BENEFIT/COST ANALYSIS OF GEOTHERMAL TECHNOLOGY R&D

Volume II: Geothermal Drilling Technology

The MITRE Corporation

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Benefit/Cost Analysis of Geothermal Technology R&D

Volume II: Geothermal Drilling Technology

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ABSTRACT

This report describes benefit/cost analyses of 24 research and development (R&D) projects of the Geothermal Drilling Technology Program of the Utilization Technology Branch (UTB) of the Division of Geothermal Energy (DGE). The analyses are focused on the economic impacts that these projects might have on the cost of electric power produced at 27 hydrothermal prospects in the U.S. between 1978 and 2000.

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EXECUTIVE SUMMARY

This report (Volume II of four volumes) describes the approach, methods, and results for benefit/cost analyses of 24 R&D projects sponsored in F.Y. 1978 by the Geothermal Drilling Technology Program of the Utilization Technology Branch, Division of Geothermal Energy, Department of Energy.

Benefits of the R&D projects were estimated as potential future cost savings in electricity production at United States liquid-dominated geothermal prospects. The estimated benefits were based on the DGE hydrothermal electric development scenario for power plant installation at 27 United States liquid-dominated geothermal prospects in the year 1979-2000.

Important definitions for this summary are:

- R&D Subelement - A set of one or more R&D projects or contracts that promises to develop a practical commercializable product that will improve a geothermal energy system component or process.
- Sunk Costs - R&D costs incurred through FY1977 for the subelement, inflated at 10%/year to 1978 dollars.
- Planned Costs - Expected future (including FY1978) R&D costs to the Federal program. These include costs planned by DGE, and in many cases "additional" costs estimated by MITRE to be required to bring the anticipated products of the subelement to commercialization. Expressed in 1978 present value; discount rate = 10%.
- Date of Commercialization - Year in which the product of the subelement is expected to be available for commercial incorporation into geothermal wells or electric plants.
- Estimated Benefit - Savings in the costs of electricity production in the years 1979-2000 at the 27 U.S. liquid-dominated geothermal prospects included in the hydrothermal electricity development scenario. This benefit is based on technical considerations only, and is the modelled consequence of either a pessimistic or optimistic estimate of the degree to which the R&D subelement activities will alter technology performance and/or costs expressed in 1978 dollars; assumed discount rate of 10% per year.

- Degree of Success - A scaling factor between 0.0 and 1.0 that reflects MITRE's estimate of the degree to which the possible (estimated) benefit will be delivered commercially. The estimate of degree of success includes such considerations as probability of technical success in the R&D activities, competition between subelement products for shares of the same market, and sundry factors that could affect commercial use of the R&D product.
- Expected Benefit - Product of the estimated benefit and degree of success; final estimate of how much savings in the cost of electricity production is most likely to result from the R&D subelement.
- Figure of Merit - Expected benefit divided by planned R&D costs. This is the benefit/cost ratio for the R&D subelement. It disregards sunk costs to provide a forward look of the relative value of each subelement throughout its entire life span.
- Historical Figure of Merit - Expected benefit divided by sum of sunk plus planned costs. This value provides an estimate of the relative value of each subelement throughout its entire life span.

The benefit/cost analysis required to creation of two new major models of geothermal drilling technology. The first, WELCST, is a comprehensive computerized engineering cost model for geothermal wells, which includes accounting for most major drilling mishaps. The second is a model of the impacts of logging sondes on geothermal drilling and completion operations.

The major conclusions of the analysis are:

- The total expected benefit from the activities of this R&D program is between \$1,037 million and \$1,970 million at liquid-dominated prospects (present value, 1978, 10% discount rate).
- An additional benefit of between \$150 million and \$330 million might be obtained at geopressured and hot dry rock sites if the SUBTERRENE project is reinitiated.
- Most of the expected technology improvements will be commercialized by 1985.

- Future costs (including FY1978) to achieve these benefits are about \$18.2 million. Sunk costs are on the order of \$9.2 million.
- The overall benefit/cost ratio for the program falls between 65 and 126, based on FY1978 plus anticipated future R&D costs.
- As an average across the U.S. scenario for geothermal electricity development, the program activities could reduce electricity costs by 9.5% to 18.0%.
- The cost of geothermal wells at these sites could be reduced by 20% to 39% by 1985.
- There is a good balance of funds distribution across the six technical areas of this program, as evidenced by fairly uniform benefit/cost ratios across the spectrum of areas.
- The largest share of the expected benefits come from R&D activities in the Drilling Bits area.
- Continued R&D activity is needed to realize potentially large cost savings in the areas of Downhole Motors and Geothermal Drilling Fluids.

