutter interaction for rolling, crushing bits has been studied extensively. However, the drag-type PDC bits being developed under this program utilize a different rock fracture mechanism. To achieve optimal bit design, the interaction of drag cutters with rock requires additional study.

The objectives of this subtask are:

(1) To determine the stresses and temperatures that build up in a drag cutter as a function of cutter rake angle and depth of penetration.

(2) To determine the mechanisms of drag cutter wear and to define ways to minimize the wear through design and material changes.

(3) To develop a suitable chip-formation model for a drag cutter/rock interaction problem.

(4) To determine the optimal cutter placement pattern for a geothermal bit.

Experimental and analytical investigations of the physics of rock failure by drag cutters will be carried out in order to select more efficient means of transmitting energy to the formation. In addition, new designs and new materials will be sought in order to minimize tool wear rates, thus increasing the life of drag cutters. Rock failure as a function of loading in both the microscopic and macroscopic range will be investigated under representative reservoir conditions of pressure and temperature. The results of these studies will then be used to design longer lasting, faster penetrating drill bits.

- <u>Subtask 6 -- Drill String Dynamics Studies</u>

The objectives of this subtask are to develop improved analytical models that will allow the proper design of downhole assemblies and shock subs to reduce hole deviation problems and problems associated with severe drill pipe vibration. Specifically, the activities include the following:

(1) Formulation of the downhole assembly, bit and formation interaction equations.

(2) Solution of the bit/formation interaction problem.

(3) Coupling of bit/formation interaction dynamics to the downhole assembly model.

(4) Formulation and solution of both the drill string and downhole assembly equations.

The purpose of this study is to determine the dynamically unstable failure modes and the peak stresses, strains, and displacements along a straight and deviated rotating drill string. A user-oriented computer code will be developed that will be available to industry for design applications. This study will establish how different drilling parameters affect the deflection and stress distributions and show how to improve drilling programs. Of particular interest are the frequency and amplitude of the motions induced in the string and in the motor bearings when high-speed motors are utilized with PDC bits. The analysis will use laboratory measurements of bit and motor dynamics obtained during motor tests. Then, assessments of the need for shock subs to protect the motor components can be made and proper shock sub designs can be developed.

III. Management Plan

A. Approach

The DOE Division of Geothermal Energy has overall programmatic responsibility for direction of the Geothermal Drilling and Completion Technology Development Program. Field program management responsibility has been assigned to Sandia National Laboratories. DOE/DGE, with assistance from Sandia, sets the program goals, establishes milestones and budget, and plans programs toward meeting them. Sandia plans, initiates, directs, and coordinates technical work within the scope and objectives of the program. Close technical and administrative coordination is maintained between the Sandia Program Manager and the DOE/DGE Program Manager.

B. Program Management Structure

The Drilling and Completion Technology Development Program is structured as shown in Figure 11. The DOE Program Manager has overall administrative responsibility for the program including the preparation of the annual budget requests. In addition, he authorizes and monitors Sandia's in-house research projects. The Sandia Program Manager has overall responsibility for accomplishing the technical objectives of the project within the specified budgets and schedules. Working under Sandia policies, he will obtain appropriate Sandia management concurrence in the expenditure of project funds. He will be versed in all technical aspects of the program and will maintain familiarity with relevant R&D activities outside the program. He is responsible for updating the program plan and for contracting and

