SAND77-1630

Unlimited Release

Geothermal Well Technology Drilling and Completions Program Plan

Melvin M. Newsom, Jon H. Barnett, Leonard E. Baker, Samuel G. Varnado, Joseph Polito

Sandia Laboratories

energy report

DISCLAIMER

DISCLAIMER

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

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $4.50
Microfiche $3.00

GEOTHERMAL WELL TECHNOLOGY

DRILLING AND COMPLETION PROGRAM PLAN*

SAND77-1630

March 1978

M. M. Newsom
J. H. Barnette
L. E. Baker

Drilling Projects Division - 5735

S. G. Varnado
J. Polito

Systems Analysis Division - 5742

Abstract

The Drilling and Completion portion of the long-range Geothermal Well Technology Program is presented. A nine-year program is outlined based upon an objective of reducing the cost of geothermal energy development and providing a major stimulus to meeting the power-on-line goals established by the Department of Energy. Major technological challenges to be addressed in this program include improvements in geothermal drilling fluids, downhole drilling motors, rock bits and the development of high flow rate, high temperature completion and reinjection techniques. In addition, fundamental studies will be conducted in drilling energetics to improve the understanding of drilling mechanics. This will lead to advanced development of high performance, low cost geothermal drilling systems. This program plan has been prepared for the Division of Geothermal Energy of the Department of Energy.

*This work was supported by the United States Department of Energy.

Table of Contents

Figure Captions

Tables

GEOTHERMAL WELL TECHNOLOGY
DRILLING AND COMPLETION PROGRAM PLAN

SAND77-1630

I. THE GEOTHERMAL WELL TECHNOLOGY PROGRAM

A. The Role of Well Technology in the Geothermal Energy Program

The power-on-line goals of the National Geothermal Energy Program are 3,000 MW_e by 1985 and 20,000 MW_e by the year 2000.[1] To meet these goals, it is estimated[2] that 8,000 new geothermal wells will be required by 1990 (see Table I). Furthermore, it is estimated that between 30 and 70% (depending on reservoir temperature and conversion cycle) of the cost of geothermally generated electric power will result directly from the cost of drilling and completing these geothermal wells. Electricity generated from many of the geothermal prospects which are projected to contribute to the 1985 goal is expected to be marginally competitive with power from other sources. This is due in part to high well cost. Reductions in geothermal drilling costs will have direct impact on both the amount and the rate of geothermal energy development because reduced well costs will result in significant reductions in the cost of exploratory and development drilling and in the cost of power generated by the geothermal plant. As the cost of geothermally generated power becomes more economically attractive, risk capital for development will become more available and utilities will accelerate their capital investments in geothermal power. Also, the need for large cash flows in the early stages of the development cycle will be reduced and thus make a more aggressive exploration program possible.

The cost of drilling and completing geothermal wells is presently two to four times[3,4,5] that of comparable oil/gas wells of the same depth, and larger diameter holes are frequently used to achieve acceptable flow rates in geothermal wells.

Table I. Estimated Number of Wells Required in the National Geothermal Energy Program[2]

Prospect	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	Total
Geysers (steam)	74	51	79	55	66	44	22	23	23	23	23	23	23	529
Brazoria	0	0	0	10	0	0	35	5	126	126	250	254	262	1068
Salton Sea	0	0	0	12	5	19	16	17	21	22	23	24	25	184
Valles Caldera	0	0	0	16	5	1	38	1	40	8	42	42	44	237
Brady	5	0	0	22	5	2	29	2	53	9	56	56	59	298
Brawley	0	0	0	15	0	16	6	27	27	28	29	30	31	209
Roosevelt	0	0	0	13	5	1	19	1	20	7	34	34	35	169
Beowawe	5	0	0	16	5	1	22	1	23	7	40	40	42	202
Coso	0	0	10	0	5	25	25	26	67	63	67	11	15	314
Mono-Long Valley	0	0	10	0	0	25	0	41	6	4	44	4	7	141
Cove Fort Sulfurdale	0	0	10	0	0	24	0	25	6	26	26	46	47	210
Heber	0	0	0	0	0	28	0	30	7	55	55	58	61	294
Geysers (hydro)	0	0	5	0	5	45	45	48	51	54	57	60	63	433
East Mesa	0	0	0	0	0	27	5	2	29	2	4	4	4	77
Steamboat	0	0	10	0	0	23	5	2	30	2	50	4	7	133
Surprise Valley	0	0	0	10	0	0	35	5	37	67	69	73	77	373
Chandler	0	0	0	10	0	0	28	0	7	7	58	30	6	146
Leach	0	0	0	0	10	0	0	34	5	7	41	75	77	249
Calcasieu Parrish	0	0	0	0	10	0	0	60	5	7	67	67	124	340
Bruneau-Grandview	0	0	0	0	10	0	0	19	5	6	44	44	47	175
Lassen	0	0	0	0	10	0	0	16	5	1	17	1	2	52
Kenedy County	0	0	0	0	10	0	0	60	5	7	67	67	69	285
Alvord	0	0	0	0	10	0	0	19	5	6	25	25	26	116
Matagorda	0	0	0	0	10	0	0	60	5	7	67	67	69	285
Cameron	0	0	0	0	10	0	0	60	5	7	67	67	69	285
Acadia	0	0	0	0	10	0	0	60	5	7	67	67	69	285
Corpus Christi	0	0	0	0	10	0	0	60	5	7	67	67	69	285
Safford	0	0	0	0	10	0	0	19	0	1	1	1	1	33
Weiser/Crane Creek	0	0	0	0	0	10	0	0	47	5	92	92	98	344
Vale	0	0	0	0	0	10	0	0	47	5	50	50	53	215
Thermo	0	0	0	0	0	10	0	0	19	0	6	6	44	85
Raft River	0	0	0	0	0	5	0	0	81	0	82	6	12	186
Glass Mountain	0	0	0	0	0	0	0	10	0	0	24	0	2	36
Hawaii	0	0	0	0	0	0	0	10	0	5	29	53	55	152
Mt. Hood	0	0	0	0	0	0	0	10	0	0	72	0	5	87
Cascades	0	0	0	0	0	0	0	10	0	0	38	0	3	51
W. Yellowstone	0	0	0	0	0	0	0	10	0	0	72	0	5	87
Total	84	51	124	179	211	316	330	773	817	588	1922	1548	1707	8650

These high costs are due primarily to the degraded performances of standard petroleum drilling methods, materials and tools when applied in the geothermal environment. The high temperatures of the rock formation and the corrosive nature of many geothermal formation fluids lead to conditions which exceed the design limitations of current drilling equipment.[6,7] In addition, the producing zones of most geothermal reservoirs are composed of thermally altered, fractured hard rock which leads to slow and therefore expensive drilling.

Unfortunately, temperature and corrosion problems affect all aspects of well drilling and completion. Virtually all equipment exposed to geothermal borehole conditions displays degraded performance. It will be necessary to develop improved designs with new materials capable of operating in these harsh environments in order to reduce the cost of geothermal wells.

Certain aspects of the lithology and location of geothermal reservoirs also contribute to the high costs of drilling and completion. Geothermal reservoirs frequently exist in hard, highly fractured, metamorphic and igneous rocks. Drilling of these formations is difficult and slow. Well sites are often located in remote areas with very difficult terrain, where site preparation and transportation costs are very high. In addition, environmental concerns have increased the difficulty of obtaining drilling permits. The problems of site location and environmental concerns have increased the practice of drilling several wells from a single location. The wells are directionally drilled to provide adequate separation in the reservoir. Improvements in directional drilling techniques for geothermal environments are necessary to realize the full benefit of the cost savings that can accrue from this technique.

The Geothermal Well Technology Program is an essential part of the overall DGE effort to develop national geothermal resources. Since drilling and completion costs account for a substantial portion of the cost of on-line generating capacity, reductions in the cost of geothermal wells will have strong impact in increasing the development of geothermal energy.

Furthermore, the scientific and engineering resources are available now to effect a substantial reduction in these important costs.

B. Approach to Program Implementation

1. Program Objective

The objective of this program is to develop and commercialize the technology required to reduce the cost of drilling and completing geothermal wells. An analysis of existing geothermal well cost data indicates that technological improvements, such as higher penetration rate, longer life rock bits, higher temperature drilling fluids, improved completion techniques and improved directional drilling techniques, have the potential for reducing the cost of geothermal wells drilled with conventional rotary technology by approximately 25%. (See Appendix A for an example of how technological improvements can reduce well costs.) Further cost reductions will require the use of new drilling techniques, e.g., water jet drilling, downhole motors with flexible tubing, etc. Research in these and other novel methods is presently underway, and the successful implementation of new techniques could reduce well costs by as much as 50%. Based on these facts, cost reduction goals of 25% by 1982 and 50% by 1986 (in constant 1977 dollars) have been set for this program. Achievement of these goals will provide a substantial contribution to DOE's geothermal power-on-line goals.

2. Program Approach

The desired approach in this program is to define goal-oriented research tasks and to relate the expected reduction in geothermal well cost to each goal. For example, a determination of the reduction in geothermal well cost attributable to improved penetration rates can be used to set research goals for development of improved bits and downhole motors. At the present time, insufficient data is available to allow this quantification for all reservoir types and for all potential development tasks. This leads to a requirement for systems studies in the early phases of this program to establish a framework for assessing the impact of technological improvements on well cost. Concurrently, research tasks with well known potential, such as improved penetration rate, will be initiated.

Development strategy for this program, therefore, calls for the following:

a) Studies to identify those areas of geothermal well technology in which improvements can lead to significant cost reductions

b) Systems analyses to determine the cost/benefit ratio of improvements in each identifiable area as an aid to establishing goals and planning the program

c) Research, development and testing necessary to achieve program goals

d) Commercialization of new technology through industrial participation in all phases of the program.

3. Areas of Potential Cost Reduction

The total cost of drilling and completing a geothermal well consists of a number of factors, but the single largest contributor is the payment to the drilling contractor. This cost is determined by the amount of time the rig is on location and generally ranges from 20 to 40% of the total well cost. Approximately one-half of this time is spent in actual drilling. The cost incurred while drilling, i.e., the footage cost, can be reduced by technological improvements in bit and rig design that increase the instantaneous penetration rate, extend bit life and reduce overall drilling time.

Charges also accrue during times when the rig is on location, but no drilling. This non-rotating time is spent in running casing, fishing for lost tools or pipe, waiting on cement, etc. Reductions in the cost of the rig time and services associated with non-rotating activities are possible through the development of more efficient completion methods and improved fluids and cementing procedures which will reduce the likelihood of failures in the well.

Other factors which contribute to well cost include site preparation, cementing and logging services, transportation, equipment rental, and completion costs.

Areas where technological improvements can potentially contribute to cost reduction are discussed below.

a) Drill Bits

The effectiveness and useful life of conventional rock bits is reduced by several high temperature effects. Elastomers are frequently used to seal lubricated bearings in rock bits. Under high temperature and pressures these rubber or rubber-like substances become brittle or disintegrate. As a result, unsealed bearings that are lubricated only by the drilling fluid are often employed in geothermal wells. Such bits have reduced life due to excessive bearing wear caused by solids in the drilling fluid. These factors combine to reduce the useful life of the bits.

Diamond bits provide a partial solution to these problems, but they are expensive and their rate of penetration is low. Degraded bit performance increases rotating rig costs by extending the time required to drill the well. A reliable, long-lived, rock bit capable of high penetration rates in hard rock at geothermal temperatures is needed to reduce well costs.

b) Drilling Fluids

New bit development is an important part of this program; however, programmatic goals cannot be achieved by reductions in rotating time (time spent actually drilling) alone. Reductions in other areas must also be achieved. Non-rotating rig time is a necessary part of drilling and completing a well. However, this time and the resultant cost can become excessive when problems are encountered during drilling and completion operations. These problems include fishing operations, sticking drill pipe and well control difficulties. In many geothermal wells, problems of this type can be traced directly to the lack of a suitable high temperature drilling fluid. Drilling fluids lubricate and clean the rock bit, carry cuttings to the surface and control formation pressures. Conventional drilling muds have the undesirable property of thickening and solidifying when heated to geothermal temperatures. This effect is particularly pronounced when circulation is stopped for bit changes and for logging. The drill string may stick or logging tools fail to descend when this occurs. Furthermore, lubricating and anti-corrosion additives, which are sometimes added to the mud, often lose their effectiveness at high temperatures. Failure of the mud to perform properly can result in secondary failures which may be very expensive to correct, e.g., drill stem twist-off and lost tools. These secondary failures are major contributors to non-rotating rig costs and often require extensive and expensive specialized services to correct. Also, expensive delays occur if the complete mud system must be replenished. It has been estimated that fluids and fluid related problems may comprise up to 30%[8] of the cost of a geothermal well.