The principal results of the analysis are presented in Table S-1 and in Figure S-1.

TABLE S-1

BENEFIT/COST RATIOS OF STANDARD TECHNICAL AREAS
IN THE GEOTHERMAL DRILLING TECHNOLOGY R&D PROGRAM

STANDARD TECHNICAL AREA	COST (\$1000, 1978)		EXPECTED BENEFIT ¹ (\$Millions, 1978)		FIGURE OF MERIT ²		HISTORICAL FIGURE OF MERIT ³	
	SUNK ←FY77	PLANNED FY78→	PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC
Drill Bits	5,489	8,642	708.3	1,166.7	82.0	135.0	50.1	82.6
Downhole Motors	1,304	3,139	204.4	474.0	65.1	151.0	46.0	107.0
Drilling Fluids	494	3,239	121.0	248.2	37.4	76.6	32.4	66.5
Logging Sondes	805	1,490	65.3	192.4	43.8	129.0	28.5	83.8
Measurements for Drilling & Pumps	868	1,624	60.0	160.0	36.9	98.5	24.1	64.2
Descaling	227	100	28.3	58.6	283.0	586.0	86.5	179.0
ENTIRE PROGRAM	9,187	18,234	1,187.3	2,299.9	65.1	126.0	43.3	83.9

(1) Product of calculated benefit and degree of success.

(2) Includes planned and additional costs only.

(3) Includes sunk, planned, and additional costs.

FIGURE S-1
EXPECTED BENEFIT VS. PLANNED PLUS ADDITIONAL R&D COST
FOR THE WELL DRILLING AND COMPLETION SUBELEMENTS OF THE
GEOHERMAL DRILLING TECHNOLOGY R&D PROGRAM

1.0 INTRODUCTION

1.1 Purpose and Scope

The purpose of the analysis reported in this volume was to assess the benefits and costs of 24 R&D projects of the Geothermal Drilling Technology Program of the Division of Geothermal Energy, U.S. Department of Energy, as of FY78. The specific goals of the analysis were to:

- Provide a uniform basis on which to evaluate the probable impacts of disparate R&D projects upon the cost of producing electricity at 27 designated geothermal prospects in the U.S. between 1978 and 2000.
- Estimate the likely technological and economic impacts of 24 specific R&D projects.
- Estimate relative benefit/cost ratios for the R&D projects.
- Present the resulting estimates in a way that could assist DGE officials in monitoring the progress and potentially changing relative importance of the various R&D projects to meeting DGE programmatic goals.

The uniform basis for R&D project evaluation was required to extend across the three R&D programs of the Utilization Technology Branch:

- Geothermal Drilling Technology (this volume)
- Utilization Technology (Volume III)
- Geochemical and Materials Engineering (Volume IV)

The scope of this volume of the report is limited to analysis of R&D projects related to geothermal well drilling, logging, and completion. The specific projects and the technical areas into which they all fall are detailed in Section 2.0.

The general scope of the benefits analysis as a whole was limited to effects on the economics of electricity production at 27 specific geothermal prospects. All of these prospects are moderate to high temperature (140-356°C) liquid-dominated reservoirs of moderate depth (up to 3 kilometers, or about 10,000 feet). Volume I of this report, and Section 1.2 (below) may be consulted for further details on the scope of the analysis.

This benefit/cost analysis is, by design, project-oriented rather than program-oriented. The analysis considers, almost exclusively, the impacts of R&D activities upon the future cost of producing electricity from an assumed fixed scenario of powerplant development at U.S. hydrothermal sites. This is intended to give the R&D Program Managers a forward look at the degree to which various R&D activities are most likely to impact on the types of technologies that will be used to extract and deliver geothermal electricity in the U.S. (1).

Since the analysis is not program-oriented, it specifically ignores some of the traditional aspects of federal programmatic benefit/cost analyses. For example, no attempt is made here to compare the future cost of geothermal electricity to electricity derived from other kinds of resources. Nor is there any attempt to predict the cost of electricity from specific prospects, or to predict market penetration shares at specific prospects. Such estimates will require additional analyses, which could be based in part on the results presented here.

1.2 General Approach

"General" here refers to components of the approach that were common to the analysis of R&D Projects in all three of the Utilization Technology Branch research programs. Full details of the general approach used for the benefit/cost analysis of these projects can be found in Volume I of this report. Only a brief description of the general approach of the analysis is given here.