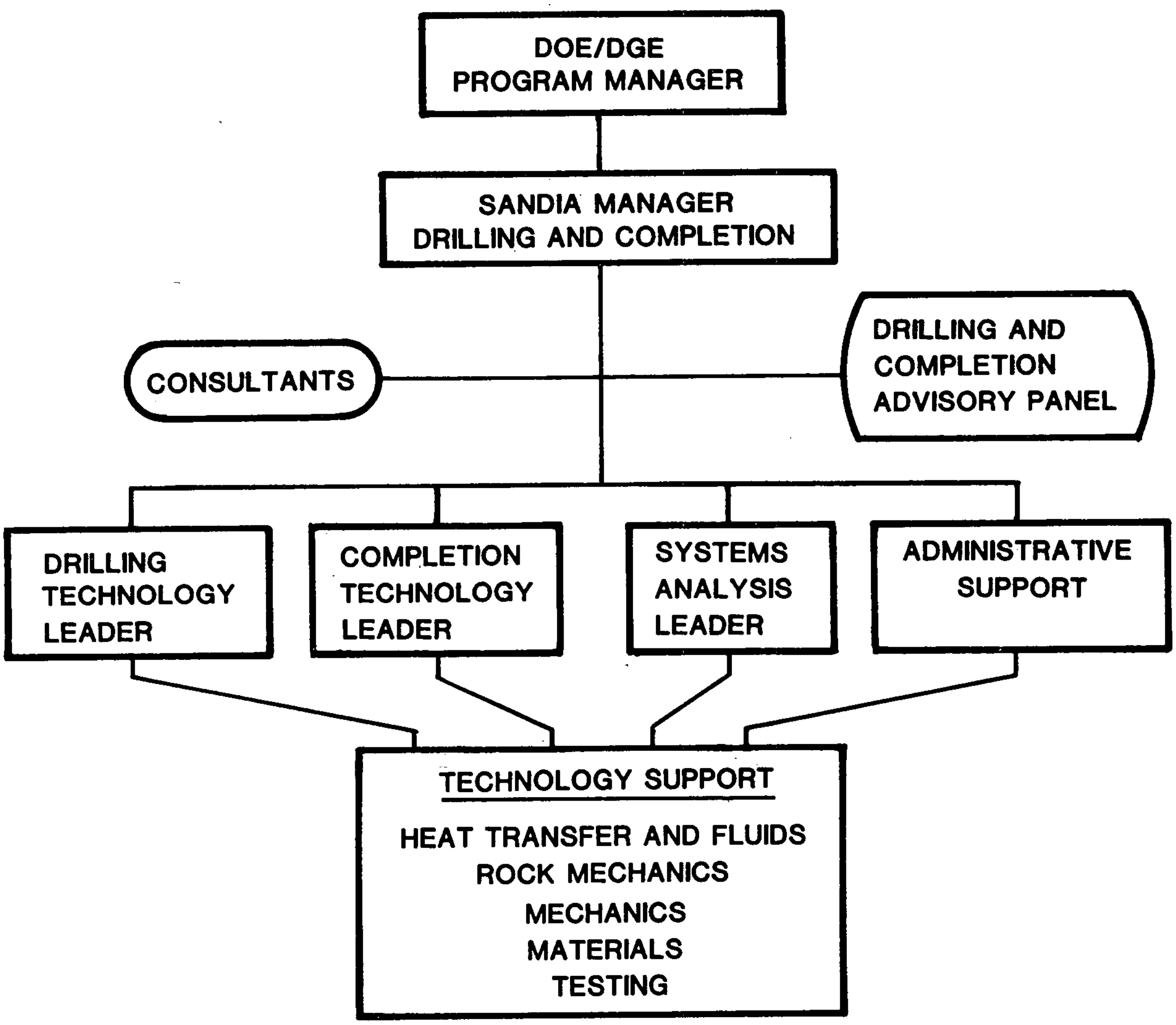

Figure 11. Program Management Structure

procurement activities. In addition, he will insure effective coordination and integration of the various tasks under the program and will establish and insure effective working interfaces with the other projects of the Federal Geothermal Energy Program. He will also be responsible for maintaining close coordination and direct communication with the DOE/DGE Program Manager.

A Geothermal Drilling and Completion Advisory Panel comprising several industry representatives serves as a steering committee for the Drilling and Completion Program. The Sandia Program Manager will work closely with this panel. The panel meets semiannually to review the program activities and provide guidance to the Sandia Program Manager.

C. Procurement and Contract Management

Procurement activities will be conducted in general accordance with established Sandia procurement policy. Within the framework of the procurement system, there is strong emphasis on competitive solicitation, with DOE-approved guidelines for requests for quotation (RFQ's), proposal evaluation, and source selection techniques. Advance notice of intent to contract will be published in the Commerce Business Daily, when appropriate. Where facts and circumstances indicate the impracticality of placing a specific requirement on a competitive basis, the system provides for the possibility of noncompetitive procurement on a sole source basis.