An additional fluid related problem in some geothermal reservoirs is that conventional drilling fluids may severely impair the flow in production zones. Suspended solids in the mud that are designed to prevent lost circulation can filter into highly permeable, low pressure zones. This filtration can, under high temperature conditions, result in filter cake buildup that severely limits production of the geothermal well. In these cases aerated drilling fluids are used.

Air drilling is effective in competent formations but produces erosion of the drill string from cuttings traveling up the annulus at sonic speed. Higher rotating costs are incurred due to frequent inspection, replacement and erosion treatment of the drill pipe. In addition, formation pressures are difficult to control with air. Water is an attractive alternative in some cases, but it can become contaminated by dissolved gases and solids and can flash to steam unless cooling towers or other methods are employed to reduce its temperature.

Based on these observations, it appears that improvements in high temperature drilling fluids can be effective in reducing overall well cost. This topic will therefore be addressed in this program.

c) Downhole Motors

In many instances, well sites are located in remote areas in rugged terrain. This usually results in very high site preparation costs. In addition, environmental concerns increase the difficulty and cost of obtaining drilling permits. These facts encourage the drilling of multiple wells from one location. Accurate directional drilling is required to effect multiple completions from the same location and can result in lower overall well cost. In the long-term, improved, high horsepower, downhole motors with bits designed for high speed operation offer the potential for both directional and straighthole drilling improvements. The power applied to the rock face with current rotary technology is limited to about 40 horsepower. Advanced motors and bits should allow the applied power to be significantly increased with a corresponding reduction in time and costs. In addition, many geothermal formations are highly fractured and considerable directional drilling is required to correct deviations. Present downhole motors utilize elastomeric materials for both seals and major structural members. These materials degrade severely at high temperature. In addition, the high rotational speed of these motors is not compatible with conventional roller cone bits. Diamond bits with their slower penetration rates are often used. Directional drilling in the geothermal environment is therefore presently characterized by frequent tripping out to repair the motor, change the bit, and survey the hole. All add to drilling cost. Improved designs for downhole motors and bits have the potential for substantially reducing the cost of both directional and straighthole geothermal drilling.

d) Well Completions

The requirements and techniques for completing geothermal wells vary substantially with reservoir type. However, virtually all geothermal wells require some casing and cementing. Cements tend to set up quickly at geothermal temperatures. Retardants are added to increase the set-up time. The proper amount of retardant is dependent upon the borehole temperature. Unfortunately, it is difficult to accurately predict the proper amount of retardant to use. Early cement set-up can result in very expensive squeezing operations. Conversely, the use of too much retardant can delay or even preclude the setting up of the cement. In either case, delays and added expense are the result. Research directed at improving high temperature cementing techniques can be effective in reducing completion costs.

In some reservoirs, particularly the geopressured zones, extremely high flow rates are required for economic viability. These rates can result in high sand production. In hydrothermal reservoirs, severe scaling may occur if geothermal fluids flash to steam in the wellbore. In either case, frequent reworking of the well may be required to maintain a sufficient flow rate. It is therefore important to consider the life cycle cost of completing the well and to design the completion to minimize this cost.

Disposal of geothermal fluids after energy extraction is usually accomplished by using reinjection wells. These wells are also subject to sanding, scaling and rework problems. To reduce the cost of geothermal wells, these problems must also be defined, assessed and solved.

Finally, stimulation techniques such as fracturing may be required in some cases to achieve economically acceptable flow rates. These techniques will require the development of packers which can operate at high temperatures for extended periods. Materials developments in the DOE/DGE Geochemical Engineering Program are expected to contribute substantially to the design of this equipment.

e) Advanced Drilling Techniques

Several novel or advanced drilling methods have been proposed over the past several years.[7] For example, electric sparks, electron beams, water jets, and projectiles have all been proposed for drilling in hard rock. Some of these novel techniques have the potential for increasing penetration rate and for utilizing smaller, less expensive rigs; however, problems exist in the implementation of many of these ideas in an actual field environment. Investigations of at least two of these approaches will be conducted in the Well Technology Program; namely, water jet drilling and drilling with high horsepower downhole motors in straight hole applications. Both these approaches offer the potential for increased penetration rates and, therefore, lower well cost. In addition, it may be possible to use less expensive rigs with these two approaches. As other novel techniques are suggested or discovered, it will be necessary to evaluate the technical and economic feasibility of these approaches. An understanding of basic rock mechanics will be required to properly assess the technical feasibility of new concepts. For this reason, a research program in rock mechanics, as it relates to the drilling operations, will be initiated. The thrust of this program will be to develop an understanding of the energetics of removing rock. Practical applications of this research are expected to yield new techniques for drilling that are less expensive than conventional rotary techniques.

4. Procedure for Defining R&D Tasks

As outlined in the previous section, there are several areas in which technological improvements will yield reduced geothermal well cost. As a result, many research tasks can be proposed which will contribute to the overall goals. However, resource limitations dictate that those research tasks that have the potential for achieving significant, near-term reductions in well costs be identified and receive primary emphasis in terms of resource allocation. The participation of the DOE/DGE Mission Team Leaders and of private industry in the identification of these tasks will be encouraged. In addition, analytical models will be developed and used to evaluate the relative merits of alternative proposals and designs.

Close communication between the DOE/DGE Mission Team Leaders and the Drilling and Completions Program Manager will be maintained to insure that any unique regional drilling requirements are addressed in the Drilling and Completions Program. The Department of Energy field program provides a unique opportunity to test new hardware developed under the Drilling and Completions Program. Suggestions for R&D tasks will be solicited from the Mission Team Leaders at the outset of the Drilling and Completions Program and a continuing interaction between the two programs will be maintained.

Industrial participation in the identification of research tasks is an important part of the program strategy. Inputs are being solicited from the Geothermal Well Technology Panel, which is comprised of drilling equipment manufacturers, drilling contractors, service companies, operating companies and laboratory and Government representatives. This panel, which was formed to oversee this program, will be convened periodically to review the elements of the Well Technology Program, to suggest areas where further research is needed and to advise of program priorities. This joint industrial/Government involvement will encourage the rapid commercialization of new technology.

Finally, technology-based cost sensitivity models will be developed in order to provide a decision framework for allocating resources among the various program tasks. Suggested research topics will be analyzed from the standpoint of cost/benefit ratio to insure that all funded tasks will contribute to programmatic goals. This model may also be useful to Mission Team Leaders in predicting funding requirements for ensuing years for their field drilling programs.

Some of the technical issues which will be addressed in geothermal well technology are shown in Figure 1, along with the task identification strategy. Many of the issues are inter-related, e.g., improvements in elastomer performance at high temperature may result in improved bit life; bit design is influenced by the drilling fluid, etc. The cost sensitivity model will aid in assessing these interrelationships and the sensitivity of total well cost to each issue. The impact of the successful completion of a proposed task on the total well cost will be assessed using the cost sensitivity models. Continuing discussion between the Mission Team Leaders, the Geothermal Well Technology Panel and the Sandia Program Manager will assure that the proper research plan is established, reviewed, updated and followed. It should be emphasized that the cost sensitivities may be different for a given task in different reservoir types. Hence, it is important that information transfer between the Sandia Program Manager and the Mission Team Leaders be performed in a timely manner.

It is also important that close communication be maintained with the DOE/DGE Geochemical Engineering Program. This program is developing high temperature materials that will be extremely useful in the design of high temperature bits, downhole motors, packers and blowout preventers. The Drilling and Completions Program will assume the responsibility for field testing of the new materials as they emerge.

5. Program Implementation

Implementation of the research tasks that are identified will be primarily through contracts with private industry and universities. However, supporting in-house research will be conducted when appropriate.

Contracts will usually be awarded on a competitive basis, and activities involving joint funding by Government and private industry will be encouraged. Jointly funded programs are desirable because the Government funds are leveraged by industry funds. In addition, past experience indicates that

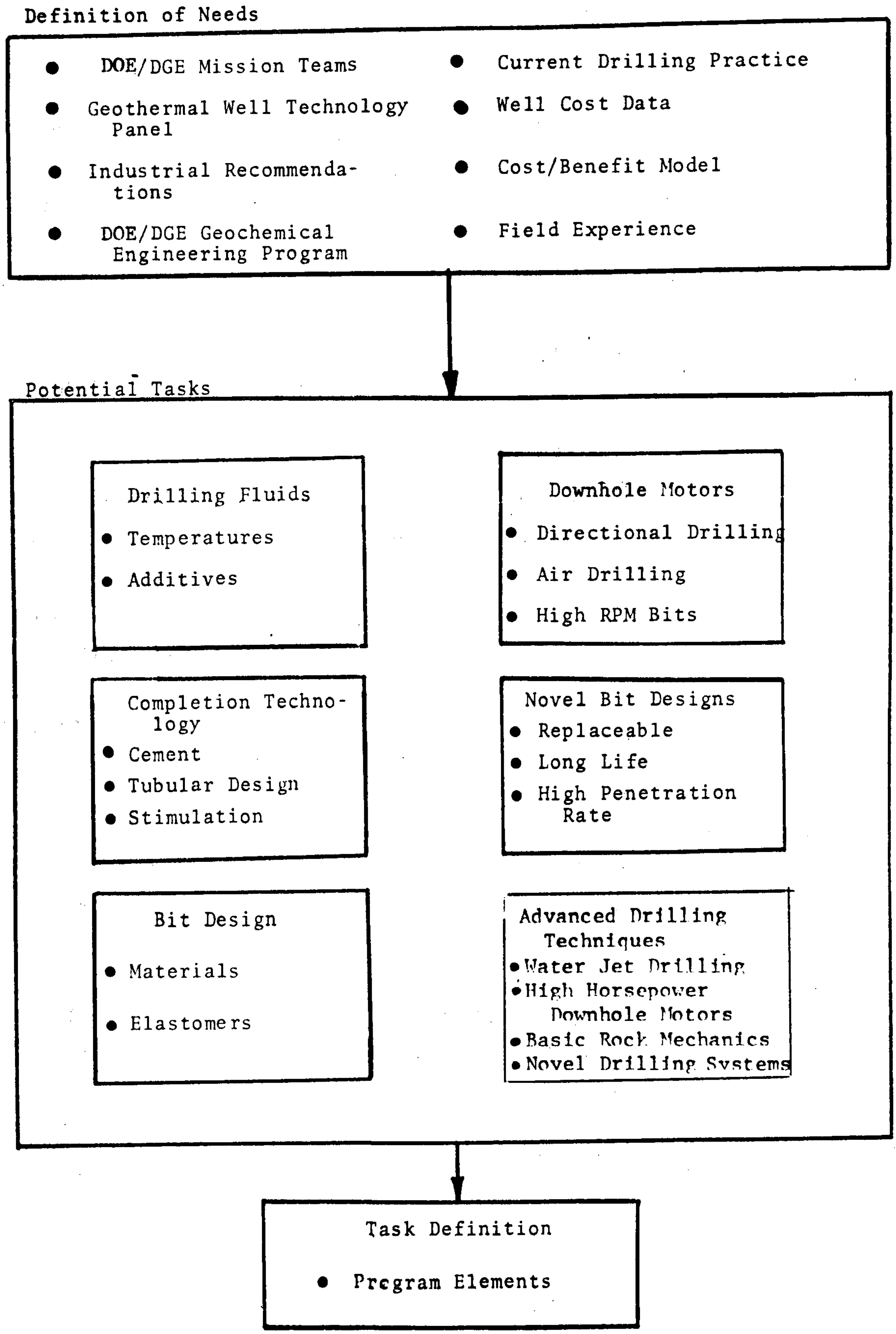

Figure 1. Task identification strategy

the drilling service companies are more willing to work on this basis since their current patents are not jeopardized. The new technology will be commercialized quickly by the company involved in the development. In the university sponsored work, Sandia will provide the interface between the university and industry to assure that the results are made available to the drilling industry in a timely manner.

The question of patent rights is a major impediment to active industry participation in the DOE/DGE technology program. Industry is reluctant to accept Government funds for development work if the company's competitive position might be jeopardized by public disclosure. In some cases it may be necessary to grant exclusive patent rights to participating companies. Contractual arrangements which allow private industry to participate in joint research programs while not compromising their competitive position will be sought. This strategy is designed to involve industry to the fullest extent in technology development so that commercialization of new technology is encouraged.

Rapid commercialization is necessary to achieve the goals of the program. Industry acceptance of new techniques is predicated on the proven reliability and economic benefit of the technique. It is necessary, therefore, to thoroughly demonstrate the technical and economic viability of new concepts. Toward this end, laboratory and field testing programs will be an integral part of the Drilling and Completions Program. New concepts will first be tested under laboratory conditions; industrial involvement in follow-on field tests will then be encouraged. Operating companies, drilling contractors, equipment manufacturers and service companies will be encouraged to observe, participate, evaluate and comment on these tests. In addition, test results and major program developments will be made available through publication in the open literature and presentations at technical meetings.