It was most important to identify the ways in which the expected results of the R&D projects could impact on geothermal power technology to reduce the cost of producing geothermal electricity. In some cases (e.g., "Continuous Chain Bit"), a single R&D project could produce a direct impact on costs. In other cases, projects had to be grouped together before they would result in a practical direct impact. To handle this diversity, the benefit/cost analyses were defined in terms of R&D "Subelements", where each subelement is a single DGE project or a group of projects that holds promise of resulting in a commercialization improvement in a geothermal power system component or process.

For each R&D subelement, three independent quantitative factors were analyzed:

- Benefit - The total dollar savings that the technical impacts of the subelement could produce at electricity plants expected to be installed at 27 United States geothermal prospects in the years 1979-2000,
- R&D Cost - The total amount of DGE funds expected to be expended on the projects of the subelement from fiscal year 1978 through the estimated commercialization date of the product(s) of the subelement, and
- Degree of Success - An estimate of the likelihood that the total estimated benefit of the subelement will be realized, considering factors such as likelihood of technical success in the R&D work, market penetration barriers, etc.

The final result of each benefit/cost analysis is presented as a figure of merit for each subelement:

$$\text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

This figure of merit reflects only current and future costs. A parallel "Historical Figure of Merit" which includes past sunk costs as well was also calculated to reflect the entire expected life-span of each R&D subelement.

The analysis followed a series of steps:

STEP 1 - R&D project documentation was reviewed to identify the technical objectives, performance goals, latest test results, and any other information that could indicate likely quantitative impacts of each project on the cost of geothermal wells. Expected impacts on

the performance and cost of geothermal plants and wells were identified. This information collection and impact identification effort included sending a letter to each R&D contractor requesting as much impact and benefit evaluation material as each could readily supply.

STEP 2 - The projects were grouped into Standard Technical Areas of projects that had many common or potentially overlapping technical/economic impacts. For example, projects concerning drill bits were grouped into a "Drilling Bits" area, and projects concerning the development of a number of different borehole logging sonde components were grouped into a "Well Logging Instruments" area.

The projects within each Standard Technical Area were then further subdivided into subelements. Each subelement contains one or more R&D projects aiming toward common goals and the same commercializable practical impact.

STEP 3 - Quantitative estimates were made of likely technical/economic impacts of each subelement, the year in which the product(s) of the subelement are likely to be commercially available, the past, present, and anticipated costs to DGE of the subelement, and the degree of success expected for each subelement. The estimates were based on information received from R&D project contractors, project reports and test results, and consultation with DGE program managers.

The quantitative estimates of the technical and economic impacts on electricity production systems were then mathematically transformed into appropriate terms as inputs to a general geothermal

R&D benefits estimation model.

STEP 4 - The R&D benefits model, GEOBEN, was exercised.

The benefits model calculates the total dollar savings that a given set of engineering/economic impacts would produce at electricity plants expected to be installed at 27 U.S. geothermal prospects in the years 1979-2000.

GEOBEN (for "Geothermal R&D Projects Benefits Analysis Code) is described in detail in Volume I of this report. GEOBEN is an expansion of GELCOM, the geothermal levelized busbar cost of electricity model developed at MITRE (1). The benefits model has five main parts:

- A postulated geothermal electricity plant installation scenario for the 27 prospects. This file includes estimates of primary physical characteristics of the sites (e.g., resource temperature, reservoir depth, brine salinity),
- Engineering cost models for geothermal wells and for six types of geothermal electricity plants,
- A R&D technical/economic impacts data file. Impacts derived in Step 3 above for one subelement are placed in this file, and are used by the program to adjust capital and O&M costs for plants expected to go on line after the commercialization date of the R&D subelement.
- A levelized busbar cost model (GELCOM). This model uses the three above files, as well as pertinent financial factor estimates to calculate the levelized busbar cost of electricity at a particular plant in a particular year. And, finally,
- A summation and discount program. This code stores the electricity costs calculated for all the plants in the scenario, and then sums them for the years 1979 to 2000. The calculations include the fiscal impacts of the 1978 Federal Energy Act. The summation

of costs is performed for two cases: with and without the R&D impacts, and discounted to present value (1978 dollars).

The electricity cost difference between the "with R&D" and "without R&D" cases is the estimated economic benefit of the R&D supplement.