The Sandia Program Manager, in coordination with the responsible DGE management, will establish the requirements of major project tasks to be contracted. Procurement and competitive solicitation will be handled by a combination of Sandia technical and administrative personnel. Contractor technical and fiscal activities and performance will be monitored through plant visits, review of contractor reports and records, and independent analysis or experimental verification of component or subsystem performance at Sandia facilities or other outside facilities, as appropriate.

Specifically, technical monitoring will be accomplished by the following:

1. Informal monthly letter reports by the contractor which will be reviewed by Sandia and combined into a quarterly status report to DOE.

2. Formal semiannual status reviews of all program elements, utilizing presentations by the contractors to DOE, the Sandia Program Manager, and the Geothermal Drilling and Completion Panel.

3. Plant visits on a semiannual basis by the Sandia engineer responsible for the progress of the work.

The Sandia Laboratories Case Cost System is used for the control and allocation of resources. Cost data are aggregated by major task level and periodic reports are issued to DOE.

D. In-House Research and Development

DOE has assigned to Sandia certain in-house technical work that is necessary to maintain a viable technical expertise in the program management staff. In addition, Sandia possesses many unique technological resources which can benefit the Federal Geothermal Energy Program. DOE/DGE monitors and approves the Sandia in-house level of effort on the technical work of the Drilling and Completion Program. In-house activities fall into one or more of the following categories:

1. Research and development (R&D) that supports or complements the work of outside contractors.

2. Advanced R&D that utilizes unique capabilities or facilities developed under other programs at Sandia.

3. Development of systems analysis methods for identifying critical R&D areas and evaluating proposals.

4. R&D for which no outside source is available.

5. Application of advanced weapons technology as appropriate to geothermal drilling and completion problems.

6. Development that must be accomplished on short time scales so that procurement activities are precluded.

E. Program Reporting and Technical Review

1. Program Reviews -- In addition to periodic internal Sandia program reviews, formal progress reviews will be conducted semi-annually for evaluation by DOE/DGE management, Sandia management, the Advisory Panel, and other designated program reviewers. The reviews will be in the form of detailed presentations on the status of the various program tasks to be given by involved Sandia personnel or by the contractors. Project accomplishments as well as problem areas affecting objectives, schedules, and costs will be emphasized. Evaluations from these reviews will be utilized to update program plans and schedules. Special reviews and interface meetings may also be necessary at other times, such as, prior to major program decision points.

2. Management Reports

(a) Quarterly and Annual Progress Reports. Quarterly progress reports will be prepared that will review all aspects of the program. These reports will cover the achievements of the period and their implications relative to overall program objectives and milestones and will provide a measure of performance with respect to goals set forth at the beginning of the year. Annual reports will be issued on a fiscal year basis.

(b) Contractor Reports. Contractors will submit monthly progress reports to Sandia detailing the activities and accomplishments of their work. Emphasis will be on technical results, schedules, costs, and problem areas. Interim and final contract reports for public dissemination will be issued.

(c) Special Reports and Project Information. From time to time it will be necessary to prepare special summary reports which might be dictated by completion of a major program activitiy or by unusual or unexpected developments affecting the overall program. Program information in the form of visual aids, desk-top models, and prototype hardware will be furnished to DOE/DGE to aid the staff in presenting program overviews as needed.

3. Dissemination of Technical Information -- In order to provide timely technical information to interested scientific and industrial communities at large, Sandia personnel actively involved in the technical work will participate in and present technical papers at scientific meetings and workshops. Contractor representatives will also be encouraged to do so. Significant technical accomplishments will be written in the form of special reports or will be submitted to appropriate scientific and technical journals. Publication of research results by contractors will be encouraged, but will be in accordance with the terms of the contract and conditions regarding release of information. Seminars and workshops will be organized as deemed useful.