C. Milestone Schedule and Budget

An estimate of the level of effort required to reach the program goals, major program elements and cost are presented in this section. These estimates are preliminary and will be reviewed and updated as the well cost data base and cost sensitivity analysis programs evolve. It is estimated that a concentrated effort will be required over a nine-year period to reach the goals of the Drilling and Completion Program.

The projected budget and milestones are presented in two levels. Level A represents a minimum program budget while Level B represents the enhanced budget. With Level A funding, the primary program thrust will be directed at making improvements in conventional rotary drilling. It should be possible to achieve the 25% cost reduction goal at this level of effort but funds would not be available to investigate and develop the more advanced technology necessary to reach the 50% cost reduction goal. In addition, the timing required to reach the 25% cost reduction goal would slip approximately one year to 1983. The major program milestones for the minimum budget are presented in Figure 2, and the annual funding required to support this program is presented in Figure 3. During FY-78, a goals-oriented program plan will be formulated to illustrate the approach that will be taken to reach the 25% cost reduction. This plan, which will be developed as the drilling and completion model evolves, will provide the rationale for program element selection and also provide a means for measuring the progress of the program vs the projected milestones.

Level B funding will provide the resources necessary to reach the total program goals of 25% well cost reduction by 1982 and 50% cost reduction by 1986. The major program milestones are presented in Figure 4 and the annual funding required to support this program is presented in Figure 5. The major new areas that will be pursued in the enhanced program include the initiation of basic drilling energetics studies and advanced systems development in FY-79. The thrust of the basic work will be to determine the most efficient, reliable mode of rock

Level A - Minimum Program

Program Element	FY-78	FY-79	FY-80	FY-81	FY-82	FY-83	FY-84	FY-85	FY-86
1. High Performance Rock Bits									
a. Continuous Chain Drill	● 7	16	19						
b. Geothermal Bit	●	15	20	19					
c. Compax Drill Bit	● 8	12	19						
d. 3rd Generation Bits					●		34		19
2. Downhole Motors									
a. Bearing & Seal Package	● 2 9	13	18	19					
b. High Temp Directional System		●		24		30		19	
3. Geothermal Drilling Fluids									
a. High Temperature Muds	● 3		21				19		
b. Fluid Research Inst.	●	17							
c. Advanced Test Facilities	● 4	14							
d. High Temp Foams	● 10			27		33			19
4. Geothermal Well Completions									
a. State-of-the-Art Study	● 5								
b. High Flow Sand Control	●			25	28		35		19
c. High Flow Reinjection	●			23		31		19	
d. High Temp Packers	●			22	29			19	
e. Workover Technology	●				26		32		19
5. Management Planning									
a. Long-Range Plan Developed	1	11	11	11	11	11	11		
b. Well Cost Sensitivity Model	● 6								

Milestone Keys

1. Long-range program plan approved by DOE/DGE
2. Lab test of seal and bearing package
3. Fluid development plan completed
4. High temperature fluid test loop operational
5. Completions state-of-the-art study completed. Program formulated.
6. Second stage well cost sensitivity model completed
7. Field test of prototype chain bit
8. Field test of Mod I Compax bit
9. Mod II bearing and seal package tested
10. State-of-the-art study completed. Program formulated.
11. LRP updated
12. Field test of Mod II Compax bit
13. Motor lab test completed
14. Fluid test loop commercialized
15. Field test of sealed bit
16. Field test of Mod II bits
17. Laboratory equipment completed for high temperature work
18. Field test of motor bearing and seal package
19. Program complete
20. Testing of second generation bit completed
21. Phase I geothermal fluids field tested
22. Laboratory test -- high temperature packers
23. High flow rate reinjection system tested in DOE well
24. Initial lab testing of directional system
25. High flow rate completions tested in DOE well
26. Preliminary field testing workover system in DOE wells
27. Initial field test of stable high temperature foams
28. High flow rate completions tested in industry wells
29. Field testing of Mod II packer designs
30. Field testing of directional system complete
31. High flow rate reinjection system jointly tested with industry
32. Field testing of workover system in industry wells
33. Field testing of Phase II foam systems
34. Field testing of third generation bits completed
35. Improved high flow rate completions tested in industry wells

Figure 2. Geothermal Drilling and Completions Program Milestone Schedule

Program Elements	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	Program Totals
1. High Performance Bits	1438	520	700	700	750	775	775	725	400	200	6983
2. Downhole Motors											
a. Directional Systems	883	500	600	700	750	850	850	800	500	200	6633
b. Straight Hole Systems	0	0	0	0	0	0	0	0	0	0	0
3. High Temperature Fluids	279	350	600	700	700	750	750	750	325	300	5504
4. Completions Technology											
a. Production Well Technology	85	150	400	450	400	425	425	425	400	300	3460
b. Reinjection Well Technology	0	100	350	350	400	425	425	425	400	300	3175
c. Workover Technology	0	0	200	250	300	325	325	325	275	300	2300
5. Basic Research and Advanced Drilling System Development											
a. Basic Drilling Mechanics	0	0	0	0	0	0	0	0	0	0	0
b. System Studies & Supporting Research	370	80	100	100	100	100	100	100	100	100	1250
c. Advanced System Development	550	0	0	0	0	0	0	0	0	0	550
6. Supporting Technology											
a. Management & Planning	78	300	350	400	400	400	450	450	450	450	3728
b. New Materials Applications	558	0	50	50	50	50	50	50	50	50	958
c. Field Testing Support	0	0	250	300	350	400	450	550	600	1000	3900
Total Obligations by Fiscal Year	4241	2000	3600	4000	4200	4500	4600	4600	3500	3200	38441

Figure 3. Geothermal Well Technology Drilling and Completions Program
Level A Obligations -- Minimum Budget

Program Element	FY-78	FY-79	FY-80	FY-81	FY-82	FY-83	[illegible]	[illegible]	[illegible]
1. High Performance Rock Bits									
a. Continuous Chain Drill	• — 7	16	20						
b. Geothermal Bit	•	15	21	20					
c. Compax Drill Bit	• 8	12	20						
d. High Speed Bit		•			33		44	20	
e. Hard Rock Core Bit			•		31		20		
f. Jet Augmented Diamond	•	17	20						
g. 3rd Generation Bits				•				49	20
2. Downhole Motors									
a. Bearing & Seal Package	•2 9	13	19	20					
b. High Temp Directional System	•				32		45	20	
c. Highpower Downhole Motors		•			33		46		20
3. Geothermal Drilling Fluids									
a. High Temperature Muds	•3		22			20			
b. Fluid Research Inst.	•	18							
c. Advanced Test Facilities	•4	14							
d. High Temp Foams	• 19			28		33			20
4. Geothermal Well Completions									
a. State-of-the-Art Study	•5								
b. High Flow Sand Control	•			24	34		47		20
c. Stimulation System		•			35			20	
d. High Flow Reinjection	•			25		39		20	
e. Cement Testing		•		29		40			20
f. High Temp Packers	•		23		36			20	
g. High Temp B. O. P.		•			37		48		20
h. Workover Technology	•			30		41		20	
5. Basic Research & Advanced Systems Development									
a. Basic Drilling Energetics Studies		•		26		42		20	
b. Advanced Systems Develop.		•		27		43		50	20
6. Management & Planning									
a. Long Range Plan Developed	1	11	11	11	11	11	11		
b. Well Cost Sensitivity Model	• 6								

Milestone Keys

1. Long-range program plan approved by DOE/DGE
2. Lab test of seal and bearing package
3. Fluid development plan completed
4. High temperature fluid test loop operational
5. Completions state-of-the-art study completed. Program formulated
6. Second stage well cost sensitivity model completed
7. Field test of prototype chain
8. Field test of Mod I Compax bit
9. Mod II bearing and seal package tested
10. State-of-the-art study completed. Program formulated.
11. LRP updated
12. Field test of Mod II Compax bit
13. Motor lab test completed
14. Fluid test loop commercialized
15. Field test of sealed bit
16. Field testing Mod II bits completed
17. Field testing of Mod I bit completed
18. Laboratory equipment completed for high temperature work
19. Field test of motor completed
20. Program completed
21. Testing of second generation bit completed
22. Phase I geothermal fluids field tested
23. Laboratory test -- high temperature packers
24. High flow rate completions tested in DOE well
25. High flow rate reinjection system tested in DOE well
26. Study of novel rock failure mechanism completed
27. Selection of optimum advanced drilling system made
28. Initial field test of stable high temperature foams
29. Polymer cements field tested
30. Field testing workover system
31. Hard rock coring system field tested
32. Initial lab testing of directional system
33. Laboratory testing completed
34. High flow rate completions tested in industry wells
35. Initial field test of geothermal stimulation systems
36. Field testing of Mod II packer designs
37. Laboratory test -- high temperature B. O. P.
38. Field testing of Phase II foam systems
39. High flow rate reinjection system jointly tested with industry
40. Polymer cements tested -- industry wells
41. Field testing of workover system in industry wells
42. Comparison of drilling system energetics completed
43. Laboratory test of advanced drilling system completed
44. Field test high speed bit with mud motors
45. Field testing of directional system complete
46. Field testing complete
47. Improved high flow rate [illegible] tested in industry wells
48. Field testing -- high temperature B. [illegible] P.
49. Field testing of third generation bits completed
50. Field testing of advanced [illegible] system complete

Figure 4. Geothermal Drilling and Completions Program Milestone Schedule
Level B -- Enhanced Program

Program Elements	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	Program Totals
1. High Performance Bits	1438	520	1000	1200	1200	1200	800	700	400	200	8658
2. Downhole Motors											
a. Directional Systems	883	500	700	750	750	850	850	800	500	200	6783
b. Straight Hole Systems	0	0	500	500	750	850	900	800	800	500	5600
3. High Temperature Fluids	279	350	600	700	700	750	750	750	325	300	5509
4. Completions Technology											
a. Production Well Technology	85	150	500	500	450	450	450	425	400	300	3710
b. Reinjection Well Technology	0	100	450	450	400	400	400	400	400	300	3300
c. Workover Technology	0	0	450	450	400	400	400	400	275	275	3050
5. Basic Research and Advanced Drilling System Development											
a. Basic Drilling Energetics Studies	0	0	300	350	350	300	200	100	100	0	1700
b. System Studies and Supporting Research	370	80	300	300	300	200	100	100	100	100	1950
c. Advanced Systems Development	550	0	1100	1100	1450	1750	1750	1800	2000	1000	12500
6. Supporting Technology											
a. Management & Planning	78	300	500	500	550	600	600	600	600	500	4828
b. New Materials Applications	558	0	500	500	400	300	200	200	100	100	2858
c. Field Testing Support	0	0	600	550	700	850	850	1000	1000	1000	6550
Total Obligations by Fiscal Year	4241	2000	7500	7850	8400	8900	8250	8078	7000	4775	66991

Figure 5. Geothermal Well Technology Drilling and Completions Program Level B Obligations -- Enhanced Budget

failure, evaluate the more promising new drilling techniques, select the leading contender, develop and transfer this system to the drilling industry. In addition, the development of a high horsepower downhole motor with a high speed bit will be pursued as an alternate to rotary for rapid, straight hole drilling. This system promises an intermediate step in major drilling cost reduction and could be very efficient in both soft and hard geothermal formations when combined with a flexible drill pipe system. The scope of the completions development program will also be expanded to include well stimulation and additional high temperature downhole tool development to improve geothermal completion techniques. The Level B funding will allow a more balanced program to be conducted pursuing both conventional rotary improvements and advanced techniques supported by the basic research programs. As in the Level A budget, a goals-oriented plan will be developed during FY-78 to outline the course that will be followed to reach the program goals.

Many of the program elements for FY-78 are extensions of present work that is underway on bits, motors and fluids. New starts in FY-78 are directed at the critically important completions, reinjection and workover areas. These program elements are presently being defined, will be contracted in FY-78 and will be accelerated in FY-79. New starts in FY-79 will include development of high temperature directional drilling systems, geothermal packers and other downhole tools. New work in FY-80 will include field testing of new high temperature cements and initiation of development of improved well control equipment.

It is anticipated that the Government investment can be leveraged by about a factor of two in joint industrial/DOE funded projects. Several cooperative programs are already underway with industry on an informal, cost-sharing basis. Prospects for additional cost sharing activities are good. Industry representatives have often expressed willingness to field test the new downhole tools being developed in this program. Initial field testing will be done, where possible, in DOE wells, with subsequent field demonstrations done in cooperation with industry in industry wells.