Sandia is a no-fee, non-profit DOE laboratory, and energy R&D information is made available to all interested parties. All patents awarded to Sandia's staff are assigned to the U.S. Government and are handled in accordance with DOE policies to protect the public interest. All reports generated by this program are available through the National Technical Information Service.

IV. Technology Transfer and Research Utilization

The Drilling and Completion Program and the overall DOE Geothermal Program are designed to encourage the development and implementation of geothermal energy sources by private industry. Therefore, special attention is given to technology transfer and research utilization.

Results of work performed under the program will be communicated on a timely basis by both contractor and Sandia staff to suppliers, manufacturers, users, and regulatory agencies. Various modes of communication will be employed including:

1. Publication of results in frequent progress reports and in scientific, technical, and trade journals;

2. Presentations at appropriate meetings and conferences; and

3. Scheduling of information meetings, conferences, workshops and symposia which will be open to the general public.

Industrial participation and guidance are strongly encouraged. One formal point of contact between industry and the program is the Drilling and Completion Advisory Panel. This panel comprises drilling contractors, equipment manufacturers, and representatives from the operating companies. Semiannual meetings of this panel are convened to discuss research results and to identify areas where further research is needed. These meetings provide information to the industry at the earliest possible time.

An important factor pertaining to technology transfer is the fact that Sandia is fully committed to the concept of early and extensive involvement of industry, university, and other agencies in all phases of energy research and development. Thus, the major portion of the program's activities will be performed by the private sector and other institutions under contract to Sandia.

References

1. Interagency Geothermal Coordinating Council, "Geothermal Energy Research, Development and Demonstration Program," 4th Annual Report, DOE/RA-0050, IGCC-5, June 1980.

2. Bloomster, C. H. and Engel, R. L., "The Potential Benefits of Geothermal Electrical Production from Hydrothermal Resources," BNWL-2001, Battelle Pacific Northwest Laboratories, June 1976.

3. Polito, J. and Varnado, S. G., "A Program in Geothermal Well Technology Directed Toward Achieving DOE/DGE Power-on-Line Goals," Sandia Laboratories Report SAND78-0766, October 1978.

4. Varnado, S. G., "Report of the Workshop on Advanced Geothermal Drilling and Completion Systems," Sandia Laboratories Report No. SAND79-1195, June 1979.

5. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Semi-Annual Progress Report October 1978-March 1979," Sandia Laboratories Report SAND79-1499, September 1979.

6. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Semi-Annual Progress Report April-September 1979," Sandia Laboratories Report SAND79-2397, May 1980.

7. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Quarterly Progress Report October-December 1979," Sandia Laboratories Report No. SAND79-2398, January 1980.

8. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Quarterly Progress Report January-March 1980," Sandia Laboratories Report SAND80-0703, April 1980.

9. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Quarterly Progress Report April-June 1980," Sandia Laboratories Report No. SAND80-1234, July 1980.

10. Varnado, S. G., "Geothermal Drilling and Completion Technology Development Program Annual Progress Report October 1979-September 1980," Sandia Laboratories Report No. SAND80-2179, November 1980.

APPENDIX A

Current Program Status

CURRENT PROGRAM STATUS

This appendix presents a brief summary of the current status of the work under way in each program element.

Drilling Hardware

A completed project on unsealed geothermal drill bit development has identified new materials for use in critical areas of conventional roller cone bits. These materials demonstrated improved hardness and toughness at high temperatures and extended the life of the bits in hard geothermal formations. Six experimental bits using these new materials were tested in a geothermal well at The Geysers along with seven conventional bits. The material improvements allowed the experimental bits to drill 30 percent longer before incurring the same gage wear as the conventional bits, and 70 percent more hole was drilled to gage than with a conventional bit. Bearing wear was also reduced significantly. By decreasing the number of bits needed to drill a well and reducing rig time cost, the experimental bits could potentially save between 2 and 4 percent of the total cost of wells drilled in The Geysers.

Experiments with high-temperature seal designs, materials, and lubricants for sealed bearing bits have identified promising seal/lubricant systems for geothermal use. An oil, designated PLX-014, has been developed under this program and has demonstrated a load-bearing capability at 316°C (600°F) roughly twice that of the standard rock-bit lubricant at room temperature. A grease version of PLX-014 oil tested at 317°C (603°F), while showing, as expected, an average load-carrying capability somewhat less than the oil, still exceeded standard lubricant load capabilities by 50 percent. Both the oil and grease versions of PLX-014 proved compatible with elastomeric seals fabricated from Viton and Teflon-coated Viton materials. The new lubricant, PLX-014, is now available commercially under the trade name "Geobond."

Full-scale drag bits, modified to use polycrystalline diamond compact (PDC) cutters, have been successfully demonstrated in field tests. Steel-bodied, PDC bits built by Christensen and Smith, were tested at a location in the Baca Field, New Mexico. Testing was in andesite, the basement formation for the geothermal wells being drilled by the Union Geothermal Company of New Mexico. The tests were run at depths of approximately 1,676 to 1,707 metres (5,500 to 5,600 feet). One bit drilled with penetration rates up to 0.007 m/s (85 ft/h) at bit weights up to 88,964 newtons (20,000 pounds) and rotary speeds as high as 70 rpm. Cutter wear was not excessive, and the bit was still usable after the test. On the average, a 50-percent increase in penetration rate over that of a conventional bit was obtained. The other steel-bodied bit was found to be so aggressive in drilling this formation that bit weights greater than 44,482 newtons (10,000 pounds) could not be used. Instantaneous penetration rates as high as 0.014 m/s (170 ft/h) were obtained at a rotary speed of 60 rpm. Since these tests were limited to approximately 15.2 metres (50 feet) each, bit lifetime could not be established. Additional field testing to establish this parameter is planned in FY 1981.

The continuous chain drill is a system in which the cutting surfaces can be replaced without removing the bit from the hole. The concept is intended to reduce drilling costs by reducing the time required to replace worn bits. The cutting surface uses natural diamonds mounted on the links of a continuous chain. A prototype of this bit was field tested in drilling granite at the Nevada Test Site (NTS) in June 1979. The chain bit drilled a total of 76 metres (250 feet) with six cutting surfaces, and the chain was successfully cycled approximately 85 times downhole. Problems were encountered with the mud system. A second field test was conducted in September 1979, but internal hydraulic leakage occurred. This problem has been corrected, and a third field test at NTS was conducted in June 1980. In this test, the mechanism used for cycling the chain was proven to be reliable. If industry will cost share further development on this concept, commercialization activities will start in FY 1981. Limited industry interest will result in project termination.

Drilling Fluids

Projects are progressing with the objectives of determining the high-temperature/high-pressure rheological properties of drilling muds, of gaining a fundamental understanding of the morphology of clay particles under the influences of high temperature and various chemical compounds, of identifying and/or developing foam drilling fluids capable of operating in temperature environments to 310°C (590°F) and having chemical and foaming stability and anticorrosive and antioxidant properties, of demonstrating a technique of N_2 generation from diesel engine exhaust using a catalytic converter, and of field testing a high-temperature drilling mud.

A mud testing loop has been installed at the University of Oklahoma to evaluate drilling fluids under simulated downhole conditions of 288°C (550°F) and 20.6 MPa (3,000 psi), and testing of muds has begun. A mud test facility with extended capabilities, 371°C (700°F) and 138 MPa (20,000 psi), is under construction at NL Baroid under a cost-sharing contract with DOE. This extended testing capability is expected to be available by the end of FY 1981.

A project directed at providing a basic understanding of the effects of different chemicals and high temperatures on clay particle morphology is under way at Texas Tech University. On the basis of this understanding, clay-based, geothermal drilling fluid systems, complete with the additives dictated by downhole conditions, will be designed for use in geothermal drilling. The Texas Tech Clay and Drilling

Fluids Laboratories were remodeled to accommodate the project. The project investigations were initiated in July 1979. X-ray diffraction and electron microscopic studies of the effects of various salts and elevated temperatures on attapulgite and sepiolite have been conducted. Studies of saponite fluids are continuing. One sepiolite mud formulation developed under this program has been field tested in a geothermal well in the Imperial Valley. While data analysis is not yet complete, the mud exhibited good hole-cleaning characteristics, yet low pump pressures were required to break circulation after trips.