An adequate laboratory testing capability is a vital link in either level of this program. Downhole testing without laboratory backup is a high risk means of obtaining development data. The availability of a well instrumented, laboratory drilling environmental simulator is considered to be essential to the success of this effort. Test facilities that are available in this country will be investigated and inventoried and test requirements for downhole tools will be prepared. The options that are available for test facilities include upgrading of existing private or university laboratories, the creation of new facilities either in industry or in the universities, or creation of new facilities at DOE laboratories. The relative merits of these three approaches will be outlined as part of this investigation. Recommendations for upgraded or new facilities and the recommended locations of these facilities will be made to DGE as required.

D. Relationships to Other Programs

One function of the Geothermal Drilling and Completions Program is to demonstrate operational hardware that utilizes improved materials now under development for DGE's Geochemical Engineering Program. Work currently in progress in materials development is centered primarily on improved high temperature cements and high temperature elastomers. Both are critical areas in geothermal development and they must be rapidly moved to field application. High temperature cements are needed to assure reliable, cost effective completion of geothermal wells. The Drilling and Completions Program will assume responsibility for field evaluation of high temperature cements. It is anticipated that these cements will be used in industry drilled wells on a cost sharing basis assuming success of the development program now underway. This program will coordinate the effort in field testing.

High temperature elastomers are vitally needed in bit seals, motors, packers, logging instruments and other downhole tools. This program will insure that the latest materials are incorporated into all downhole hardware developed to assure meaningful evaluation and ultimate use of this new technology.

In addition, the Geothermal Drilling and Completions Program will closely follow the progress of any wells drilled for DOE. Where possible, this program will take advantage of opportunities to test hardware developments in DOE funded wells. These may present a unique opportunity to test new hardware, but this method of testing must be supplemented by demonstrations in commercially drilled wells.

Two additional interfaces are important to this program. These are the DOE/Division of Oil, Gas, Shale and In Situ Technology (DOGSIST) Drilling Technology Program and the proposed Continental Drilling Program. The thrust of the DOGSIST program is to develop drilling technology to support the frontier areas in oil and gas drilling. These areas would include deep sour gas land drilling as well as deep water drilling on the continental shelf. Many of the problems are common to those found in the geothermal program. 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.

Temperatures in deep gas drilling are often in the same range as those encountered in geothermal wells. High temperature borehole technology developments in this program can be directly applied to deep gas drilling. Corrosion control is another difficult problem in both geothermal and deep gas drilling. Progress in this program will assist the search for critically needed natural gas.

The technological demands of the Continental Drilling Program, if it is approved, are also similar to those of geothermal development. Deep, large diameter directional holes are needed at a modest price. High temperatures will be encountered in the deeper holes, and the proposed magma drilling experiment is clearly beyond the current state of the art. If the Continental Drilling Program is funded, it must be closely coordinated with the DGE Well Technology Program to select complementary areas for technology development support.

II. TECHNICAL PLAN

A. Approach

The drilling and completions portion of the Geothermal Well Technology Program will concentrate primarily on development of high temperature borehole hardware that will significantly reduce the cost of geothermal drilling. More specifically, three major areas of technology will be addressed:

1. Systems analysis that examines the components of well cost on a cost/benefit basis to assist in program planning and impact assessment,
2. Drilling technology development to speed the drilling process and reduce problems in high temperature wells, and
3. Well completions, workover and reinjection technology development to support reliable, long-life geothermal wells.

The primary measure of success in the drilling and completions portion of the Well Technology Program will be the degree to which emerging technology is commercialized for geothermal drilling and the resulting impact on well costs. The drilling industry must be involved in this program if it is to succeed.

Currently, the petroleum industry is not pursuing large-scale development programs in support of geothermal development because the near-term economic incentives are not sufficient to justify large expenditures for the special purpose tools required. The Drilling and Completions Program will concentrate on applying new materials and developing improved tools that can be directly commercialized by industry. It is intended that this will lead to increased activity in geothermal drilling and to sufficient incentives to stimulate continued industrial development.

Prototype geothermal drilling tools will be conceived, developed, tested and demonstrated in the course of this program. Most of the development work will be contracted to industry with Sandia and other laboratories supplying special technical assistance where required.

B. Project Elements

1. Systems Analysis

a) Objective

The objective of this task will be to examine the components of total cost in geothermal well drilling and completion and, on a cost/benefit basis, identify and rank order those areas in which technological improvements can lead to significant near-term cost savings and provide technology that is currently deficient to the needs of the National Geothermal Development Plan.

It is essential that in-house capability exists to establish priorities among alternative research proposals so that yearly, detailed planning can be done to support promising projects on a timely basis. The Systems Analysis Task will provide the analytic capability to assess the impact of proposed technological improvements on the overall cost of geothermal drilling and completions.

b) Technical Approach

This task will start with the identification of the cost factors that are common to all geothermal well drilling and completion operations. The mechanisms by which costs are accrued and how they relate to the location, depth, temperature, lithology and environment of the well will be investigated and understood. A model incorporating these factors in generic form will be constructed and analysis performed using data for specific reservoir types. The task is divided into four sub-tasks as follows:

1) Data collection
2) Development of a flexible drilling and completions well cost model
3) Cost sensitivity analysis of present geothermal drilling and completion methods
4) Cost evaluation of advanced geothermal drilling and completions methods.

c) Research Activity by Subtask

A description of the objectives and activities under each subtask is given below.

Subtask 1. Data Collection

The objectives of this subtask are to identify the components that contribute to the toal cost of geothermal drilling and completions, understand the mechanisms by which these costs are accured, determine the appropriate level of cost aggregation and establish a pool of real cost data for existing wells.

Data collected from vendors, drilling contractors, operating companies and the open literature will be compiled in order to learn how costs vary from well to well based on drilling and well parameters. This step is essential to understanding the cost impact of technology changes to these parameters.

In addition, the data will provide a basis for comparison and validation of output from the cost model which will be developed. The data will also be used to determine the level of cost aggregation most appropriate for cost/benefit analysis.

Subtask 2. Development of a Flexible Drilling and Completions Cost Model

The objective of this subtask is to construct a geothermal cost model with the capability to accurately predict costs for both conventional and advanced drilling and completions techniques in the major geothermal reservoir types.

The emphasis in the geothermal cost model will be on flexibility. Cost accuring activities will be modeled in their general forms and in a way that reflect actual practice in the field. Variations of the basic model with specific parameters for different locations and conditions will permit cost modeling in varying lithologies and reservoir types. Also, advanced concepts that entail new cost-parameter relationships will need to be examined. The model must be sufficiently flexible to accommodate a wide variety of these combinations of technology.

The model will be developed in stages with the intention of rapidly obtaining the capability to do sensitivity studies of conventional drilling and completions practices with simple cost-drilling parameter relationships. This initial development will be followed by the addition of the capability to model more complex interrelationships. The last stage will add the capability to model advanced concepts and complex relationships.

Information from the Data Collection Subtask will be used for initial model validation and calibration. Industry advice and guidance will be sought in later stages to insure model validity and credibility.

Subtask 3. Cost Sensitivity Analysis of Present Geothermal Drilling and Completion Methods

The objective of this subtask is to determine the sensitivity of total well cost to various technological parameters of conventional geothermal drilling and completions methods. A rank ordering will be determined to indicate the most promising areas for research and to aid in program planning.

Near-term reductions in geothermal well costs will result from improvements in conventional geothermal drilling methods. Timely identification and assessment of potentially high payoff projects is essential. Subtask 2 is intended to provide near-term systems analysis capability to support this subtask.

Sensitivity analysis of conventional methods will be a vital tool in evaluating the impact of projects considered under the Drilling Projects and Completions Technology Tasks. Cost saving potential will be evaluated under varying conditions of depth, temperature, flow rate, lithology, location, etc. Output from these sensitivity studies will be used in preparing the annual detailed program plans.

Subtask 4. Cost Evaluation of Advanced Geothermal Drilling and Completions Methods

The objective of this subtask is to determine the potential for cost savings of novel techniques for geothermal drilling and completion. Cost estimates for these advanced methods will be compared to costs of conventional techniques for varying well conditions.

This subtask will permit trade-off analyses of various advanced conceptual designs for geothermal drilling and completions. Promising concepts will be studied to determine their potential for high payoff and early returns in cost savings. These concepts which appear to warrant further study will be modeled in more detail and cost/benefit analyses will be performed. Completion of the final stage of Subtask 2 will provide capability for activities under this subtask to support annual program planning.

d) Near-term Milestones

The Systems Analysis Task will be programmed to provide timely guidance to other Geothermal Well Technology tasks and to achieve the task's objectives according to the following key milestones.

1) Complete initial data collection by early in FY-78
2) First stage of cost model operational with sensitivity analysis capability by mid FY-78
3) Second stage model development complete by late FY-78 with routine sensitivity analysis capability by the end of FY-78
4) Advanced concepts cost modeling complete by early FY-79 with routine sensitivity analysis capability by mid FY-79

2. Drilling Projects

a) Objectives

The objectives of the drilling projects are to develop, in conjunction with the drilling industry, the supporting technology and the advanced drilling systems that are necessary to support the power-on-line goals of the Geothermal Program.

b) Technical Approach

Petroleum drilling technology has established the base upon which geothermal drilling technology must build; however, geothermal drilling differs from oil and gas drilling in two major areas:

1) Most geothermal wells are drilled in harder formations than oil and gas wells.
2) Temperatures encountered in geothermal drilling are generally much higher than in oil and gas drilling.

These differences result in higher costs for geothermal wells. The Drilling Projects Task will contribute to geothermal well cost reduction by 1) improving the average rate of penetration by means of higher performance, longer life, high rpm rock bits, 2) developing improved high temperature downhole motors that can apply increased power to the rock face for both directional and straight hole drilling, 3) developing high temperature drilling fluids that can reduce drilling time and minimize fluid related problems, and 4) developing advanced drilling systems.

Methods to be utilized in defining specific program elements include the economic sensitivity model, input provided by the Geothermal Well Technology Panel, continuing contact with industry personnel, inputs from the DGE Mission Team Leaders and literature reviews.

c) Research Activity by Subtask

The drilling task has been divided into three major subtasks which will be discussed in detail below. These are: 1) High Temperature Drilling Fluid Development, 2) High Temperature Downhole Drilling Motors, and 3) High Performance Rock Bits. A number of worthwhile program elements are presently being pursued and will continue into future years to completion. New program elements will be initiated as existing developments are completed and commercialized.

Subtask 1. High Temperature Drilling Fluid Development

The objectives of this subtask are to:

(1) Develop a drilling mud that retains the desired properties in the geothermal environment,

(2) Develop field and laboratory instrumentation capable of measuring the properties of drilling fluids at high temperature and pressure,

(3) Formulate generalized well fluid plans for the various geothermal reservoir types,

(4) Generate a dynamic thermal model for a variety of common wellbore conditions and thermal conditions,

(5) Make testing facilities available to the industry that are capable of evaluating fluids under simulated wellbore conditions,

(6) Investigate the properties and chemistry of drilling foams; develop a foam which maintains its properties at high temperature and can be broken down after use for disposal or reuse.

Direct costs of drilling fluids, chemicals, equipment and services and indirect costs relating to drilling fluids can be a significant part of total well cost. Indirect costs include fluid related problems such as stuck pipe, pipe failures due to corrosion, time lost due to lost circulation, slow drilling from poor solids control, borehole instability, etc. All increase well costs.

Fluids used in geothermal drilling include water and oil based mud, water, air and foam. Because of the obvious simplicity, 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 addition, water alone cannot be used in a highly permeable or fractured formation because of fluid loss, and air drilling is limited by such factors as insufficient bit cooling, lack of ability to lift cuttings to the surface in deep holes and erosion of the drill string from high velocity particles.

Because of these inadequacies, high temperature muds and foams must be developed. Work previously sponsored by this program has shown that the best 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. Improved weighted fluids will be developed to control high formation pressures, provide adequate cooling for high speed cutting and seal formations to prevent fluid loss and damage.

High temperature drilling foams offer many advantages, but existing foams fail at high temperature, are not rapidly degradeable after use, and separation of fine cuttings from foams is also difficult. Improved foams can provide a balance between bit cooling and the ability of the liquid to lift the rock cuttings. Foams can fill the need for a non-contaminating, non-damaging fluid, and can also allow significant drilling rate increase. 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. This program will pursue high temperature foam development.

High temperature and pressure drilling fluid test facilities are also required to allow this development to proceed. Laboratory test facilities capable of duplicating downhole environmental conditions will be made available for development testing prior to field testing. Industry or the universities are the preferred locations for these facilities.

Subtask 2. High Temperature Downhole Drilling Motors

The objectives of this subtask are to:

(1) Apply high temperature elastomers that are being developed as part of the DGE Geochemical Engineering Program to existing downhole motors,

(2) Develop high temperature seals to allow lubrication of bearings with higher pressure drops across the rock bit,

(3) Develop a high temperature bearing and seal package capable of fitting existing motors,

(4) Develop a high temperature speed reducer and bearing assembly to allow existing motors to more efficiently utilize roller bits,

(5) Investigate drill string components such as shock subs and deviation subs to determine needs and sponsor design of the necessary improvements,

(6) Define and conduct a development program aimed at enhancing directional drilling capabilities,

(7) Develop a high-horsepower, balanced, bit/motor system for high speed straight hole drilling.