The development of aqueous foams for geothermal drilling has been initiated at Sandia National Laboratories with a goal of developing a foam that is stable and noncorrosive at 310°C (590°F). An initial report has been issued defining the basic problems to be considered, the various solutions thought to be obtainable, and a plan for conducting the required development. Initial surfactant screening has been completed. Fifty-six surfactants have been evaluated before and after exposure to a temperature cycle reaching 260°C (500°F). Twelve surfactants were selected for further testing. The evaluation of these surfactants in various chemical environments at 260°C (500°F) has been completed. Six surfactants, selected because of their good performance in the chemical environment tests, have been evaluated after exposure to 310°C (590°F) in deionized water. Four of these surfactants showed good to excellent performance and are now being evaluated in various chemical environments at 310°C (590°F). Surfactant evaluation at 260°C (500°F) is continuing on new surfactants that have been recommended.

The use of inert gas rather than air for drilling is expected to reduce corrosion problems. A program to develop portable nitrogen generation units has been initiated. At Engelhard Industries, a project to demonstrate catalytically supported thermal combustion as a means of generating an inert gas from the exhaust stream of a commercially available diesel engine is under way. An existing, proprietary catalyst will be used with supplemental No. 2 fuel over the load range of the diesel engine to achieve this objective. The performance of the catalyst will be evaluated over an extended period of time to verify that its activity can be retained under operating conditions consistent with the intended field application. The project was initiated in August 1979. The test rig design and fabrication have been completed, the facility debugged, and the unit demonstrated. The parametric test program has been completed, and the durability tests are progressing.

Completion Technology

Studies of current geothermal well completion practices and of geothermal well casing failure modes have been completed and published. These studies have been used to plan future development activities for this program. Specifically, they have pointed out the critical need to achieve proper cement placement to prevent casing collapse, buckling, and corrosion. Based on these findings and the recommendations of an industry-based advisory panel, the design of a laboratory experiment for testing cements and cement placement methods under simulated downhole conditions has been completed. Acquisition and assembly of the required equipment will begin in FY 1981.

A new technique using high-pressure cavitating jets to remove scale from pipes in geothermal power plants has been demonstrated. The possibility of using the system to remove scale from the wellbore of a flowing well has also been demonstrated, and the parameters needed for design of an operational downhole geothermal well cleaning and scale removal system were established. Development of this system is approaching the field demonstration stage.

The first phase of a project to investigate the effect on rock permeability of drilling mud invasion has been completed at Terra Tek. Cores from geothermal wells in the Imperial Valley have been exposed to different muds under simulated downhole conditions. These tests have indicated that permeability impairment is strongly dependent on temperature, and that more impairment occurs at 100°C (212°F) than at 200°C (392°F) for sepiolite-based muds. Further studies are in progress.

Lost Circulation Control Methods

A study to determine the geological characteristics of lost circulation zones has been completed. The primary objective of the study was to try to identify one or more parameters that could be used to predict with a high degree of accuracy those zones where lost circulation would be expected to occur. Insufficient data are available to correlate lost circulation with geological sequence. The study has pointed out the need for tools and field tests that would lead to the characterization of these zones.

Another study has been initiated to catalog the tools that can be used for mapping lost circulation zones and to assess their performance potential under high-temperature conditions. This study will identify development needs in this area.

In addition, provisions are being made for laboratory testing of commonly used lost circulation materials under high-temperature conditions. The cement testing facility is designed to accommodate lost circulation materials. Screening tests using this facility will provide a basis for initiating development of new lost circulation control materials, if needed.

Advanced Drilling Systems

An industry-wide workshop was sponsored by DOE and Sandia National Laboratories in January of 1979 to define an approach to developing an advanced drilling system that would provide for increases in penetration rates by factors of 5 to 10 over those currently being obtained with conventional rotary techniques. This workshop recommended[1] that three systems be investigated. These systems are: (1) systems using high-speed downhole motors, (2) high-pressure jet drilling systems, and (3) percussion drilling systems.

The primary limitation on turbodrill performance in the geothermal environment is the failure of the bearing and seal package at high temperature. To address this problem, a facility for testing downhole motor bearing and seal packages under simulated downhole conditions has been completed at the Drilling Research Laboratory. The facility permits the testing of candidate bearing/seal packages with full-scale motors at simulated downhole conditions of 300°C (572°F) and 34.5 MPa (5,000 psi). Design parameters include a differential pressure across the bearing/seal package of 0 to 13.8 MPa (0 to 2,000 psi), a flow rate of 0.006 to 0.013 m^3/s (100 to 200 gal/min), a rotational speed of 100 to 1,000 rpm, and a dynamic load to 267,000 kN (60,000 lb). The facility is currently in use in a project to improve downhole motor bearings and seals. New seal designs are being developed with a goal of achieving a 200-hour lifetime at a circulating temperature of 125°C (257°F). To date, a 45-hour seal lifetime has been obtained with elastomeric seals. Current emphasis is on metal-to-metal face seals.

Work on high-pressure jet drilling is centered around the concept of cavitating-jet nozzles. Hydronautics, Inc., has conducted laboratory tests to establish the design parameters for a cavitating-type jet nozzle using drilling mud as an erosion medium. The experimental program established the feasibility of utilizing cavitating jets to drill deep holes for geothermal and petroleum extraction. The results indicated that cavities can be formed under high ambient pressures. Once formed, these cavities have a rock damage potential which increases as the third power of borehole pressure, and rock-cutting rates increase approximately as the third power of nozzle pressure drop. It was further shown that the use of drilling mud imposes no adverse effects upon jet performance. These results led to the conclusion that cavitating jets can potentially be used in conjunction with mechanical bits to drill deep holes at increased penetration rates with existing rigs and hydraulic equipment. A follow-on project to optimize cavitating-jet nozzle design has been initiated. In addition, an engineering design study has been initiated on a downhole intensifier to assess the feasibility of using this concept rather than high-pressure surface equipment to supply the required pressure. A systems study to assess the overall cost/benefit ratio of high-pressure jet drilling systems is also under way.

The scope of the percussion drilling system evaluation is currently limited to laboratory and field testing of commercially available hammers to determine performance parameters and high-temperature failure modes. Laboratory tests to evaluate percussion drilling equipment have been conducted. The tests measured penetration rate and hammer life at temperatures of 177°C (350°F). The penetration tests were conducted in Sierra white granite. The tests compared a conventional tricone insert bit without hammer, two "oil field" hammers with the same tricone bit, and three different "industrial" hammers with solid bits. The oil field hammers drilled faster than the conventional rotary equipment, particularly at low bit weights, and the hammers with solid bits drilled 21.3 m/h (70 ft/h), much faster than conventional rotary equipment operating at realistic load. The industrial hammers were run at 177°C (350°F) and did not survive an hour of drilling at this temperature. The failure modes involved plastic parts in the hammers' air valving mechanisms, and these parts are currently being redesigned in metal for further testing.

Supporting Technology

A computer model, GEOTEMP, for predicting the temperatures of borehole fluids and downhole equipment under real-time, flowing conditions has been formulated, documented, and verified. The model analyzes single-phase flow during drilling, production, or injection. The undisturbed geothermal temperature gradient must be specified. Validation of the model involved comparison of computer predictions with actual field measurements of temperature in oil, gas, and geothermal wells. The model is now commercially available and is being used by several private companies. The model is being modified to predict temperatures for single-phase, compressible flow under transient wellbore conditions.

Development of an operations-based model for analyzing the effects of improved technology on well costs has been completed. The model has been used to predict the percentage reduction in well cost obtainable with improved penetration rates. Other technological improvements are currently being evaluated by use of the model.

Corrosion fatigue studies of conventional drill pipe steels and of new dual-phase steels in an H_2S environment are in progress with the objective of identifying alloy compositions that minimize corrosion in the geothermal environment.