Improved drilling motors can significantly reduce drilling costs and accelerate the geothermal energy program by expanding rig utilization. In brief, motors have the potential to accomplish the following:

(1) Decrease the total time to drill wells, thus providing an expanded rig force capability,

(2) Reduce total footage and number of locations required by allowing multiple completions from a central site,

(3) Allow enhanced directional drilling capability and thus decrease the number of abandoned holes,

(4) Decrease wear on drill pipe, and

(5) Provide capability for operations not now possible such as deepening small holes, high speed milling, improved workover, etc.

Despite the many advantages possible with motors and indeed their necessity in some circumstances, their current use is limited, time consuming and expensive. This is a result of several deficiencies in technology. Among these are:

(1) Elastomers used for seals and major structural members quickly degrade at high temperatures,

(2) Bearings which cannot be sealed due to short life of seals fail rapidly in the high solids content drilling fluid environment,

(3) The high rotational speeds of most motors are not compatible with existing roller cone bits,

(4) Heavy vibrations are induced in the drill string,

(5) Real time steering capability at temperature does not exist for directional drilling.

This subtask will develop the needed motor technology for both directional and straight hole drilling in the geothermal environment. Initial efforts will be devoted to upgrading existing motor systems with subsequent efforts devoted to developing greatly improved, second generation systems.

Subtask 3. High Performance Rock Bits

The objectives of this subtask are to:

(1) Develop improved high temperature roller cone bits through research in metals, seals and lubricants,

(2) Develop bits that are capable of long life performance at downhole motor speeds,

(3) Provide the industry with laboratory data, computer techniques and bonding technology to stimulate the design, production and marketing of synthetic diamond bits,

(4) Identify and sponsor the development of novel bit design and drilling techniques which show promise of significantly increased performance.

Economic analysis indicates that two of the most sensitive drilling cost factors that can be affected by drilling technology research are drilling rate and bit life.[9] Past studies have shown that footage cost is most sensitive to drilling rate. Improved bits can significantly impact drilling costs.

Experience in geothermal wells has revealed the following problems in today's bits:

(1) Unsealed bearings exhibit short life in high temperature environments,

(2) Seals and lubricants in sealed bits deteriorate rapidly in the geothermal environment,

(3) Roller cone bits exhibit short life when used at high speed with downhole motors,

(4) Diamond bits compatible with motors have slow penetration rates in some hard rocks.

The technical thrust of this task 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 bit performance.

Improved laboratory testing capabilities are also required to successfully conduct the development program for both bits and motors. While there are excellent drilling laboratories that are commercially available in this country at the present time, none can fully simulate the environmental conditions encountered in geothermal drilling. These facilities must be upgraded or new joint-use facilities constructed to provide the capability required to adequately test new geothermal drilling components. A study of these options and the required capability will be made as part of this program and the necessary action will be taken to provide the required testing capability.

d) Near-term Milestones

Work has been underway for some time on many of the program elements in the Drilling Technology Development

Task. Several of these program elements are nearing completion. In the near-term, improved fluids, bits and motors will be moving from the laboratory to field evaluations and program completion on the following schedule:

1) High Temperature Drilling Fluids -- Field demonstration testing in FY-79 and FY-80. First commercial application in FY-81.
2) Downhole Motors -- Bearing and seal package field testing completed in FY-80, technology transferred in FY-81.
3) High Performance Bits -- Synthetic diamond drill bits introduced into geothermal drilling in FY-80. Continuous chain slimhole bit in the field in FY-81.

3. Completions Projects

a) Objectives

The objective of this project is to develop the technology required to minimize the life cycle cost of completing both production and reinjection wells. While improved completions and reinjection technology may have minimal impact on the initial well cost, it is critical to the overall economics of geothermal development and must be viewed from the perspective of the total useful life of the well. This perspective must include workover considerations. Improperly completed wells can substantially reduce energy production and require additional well drilling or frequent workover. With proper completions techniques, reliability and well life can be increased, workover costs can be reduced and drilling of replacement wells can be minimized. Improvements in these areas can have a significant impact on the total cost of developing a geothermal prospect and thus on the cost of geothermal power.

b) Technical Approach

Initially, this program will investigate and identify the problems that are associated with well completions in the various types of geothermal reservoirs. Studies to identify the state-of-the-art in geothermal well completions are in progress and recommendations for needed development will be generated as part of these investigations. When these studies are complete, research efforts will be initiated to address the key problem areas that have been identified. Both economic and environmental impacts of completions techniques must be considered. Consultations with drilling and completions companies will be held to substantiate the conclusions of these studies prior to establishing new program elements.

It is anticipated that optimal completions techniques will vary with reservoir type, e.g., completions required in the geopressured sedimentary basins will certainly be different from those required in fractured, hard rock volcanic formations. For this reason, this program will address completions problems on a reservoir-specific basis.

c) Research Activities by Subtask

This task has been divided into four subtasks as follows:

1) State-of-the-Art Studies
2) Program Element Formulation
3) Production Well Completions Technology Development
4) Reinjection Well Completion Technology Development

The anticipated activities in each subtask are discussed below.

Subtask 1. State-of-the-Art Studies

This subtask will identify well completions problems associated with geothermal energy development and their impact on resource development schedules and costs.

Completions, workover and reinjection technology studies will be broadly based investigations that will consider areas such as:

(1) Corrosion control and its effects on the life of downhole tubulars and plugging of formations,

(2) Drilling and fracture fluids and their effect on skin damage and stimulation results,

(3) Sand control and formation protection,

(4) Reinjection for waste disposal and improved reservoir life,

(5) Workover for increased well life and improved well capacities,

(6) Casing programs for improved life and capacity,

(7) Cementing programs for improved placement, performance and thermal resistance,

(8) Methods of fluid production, i.e., flashing vs pumped.

The results of these studies will lead to recommendations on specific areas of development activity.

<u>Subtask 2. Program Element Formulation</u>

Based on the results of the on-going state-of-the-art studies, recommendations from the geothermal industry and comments of the Geothermal Well Technology Panel, specific program elements will be defined and prepared for DGE consideration and approval. RFP's will be prepared and issued to industrial and research concerns that are active in the completions area, and development work will begin.

<u>Subtask 3. Production Well Completions Technology Development</u>

As previously indicated, it is anticipated that the techniques required for optimum production well completions will vary with the reservoir type. If indicated in the state-of-the-art studies, reservoir specific completions techniques will be developed, tested in both the laboratory and the field, and commercialized. Major problems in completions techniques center around the high flow rates that are desired in the geothermal wells since high flows can create severe sand control problems, erosion of tubing and short well life.

It is likely that new laboratory test facilities will be required to more accurately simulate the downhole environment encountered in geothermal production wells. A survey of needed and existing facilities will be conducted during this portion of the study and appropriate recommendations made to DGE.

Subtask 4. Reinjection Well Completions Technology Development

The problems anticipated in production wells may be magnified in injection wells because very high flow rates are desired, and the deposition of solids in the formation may eventually cause increased resistance to flow into the wells. When this occurs, the well must be reworked or abandoned. Research is needed to fully understand the reinjection problem and to design minimum cost completions scenarios. Reinjection technology will also vary by reservoir type. Assessments of the needs in each reservoir will be made and the required technology will be developed to support the power-on-line goals of DOE/DGE.

d) Near-Term Milestones

The Completions Technology Task will be geared to provide maximum support to both the DGE Mission Team Leaders and to geothermal development companies. Technology that assures long lived, reliable production and reinjection wells will be provided. Specific near-term milestones include:

1) Complete state-of-the-art assessment in geopressured completions with development recommendations by the first quarter of FY-78,

2) Issue RFP's for geopressured completions technology development during the second quarter of FY-78,

3) Complete state-of-the-art assessment in hydrothermal and steam dominated reservoir completions technology with development recommendations by the third quarter of FY-78,

4) Issue RFP's for both high and moderate temperature hydrothermal and steam completions technology development during the fourth quarter of FY-78,

5) Complete detailed long-range plan for geothermal completions technology development by the end of FY-78.

4. Research and Advanced Systems Development

a) Objectives

The objective of this project is to develop a fundamental understanding of drilling energetics with the goal of providing a sound technical base for the selection and development of a significantly improved drilling system. It will be difficult, if not impossible, to reach the 50% well cost reduction goal by simply improving the rotary drilling process. The rotary system has evolved over a period of seven decades and is very mature technologically. The desired large cost reduction must come from advanced drilling systems, and this program element will attempt to provide the insight needed to intelligently select a high performance drilling approach, and then develop and transfer the technique to the drilling industry.

b) Technical Approach

If the enhanced level budget is appropriated in FY-78, basic rock mechanics studies relative to the drilling process will be initiated. There are several fundamental questions that will be addressed. Among these are the questions of energy partition among the various forms of deformation prior to macroscopic failure of the rock and the problem of ductile failure modes under reservoir conditions of pressure and temperature. A better understanding of structural rock failure at reservoir conditions should give insight into more efficient drilling techniques.

In parallel with the more basic rock mechanics work, a broad study of novel drilling techniques will be conducted. Of primary interest will be the mechanisms of rock failure brought to bear by each system, the practicality of the approach, the projected time scales and cost to bring these systems to field use.

Nearer-term variations on the rotary drilling theme will also be considered in this investigation. These candidate systems will include jet drilling, jet augmented rotary drilling, high horsepower downhole motors and advanced conventional drilling systems such as the flex-pipe rigs and fully automated, computer controlled systems. This work will be tightly coupled to the more fundamental rock mechanics studies. The results of these investigations should allow a decision to be made on the more promising advanced drilling system (or systems) that meet the criteria for near-term impact on geothermal drilling costs. When this selection is made, an expedited development program will be initiated to demonstrate the selected system.

c) Research Activity by Subtask

This task has been divided into two subtasks as follows:

1) Drilling energetics research
2) Advanced drilling systems development.

The initial activities in each subtask are described below.

Subtask 1. Drilling Energetics Research

This subtask will investigate the physics of rock failure in an attempt to select a more efficient means of transmitting energy to the formation for low cost drilling. These investigations will likely be conducted by one or more universities augmented by the rock mechanics staff at Sandia and possibly other commercial laboratories. 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 be used to aid in the selection of the more promising candidate drilling technique.

Subtask 2. Advanced Drilling Systems Development

In parallel with Subtask 1, a study of advanced drilling systems will be conducted. Systems to be considered will include jet drilling, jet augmented conventional systems, high horsepower downhole motors with advanced bits, novel rig designs and the more exotic drilling techniques that have been proposed or investigated over the past several years. The purpose of this investigation will be to select one or more advanced system concepts for development. The candidate system(s) should provide high rate, problem free, hole generation at low cost. It will be very desirable that the system be compatible with existing rigs with as little modification as possible due to the long lead time involved in major rig changes. The basic rock mechanics study will provide input into this study and the method of rock loading selected will be governed by the basic work. When the selection of candidate system(s) is made, an expedited development program will be initiated to demonstrate the system(s) and move it rapidly through commercialization to the field.

III. MANAGEMENT PLAN

A. Approach

The DOE Division of Geothermal Energy (DGE) will retain the overall programmatic responsibility for direction of this project. DOE/DGE, with assistance from Sandia, will set the project goals, establish milestones and plan programs toward meeting them.

Sandia Laboratories will provide overall, as well as day-to-day, management of the Geothermal Drilling and Completions Program and will plan, initiate and coordinate technical work within the scope and objectives of the project. Close technical and administrative coordination will be established between Sandia project management and DOE/DGE management as detailed in Section III-D.

As an addendum to this document, Sandia will, prior to the beginning of each fiscal year and as described in Section III-E, provide DOE with a Laboratories Program Approval Document (LPAD) detailing the specifics of the project for the year. This document will be prepared when the budget for that year is known.

B. Sandia Project Management Structure

The Drilling and Completions Program is structured as shown in Figure 6. 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 all relevant R&D activities outside the project. He will be responsible for updating the project plan and for the preparation of the LPAD and will have overall responsibility for the contracting and procurement activities. In addition, he will insure effective coordination and integration of the various tasks under the project

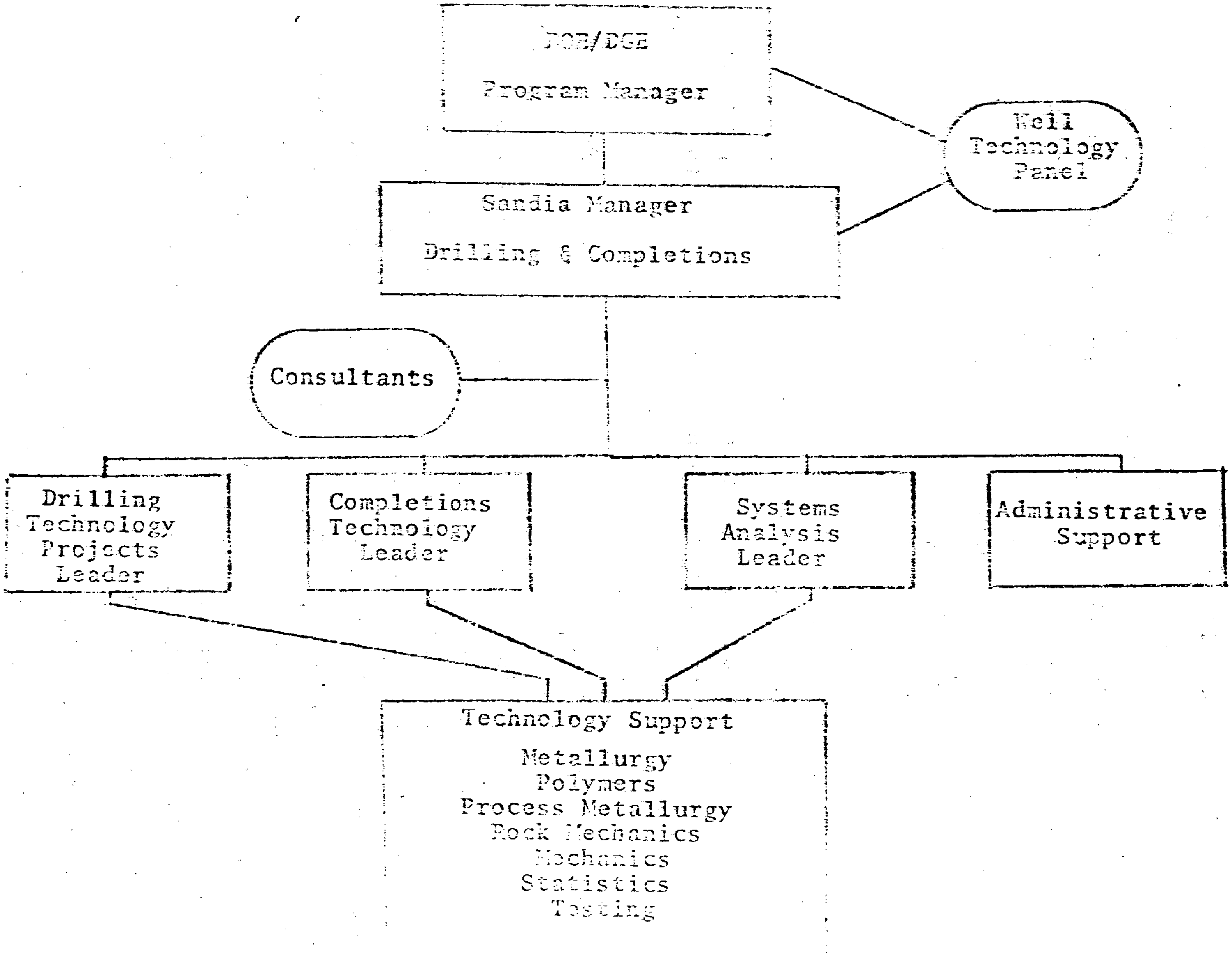

Figure 6. Geothermal Drilling and Completions Program Management Structure

and will establish and insure effective working interfaces with the other projects of the National Geothermal Program. He will also be responsible for maintaining close coordination and direct communication with the DOE/DGE Program Manager.

A Geothermal Well Technology Panel comprising several industry representatives will serve as a steering committee for the Drilling and Completions Program. The Sandia Program Manager will work closely with this panel.

The Sandia program is divided into three technical tasks and an administrative support task as shown in Figure 6. The technical tasks are:

1. Systems Analysis
2. Drilling Technology Development
3. Completions Technology Development

Each task will be headed by a task leader who will be responsible for the management of the technical aspects and the monitoring of the contracted activities in his area.

The administrative support will consist of personnel from the budgeting, purchasing, contracting and legal organizations as required.

The relationship of the Drilling and Completions Program to the Sandia Laboratories corporate structure is shown in Figure 7. It is seen that the project will be administered by the Geo Energy Technology Department of the Energy Projects and Systems Analysis Directorate. The management structure shown in Figure 7 will provide the Sandia mechanism for monitoring the technical and fiscal activities of the project. An important measure of project performance, especially in-house work, will be in the form of periodic reviews to be given by the Program Manager and his task leaders and will be evaluated by cognizant upper management.

C. Procurement and Contract Management

Procurement activities will be conducted in general accordance with established Sandia procurement policy. Within

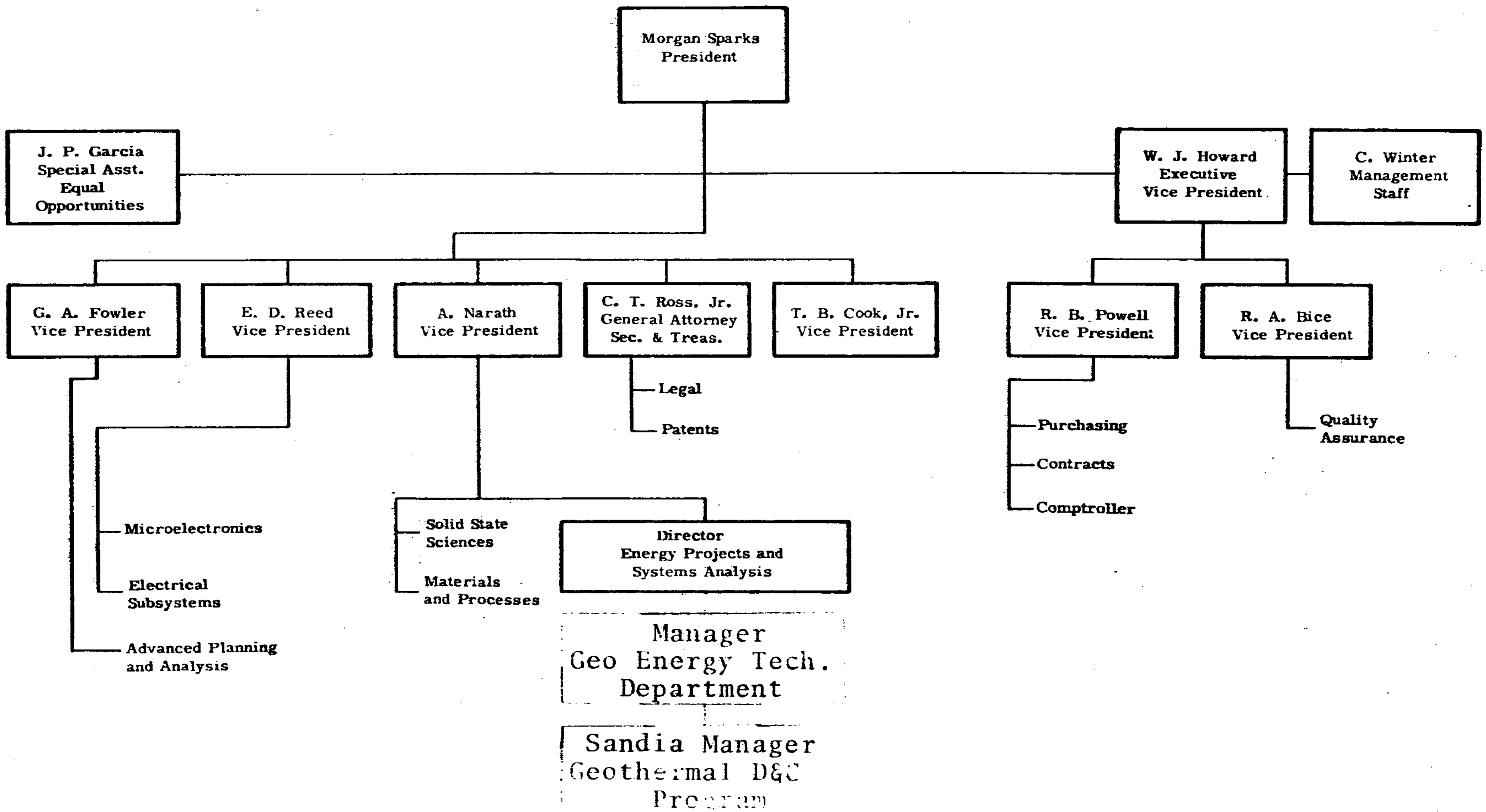

Figure 7. Sandia corporate structure

the framework of the procurement system, there is strong emphasis on competitive solicitation, with guidelines for request for quotations (RFQ's), the method of proposal evaluation and appropriate source selection techniques. Where facts and circumstances indicate the possible impracticality of placing a specific requirement on a competitive basis, the system provides for the possibility of non-competitive 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. Figure 8 illustrates a typical competitive procurement planning schedule. Sole source procurement can be completed on a much more timely schedule. 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 the Sandia Project Leader and combined into the monthly DOE status report,
2. A formal semi-annual status review of all program elements utilizing presentations by the contractors presenting their program to DOE, the Sandia Program Manager and the Geothermal Well Technology Panel,
3. Plant visit on a semi-annual basis in the alternate quarters by the Sandia project engineer for a detailed review of the progress of the work.

The Sandia buyer and project engineer will utilize the formal reporting and audit procedures to assure financial compliance to contract terms.

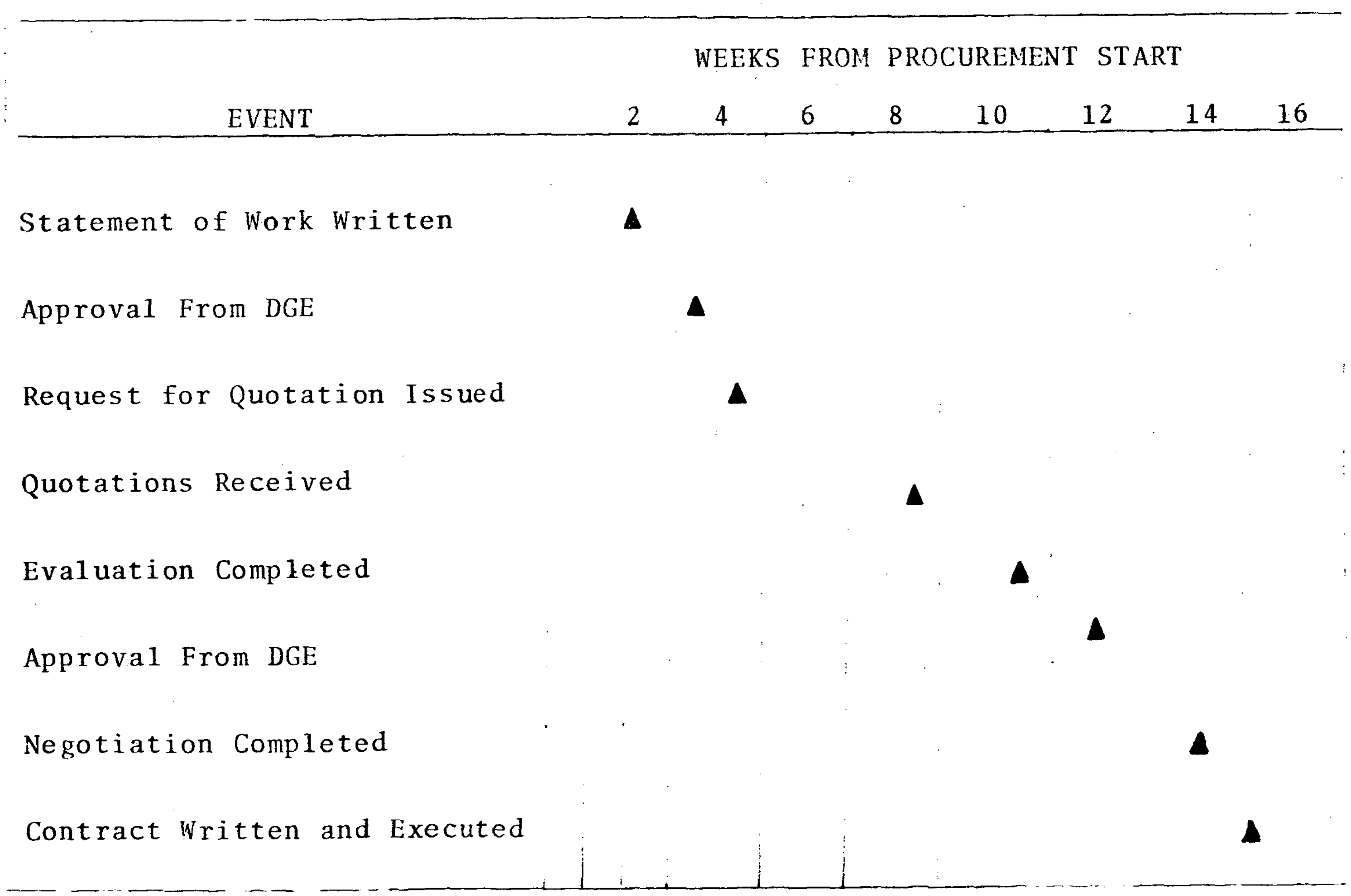

Figure 8. Typical competitive procurement planning schedule

Quality assurance functions will be performed in accordance with standard industrial practices. DOE general principles and policies for prime contractor quality control operations as stated in "Quality Policy and Operating Instructions," dated August 4, 1971, will be used where appropriate.