A laboratory facility using flow visualization techniques for optimizing drill bit hydraulics has been designed and fabricated. Experiments will be initiated in FY 1981.

A computer model for calculating the stresses induced in drag-type cutters and for modeling the tool/rock interaction has been developed and applied to the use of PDC cutters. The model is a finite element code called TOODY, which has been used extensively in predicting shock wave propagation. Use of the code is continuing for calculating tool forces as a function of rake angle and rock type.

Reference

1. Varnado, S. G., "Report of the Workshop on Advanced Geothermal Drilling and Completion Systems," Sandia Laboratories Report No. SAND79-1195, June 1979.

DISTRIBUTION:
TID-4500-R66-UC-66c (675)

Department of Energy (10)
Division of Geothermal Energy
Mail Station 3344
12th & Penn, NW
Federal Building
Washington, D.C. 20461
Attn: C. McFarland
C. Carwile (2)
M. Skalka
A. Jelacic
R. Toms
R. R. Reeber
J. Salisbury
R. Black
M. Scheve

Department of Energy (5)
Office of Oil, Gas, and Shale Technology
Mail Station D107
Washington, D.C. 20545
Attn: J. Smith
M. Adams
B. Dibona
D. Duke
A. Sikri

Amoco Production Company
Research Center
P.O. Box 591
Tulsa, Oklahoma 74102
Attn: B. Wilder

Dresser Industries, Inc.
P.O. Box 24647
Dallas, Texas 75224
Attn: J. W. Langford

Dyna-Drill
P.O. Box C19576
Irvine, California 92713
Attn: Larry Diamond

Halliburton
Drawer 1413
Duncan, Oklahoma 73533
Attn: Dwight Smith

Loffland Brothers Company
P.O. Box 2847
Tulsa, Oklahoma 74101
Attn: H. E. Mallory

DISTRIBUTION (Continued)

Los Alamos National Laboratory
Mail Stop 570
Los Alamos, New Mexico 87545
Attn: John C. Rowley

Mobil Research and Development Corporation
Field Research Laboratory
P.O. Box 900
Dallas, Texas 75221
Attn: W. Gravley

NL Baroid Petroleum Services
City Centre Building, Suite 365W
6400 Uptown Boulevard
Albuquerque, New Mexico 87110
Attn: Gene Polk

NL Petroleum Services
P.O. Box 1473
Houston, Texas 77001
Attn: J. Fontenot

Otis
P.O. Box 34380
Dallas, Texas 75243
Attn: W. D. Rumbaugh

Phillips Petroleum Company
P.O. Box 239
Salt Lake City, Utah 84110
Attn: Earl Hoff

Smith Tool Company
P.O. Box C-19511
Irvine, California 92713
Attn: J. Vincent

Texas A&M University
College Station, Texas 77843
Attn: M. Friedman
Dept. of Geology

Union Geothermal Division
Union Oil Company of California
Union Oil Center
Los Angeles, California 90017
Attn: D. E. Pyle

Shell Oil Co.
Two Shell Plaza
P.O. Box 2099
Houston, Texas 77001
Attn: W. E. Bingman

DISTRIBUTION (Continued)

400	C. Winter
1000	G. A. Fowler
2000	E. D. Reed
2300	J. C. King
2500	J. C. Crawford
4000	A. Narath
4200	G. Yonas
4300	R. L. Peurifoy, Jr.
4400	A. W. Snyder
4500	E. H. Beckner
4700	J. H. Scott
4710	G. E. Brandvold
4730	
4740	R. K. Traeger
4741	J. R. Kelsey (25)
4742	A. F. Veneruso
4743	H. C. Hardee
4746	B. Granoff
4747	
4748	B. E. Bader
4750	V. L. Dugan
4751	J. R. Tillerson
4756	H. M. Dodd
5000	J. K. Galt
5600	D. B. Schuster
5620	M. M. Newsom
5800	R. S. Claassen
3141	T. L. Werner (5)
3151	W. L. Garner (3)
8266	E. A. Aas

☆U.S. GOVERNMENT PRINTING OFFICE: 1981-0-777-023/556