D. Project Administrative Approval Structure

In addition to the normal Sandia administrative approval procedure as set forth in the Sandia Laboratories Instructions (SLI's), for major contractual tasks, DOE/DGE will retain approval rights on the Statement of Work contained in the RFQ's that Sandia will issue, and will have the opportunity to make additions to bidders lists. Sandia will send DOE documentation containing the key factors pertinent to the proposed RFQ including a proposed source list at least ten days prior to initiating procurement action. Procurement will proceed after the ten-day period if no suggested changes are received by the Sandia Program Manager. Similarly, Sandia will send DOE the results of the source selection process at least ten days before notification of winners and will proceed with contract negotiations at the end of the ten-day period in the absence of objection by DOE/DGE.

DOE reserves the right to require publication of advance notice of intent to contract in the Commerce Business Daily.

E. Laboratory Program Approval Document (LPAD)

Prior to the beginning of each fiscal year, at a time determined by DOE/DGE, the Sandia Program Manager will submit a Laboratory Program Approval Document which sets forth the specific objectives, activities, schedule, funding requirements, in-house level of effort, project management personnel and any special review or reporting procedures planned for the upcoming project year. Upon approval of the LPAD, DOE/DGE will issue a Program Authorization Letter to implement the program.

F. In-house Research and Development

In-house technical work is necessary to maintain a viable technical expertise in the program management staff. In addition, Sandia Laboratories possesses many unique technological resources which can benefit the National Geothermal Program. DOE/DGE will monitor and approve the Sandia in-house level of effort on the technical work of the Drilling and Completions Program. The scope of the in-house work is as follows:

1. Drilling Technology Development

The in-house work may include, as approved by the DOE/DGE, the development and testing of novel bit designs, novel drilling techniques, high temperature materials and component fabrication techniques.

2. Completions Technology Development

The in-house work may include, as approved by DOE/DGE, the development and testing of sensors, components and techniques for completing geothermal wells.

3. Systems Analysis

The in-house work will include, as approved by DOE/DGE, the development of the tools necessary to critically evaluate, through computer simulations, the results of contracted and in-house technical work and to assist DOE/DGE in yearly program planning.

4. Technical Contractor Support

The in-house work will include, as approved by DOE/DGE, technical specialist support to program element contractors. Support will generally take the form of trouble shooting or technical advice when a contractor is in need of technical assistance to successfully complete the scope of work.

G. Sandia Support and Relevant Experience

As manager of the Drilling and Completions Program, Sandia's role and responsibility will be to plan, initiate.

direct, integrate and evaluate the activities needed to meet the specific objectives and schedules of the program. This will be done in close coordination with DOE/DGE management. Sandia possesses the expertise, resources and enthusiasm to accomplish this role in keeping with the overall spirit and objectives of the National Geothermal Program.

Sandia is a DOE systems and component engineering and development laboratory employing about 7,100 people. Of these, about 6,000 people are at the Albuquerque Laboratories which will have responsibility for this program. Sandia Laboratories has had a wealth of experience in planning and managing important national programs, both large and small.

For the necessary technical and administrative support of the program, the Sandia Program Manager will draw upon the resources of various Sandia organizations as needed. This is indicated in Figure 7. All of the organizations listed, except the legal organization, are directorates typically having 100-150 people each. These organizations are engaged in a broad range of research and technology development and possess a pool of technological expertise relative to the program. The Program Manager will task these functional organizations for project support. Especially related to the project are Sandia's technical capabilities in the areas of

a) Systems analysis and research
b) Computer code modeling and parametric studies of energy systems
c) Materials and device physics
d) Materials and process development
e) Rock mechanics research
f) Component and subsystem evaluation and environmental testing
g) Subsystem and system compatibility testing

Sandia is strongly committed to the development of geo-energy sources as demonstrated by current programs in the following areas:

a) In situ coal gasification

b) In situ oil shale

c) Enhanced gas recovery -- massive hydraulic fracturing

d) Chemical studies of the synthoil process

e) Magma energy research

f) Offshore technology

g) Oil and gas drilling technology development

h) High temperature well logging development

Experience gained and facilities acquired in the planning, operation and management of these activities should be of value to the Drilling and Completions Program.

The FY-77 effort in the above geo-energy areas is approximately 100 man-years. While substantial, this level of effort and projected growth needs represent a very small fraction of the Laboratories' resources. It is expected that the present and future manpower and technical needs of the Drilling and Completions Program can be met without difficulty and without disrupting other Laboratory programs.

The Sandia Laboratories Case Cost System will be used for the control and allocation of resources. Cost data will be aggregated by major task level and periodic reports will be issued to DOE. For this program, a case will be originated and will contain several subordinate subcases to cover various project tasks.

H. Project Reporting and Technical Review

1. Project Reviews

In addition to periodic internal Sandia program reviews, formal progress reviews will be conducted semiannually for evaluation by DOE/DGE management, Sandia management 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) Monthly Status Reports -- A monthly letter reporting program status will be submitted to DOE, except when the month coincides with the due date for the annual report, showing:

1) Schedule status
2) Planned and actual costs and obligations
3) Planned and actual in-house manpower
4) Significant problems or accomplishments in reporting period
5) Summary of interactions between Sandia and other participants in the National Program
6) Listing of contractor reports and in-house technical reports on the program.

b) Semiannual Reports -- Semiannual reports will be prepared and 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.

c) Contractor Reports -- Contractors will submit periodic 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.

d) 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 activity 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. Sandia public releases will be coordinated with the DGE management at DOE. 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.

IV. TECHNOLOGY TRANSFER AND RESEARCH UTILIZATION

The Drilling and Completions Program and the overall DOE Geothermal Program will be designed to encourage the development and implementation of geothermal energy sources by private industry. Therefore, Sandia will give special attention to the question of technology transfer and research utilization.

It is expected that the results of work performed under this 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:

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

B. Presentations at appropriate meetings and conferences; and

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

It is essential that research results produced under this program be made available on a timely basis to DOE/DGE Mission Team Leaders and that problems arising in the respective mission regions be communicated to the Drilling and Completions Program so that needed supporting research can be initiated. The Sandia Program Manager will establish a close liaison with the Mission Team Leaders to accomplish this objective.

Industrial participation and guidance are strongly encouraged in this program. The first point of contact between industry and the program is the Well Technology Panel. This panel comprises drilling contractors, equipment manufacturers, and representatives from the operating companies. Periodic meetings of this panel will be convened to discuss research results and to identify areas where further research is needed. The composition of the panel will be modified as required to provide the proper programmatic guidance.

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. Among others, the participation of equipment manufacturers, independent research firms, drilling contractors and operating companies will be sought.

APPENDIX A

Example of Geothermal Well Cost Analysis

The identification of research tasks in this program requires an assessment of the potential impact on well cost of each proposed task. At the present time, sufficient data on well cost are not available to allow performance of this assessment for all potential tasks in the various reservoir types. An effort is presently underway to obtain appropriate technical and cost information. In the meantime, it is informative to illustrate the methods that will be used in this program to determine cost sensitivity. An example of geothermal well cost and its sensitivity to technological factors is presented here. It should be emphasized that the example shown here is for only one well and that different sensitivities will be exhibited by different wells and in different reservoir types. Further, it is not suggested that this well is either typical or average. Nevertheless, the example is useful in describing the approach.

The costs of one well in the Geysers field have been compiled and are summarized in Figure 9. This well was drilled to a total depth of 9,000 feet at a total cost of $900,000.

For illustrative purposes, the costs are broken down into four categories: fishing costs, rig costs while drilling, rig costs while on location but not drilling, and completions and other costs. Also shown are projections for cost reductions which might be achieved with certain assumed improvements in technology. Improvements are assumed in average penetration rate and in high temperature drilling fluids.

Of the total well costs, approximately 56% is attributable to completion costs and to non-rotating rig time. The "completion and other cost" category includes the cost of casing, cementing and tool rental. Non-rotating rig time includes running casing, waiting time, and other rig charges. It is likely that these charges can be reduced with improved technology; however, no estimate of the potential reduction in these costs is attempted here.

The effect of increased rate-of-penetration on footage cost can be quantified as shown in (A), (B) and (C) of Figure 9. (A) assumes an increase of 50% in average instantaneous penetration rate with a resulting decrease in well cost of 7%. For a doubling of penetration rate, the well cost is reduced by approximately 11%, and for an increase in penetration rate by a factor of 5, the well cost is reduced by approximately 18%. Note that only 22% of the total cost of this well is directly attributable to direct drilling costs. It is clear that no improvement in rate of penetration will, by itself, achieve a 25% reduction in cost.

Fishing charges on this well amounted to 22.3% of the total well cost. These charges were the indirect result of the lack of a suitable high temperature drilling fluid. While drilling with air, the well started to produce water. Attempts to control the well resulted in stuck drill pipe and subsequent fishing operations. The development of a high temperature drilling fluid capable of providing well control could potentially have prevented this problem and reduced well cost substantially. Graphs (B) and (C) assume that fishing charges are eliminated and that penetration rates are also increased. Graph (C) indicates that if a suitable drilling fluid is developed and if the penetration rate were increased by a factor of 5, a maximum cost reduction of 40% would be possible on this particular well.

This simple graphical analysis ignores certain interdependencies of the cost categories, e.g., some non-rotating rig time and additional completion costs resulting from the necessity of the fishing operations. Also, it is not suggested that cost reductions are impossible in non-rotating or completions costs. Data for this well are simply not sufficient to make defensible predictions for such improvements.

It should be emphasized that different cost breakdowns will be exhibited by other wells in different reservoir types. Costs for deeper wells may be more sensitive to rate of penetration. Other wells may encounter different problems. For example, Well No. 2 at Raft River encountered cementing difficulties due to the high temperature environment which accounted for approximately 16% of the total well cost. A computer program which will allow the assessment of well cost sensitivity to various drilling factors will be developed early in this program.

While not conclusive, this example emphasizes certain facts. First, research is needed in a broad range of technical areas to reduce rotating and contingency costs and also to reduce non-rotating and completions costs. Second, it appears that a program directed only at rate of penetration increases and materials improvements will not meet the goal of a 50% reduction in well cost by 1986. This fact emphasizes the need for a research program directed at both improvements in rotary technology and advanced methods for drilling and completing geothermal wells.

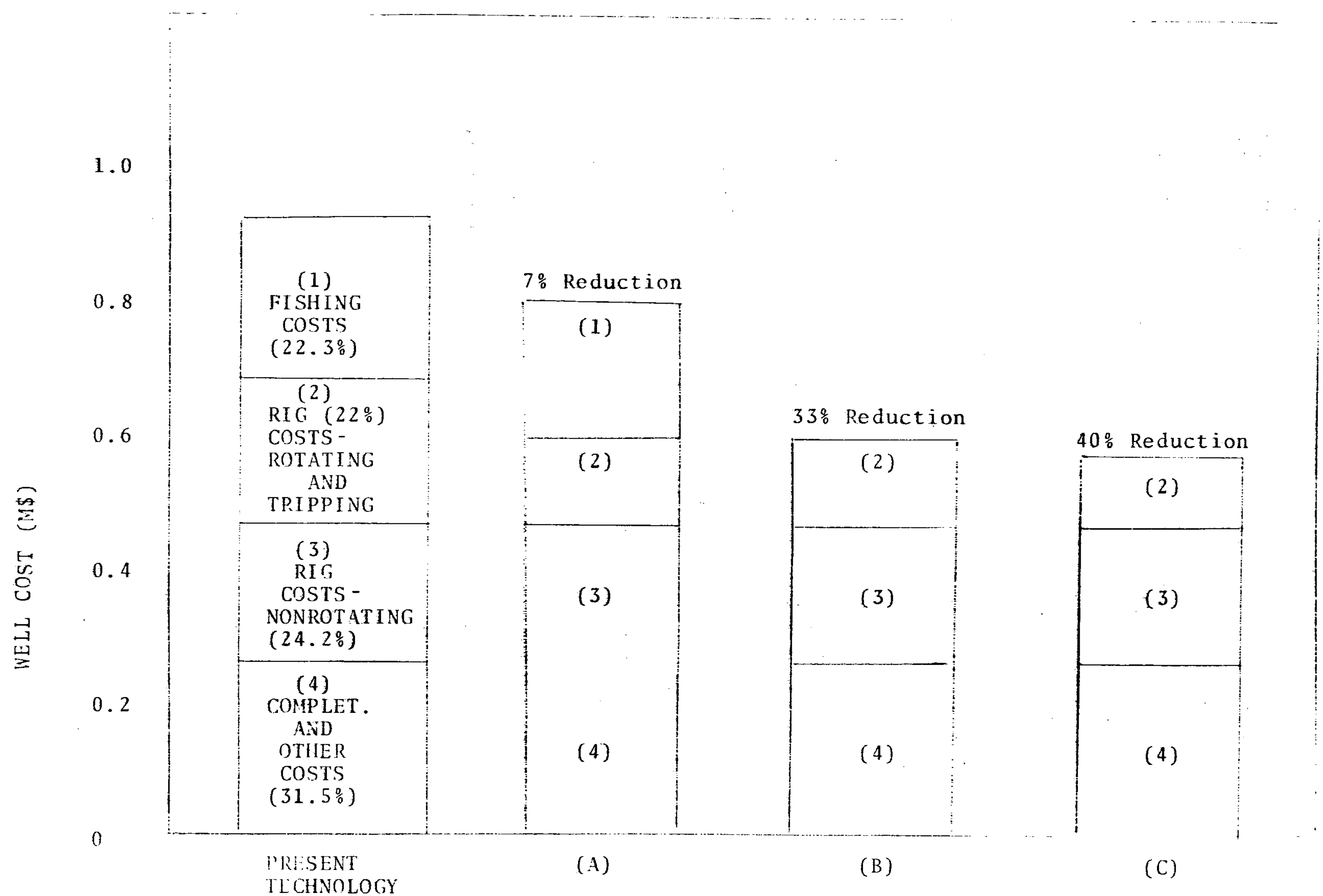

Figure 9. Potential cost reduction for one well in the Geyser's field
A. 50% increase in ROP, B. 100% increase in ROP, no fishing costs,
C. Factor of 5 increase in ROP, no fishing costs

REFERENCES

1. "Program Approval Document Fiscal Year 1977 -- Geothermal Energy Development," Solar, Geothermal and Advanced Energy Systems Development, ERDA, January 7, 1977.

2. E. J. Friedman and A. El-Sawy, "Prospects for Improvements in Geothermal Well Technology and Their Expected Benefits," MTR-7613, Mitre Corporation, December, 1977.

3. S. L. Milora and J. W. Tester, "Geothermal Energy as a Source of Electric Power," MIT Press, 1976.

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

5. J. H. Altseimer, "Geothermal Well Technology and Potential Applications of Subterrene Devices -- A Status Review," Los Alamos Scientific Laboratory Report LA-5689-MS, August, 1974.

6. L. H. Barker, et al., "Geothermal Environment Effects on Drill Bit Life," 11th Intersociety Energy Conversion Conference, 1976.

7. W. C. Maurer, "Geothermal Drilling Technology," 2nd U. N. Symposium on the Development and Uses of Geothermal Resources, 1975.

8. Private communication, Dr. W. C. Maurer, Houston, Texas.

9. H. M. Dodd, "Economic Analysis of the Replaceable Downhole Drill Bit," Sandia Laboratories Report SAND76-0301, September, 1976.

Distribution:

American Coldset Corporation (2)
P. O. Box 20514
Dallas, Texas 75220
Attention: Martin G. Browne
Larry W. Diamond

Amoco Production Research
Research Center
P. O. Box 591
Tulsa, Oklahoma 74102
Attention: J. L. Lummus

Atlantic Richfield
R&D Department
P. O. Box 2819
Dallas, Texas 75221
Attention: Thomas K. Perkins

Big Chief Drilling Company
Box 14837
Oklahoma City, Oklahoma 73114
Attention: William A. Glass

Brigham Young University
Provo, Utah 84602
Attention: K. W. Chase
Mechanical Engineering Department

Battelle-Columbus Laboratory
505 King Avenue
Columbus, Ohio 43201
Attention: Hugh D. Hanes, Manager
HIP Program Officer

Chevron Oil Field Research
Box 446
La Habra, California
Attention: R. L. Parsons

Christensen, Inc. (4)
2532 South 3270 West Street
Salt Lake City, Utah 84119
Attention: Bruch H. Walker
Coy Fielder
David Rowley
Howard Link

Continental Oil Company
Drawer 1267
Ponca City, Oklahoma 74601
Attention: Elard L. Haden

City Service Oil Company
Box 300
Tulsa, Oklahoma 74102
Attention: B. F. Caver

Dresser Industries, Inc. (3)
P. O. Box 6504
Houston, Texas 77005
Attention: Bill T. Greaves
Security Divisions
Roy M. Wolke
Oil Field Products Divisions
Lyman Edwards
Petroleum & Minerals Group

Drilco Industrial
Box 3135
Midland, Texas 79701
Attention: W. F. Olson

Department of Energy (4)
Albuquerque Area Office
Albuquerque, New Mexico 87115
Attention: D. K. Nowlin
H. E. Roser
D. Denham
P. Grace

Department of Energy (4)
Division of Oil, Gas, Shale and In Situ Technology
Washington, D. C. 20545
Attention: H. D. Guthrie
J. Ham
D. F. Guier
E. Ferrero

Department of Energy (31)
Division of Geothermal Energy
Washington, D. C. 20545
Attention: Larry Ball
J. C. Bresee
R. Black
Clifton Carwile (20)
Morris Skalka
R. Toms
E. H. Willis
R. R. Reeber
K. Westhusing
B. DiBona
L. Wermer
J. Salisbury

Department of Energy (3)
Division of Basic Energy Sciences
Washington, D. C. 20545
Attention: George A. Kolstad
Dr. Donald K. Stevens
Dr. W. C. Luth

Exxon Production Research Company
P. O. Box 2189
Houston, Texas 77001
Attention: Joe K. Heilhecker

Department of Energy
Test Construction Branch
Nevada Test Site Operations
P. O. Box 435
Mercury, Nevada 89023
Attention: G. A. Stafford, Chief

General Electric Company
11177 East Eight Mile Road
Detroit, Michigan 48232
Attention: James F. Murray

General Electric Company (3)
6325 Huntley Road
Worthington, Ohio 43085
Attention: Mahlon D. Dennis
Don Thompson
W. H. Daniels

Getty Oil Company
3903 Stoney Brook
Houston, Texas 77042
Attention: H. A. Demirjian

Gulf Research and Development Company
P. O. Drawer 2038
Pittsburgh, Pennsylvania 15230
Attention: Dr. L. A. Wilson, Jr.

General Electric Company
P. O. Box 8, Building K-1
Schenectady, New York 12301
Attention: Louis E. Hibbs, Jr.

Geothermal Resources Council
P. O. Box 1033
Davis, California 95616
Attention: David N. Anderson
Executive Director

GTE Laboratories, Inc.
40 Sylvan Road
Waltham, Massachusetts 02154
Attention: D. R. Jelley,
Supervisor
Document Services

Completion Technology Company (2)
3701 Kirby Drive, Suite 558
Houston, Texas 77098
Attention: R. Jorda
G. Suman

Helmerich & Payne International Drilling Company
P. O. Box 94968
Oklahoma City, Oklahoma 73109
Attention: Ray Marsh

Halliburton Services
Box 1431
Duncan, Oklahoma 73533
Attention: Mark Stogner

Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544
Attention: John C. Rowley
Q Division

Longyear Company
925 Delaware Street, S. E.
Minneapolis, Minnesota 55414
Attention: Gary H. Beckley

Maurer Engineering (3)
10301 Northwest Freeway
Suite 202
Houston, Texas 77018
Attention: W. C. Maurer

Mobil Research and Development
P. O. Box 900 (2)
Dallas, Texas 75221
Attention: John Fitch
Wilton Gravley

National Science Foundation (2)
1800 G. Street, N. W.
Washington, D. C. 20550
Attention: Ritchie B. Coryell
William Hakala

Phillips Petroleum Company
450 FPB
Bartlesville, Oklahoma 74004
Attention: R. R. Angel

Shell Development Company (2)
P. O. Box 481
Houston, Texas 77001
Attention: John D. Hellings
W. C. Montgomery

Smith Tool (2)
P. O. Box C-19511
Irvine, California 92713
Attention: Jim Kingsolver
Albert Krainess

Smith Tool
P. O. Box 1550
Irvine, California 92705
Attention: Robert F. Evans

Sun Oil Company
503 North Central Expressway
Richardson, Texas 75080
Attention: Joseph E. Zupanick

Superior Oil Company
P. O. Box 51108 O.C.S.
Lafayette, Louisiana 70521
Attention: D. W. Clayton

Smith Tool (2)
14451 Myford Road
Tustin, California 92680
Attention: Don Derthick
Rob Housman

Tenneco Oil Company
P. O. Box 2511
Houston, Texas 77001
Attention: Dan Johnson

Terra Tek
University Research Park
420 Wakura Way
Salt Lake City, Utah 84108
Attention: Sidney J. Green

Texaco Research Laboratories
P. O. Box 425
Bellaire, Texas 77401
Attention: Thomas S. Teasdale

Texas A&M University (3)
College Station, Texas 77843
Attention: M. Friedman
J. Hauden
R. L. Whiting

University of Texas at Austin
Austin, Texas (2)
Attention: Dr. Ken Gray
Dr. Myron Dorfman

Union Carbide Corporation
Linde Division
270 Park Avenue
New York, New York 10017
Attention: Mr. E. L. McCandless

Union Oil Company of California
Research Department (2)
P. O. Box 76
Brea, California 90017
Attention: H. D. Outmans
D. Pyle

Reed Tool Company (2)
P. O. Box 2119
Houston, Texas 77001
Attention: Chad L. Wiley
Bill Shoemaker

Rowan Drilling--U.S.
P. O. Box 1873
Midland, Texas 79701
Attention: W. J. Holbert

NL Hycalog (2)
P. O. Box 15372
Houston, Texas 77020
Attention: R. P. Radtke
H. C. Bridwell

Roton Mosle Inc.
2600 1st International Building
Dallas, Texas 75270
Attention: Fred Mills

Phillips Petroleum Company
P. O. Box 752
Del Mar, California 92014
Attention: Dr. C. W. Berge

Loffland Brothers Company
P. O. Box 688
Farmington, New Mexico 87401
Attention: George Kemnitz, Jr.

Livesay Consultants
2616 Angell
San Diego, California 92121
Attention: Dr. B. J. Livesay

Republic Geothermal
11823 East Slauson
Suite 1
Santa Fe Springs, California 90670
Attention: Dr. Bob Nicholson

Dyna-Drill
Division of Smith International, Inc.
P. O. Box C-19576
Irvine, California 92713
Attention: Kurt H. Trzeciak

Dyna-Drill
P. O. Box 327
Long Beach, California 90801
Attention: John E. Tschirky

Department of Energy
Idaho Falls Operation Office
Idaho Falls, Idaho 83401
Attention: D. Letendre

Department of Energy (3)
Division of Geothermal Energy
Washington, D. C. 20545
Attention: A. G. Follett
J. Walker
B. Barnes

Department of Energy
Division of Mining Research
Washington, D. C. 20545
Attention: W. B. Schmidt

1	M. Sparks
2	W. J. Howard
400	C. Winter
1000	G. A. Fowler
1100	C. D. Broyles
1130	H. E. Viney
1300	D. B. Shuster
1320	M. M. Newsom
2000	E. D. Reed
2100	W. J. Spencer
2150	C. M. Tapp
2300	J. C. King
2320	K. Gillespie
2325	R. E. Fox
2325	R. F. Ashmore
2325	H. K. Togami
2500	J. C. Crawford
5000	A. Narath
5100	J. K. Galt
5160	W. Herrmann
5163	D. E. Munson
5200	E. H. Beckner
5300	O. E. Jones
5400	A. W. Snyder
5700	J. H. Scott
5710	G. E. Brandvold
5730	H. M. Stoller
5730	A. Caldwell
5731	R. K. Traeger
5732	D. A. Northrop
5733	C. L. Schuster
5734	A. L. Stevens
5735	S. G. Varnado (25)
5736	A. F. Veneruso
5740	V. L. Dugan
5742	J. Polito
5800	R. S. Claassen
5810	R. G. Kepler
5814	R. C. Hughes
5820	R. L. Schwoebel
5824	C. J. M. Northrup, Jr.
5824	B. T. Kenna
5830	M. J. Davis
9400	H. E. Lenander
9412	R. K. Peterson
9414	G. L. Miller
3141	C. A. Pepmueller (5)
3151	W. L. Garner (3)
3172-3	R. P. Campbell (25) (DOE/TIC)
8266	E. A. Aas (2)