As described above, the benefit is then combined with estimates of R&D cost, and degree of success to derive a figure of merit for each subelement.

Implicit in the analysis is an assumption that the reference set of schedules for the growth of electricity production at 27 representative geothermal prospects, herein generally called the "hydrothermal development scenario," is a reasonable basis for estimating benefits of R&D. While hydrothermal-electric development is unlikely to materialize precisely as postulated in the schedules, this site-specific basis for R&D impact assessment is more realistic than generic resource utilization projections.

1.3 Organization of this Volume

The body of this report contains general information of the R&D projects of the Geothermal Drilling Technology Program (Section 2.0). Section 2.0 emphasizes classification of the projects into Standard Technical Areas and Subelements. Section 3.0 discusses specific methods used to analyze benefits from projects in this Program. The analyses are collected in Appendix A. The results of the analyses are collated in Section 4.0. Section 5.0 discusses the results.

Appendix B contains a comprehensive analysis of the likely benefits of seven R&D projects in the geothermal "Well Logging Instruments" technical area.

A separate report describes an engineering/economic model of geothermal well drilling and completion costs, "WELCST," prepared specifically for the analysis of benefits of the R&D projects of this program. (2)

2.0 TECHNICAL AREAS AND PROJECT CLASSIFICATION

The Geothermal Drilling Technology program is concerned with all aspects of geothermal drilling and well completion technology. Its primary objective is to reduce the costs of drilling geothermal wells. Therefore, it concentrates on the development of devices and processes that can withstand the severe conditions of temperature, pressure, and fluid composition that are encountered in drilling and operating geothermal wells.

The six standard technical areas for this program were selected through discussion with the program manager. This section lists the areas and explains the basis for their selection.

Area 1-1: Drilling Bits

This area includes eight projects that seek to improve rotary drilling bits or develop rock removal devices based on novel concepts. Common themes of the projects are to increase the rate of penetration, which would reduce total drilling time; and to increase the life of bits, which would reduce the amount of nonproductive time spent in tripping worn-out bits.

The projects are listed in Table 1.

Area 1-2: Down-Hole Drilling Motors

The two projects in this area are developing downhole drilling motors that are optimized to geothermal drilling conditions. Survivability at high temperatures and matching motor speed and torque to bit requirements are important goals here.

TABLE 1

TECHNICAL AREA 1-1: DRILLING BITS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-1-1	Continuous Chain Bit	Sandia Labs	CO 40789	Develop device that allows replacement of cutting faces of diamond bit while the bit is downhole.
1-1-2	COMPAX Drill Bit	General Electric	CO 12360	Develop improved diamond cutters and bit designs to be incorporated into a new generation of drag bits for all rock types.
1-1-3	Improved Geo- thermal Drill Bit	Terra Tek	CO 71546	Develop high temperature - high pressure drill bit testing rig. Develop bearings and seals for rotary bits to better with- stand high temperature drilling conditions.
1-1-4	Study of ERODRILL Concept	Physics Inter- national	CO 31312	Study designs and economics of a bit that combines rotary and erosive rock removal. Fluid force developed by pro- pellant charges burned immediately above the bit.
1-1-5	Water Jet Coring Bit	Flow Industries	CO 62325	Study the feasibility of high pressure water jet coring for geothermal explo- ration applications.

(Continued)

TABLE 1 (Concluded)

TECHNICAL AREA 1-1: DRILLING BITS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-1-6	Design of Water Jet Drill	University of Missouri	SO 22677	Studies to optimize design of high pressure jets for geothermal drill bits.
1-1-7	CAVIJET Bit Development	Hydronau- tics, Inc.	?	Design of cavitating nozzles for geothermal drill bits.
1-1-8	SUBTERRENE	Los Alamos Sci. Labs	05 ENG 36	Develop electrically heated drill point that makes holes by melting rock.

TABLE 2A

TECHNICAL AREA 1-2: DOWN-HOLE DRILLING MOTORS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-2-1	Down-Hole Drilling Motors	TERRA TEK	CO 71581	Develop high-temperature seals for mud-driven down-hole motors.
1-2-2	Electro Drill Telemetry	General Electric	CO 24033	Develop electrically-driven down-hole drilling motor.

TABLE 2B

TECHNICAL AREA 1-3: DRILLING FLUIDS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-3-1	High Temperature Drilling Fluids	Maurer Engineering	CO 71603	Measure Characteristics of available muds at elevated temperature and pressure.
1-3-2	High Temperature/High Pressure Mud Test Instrument	NL Baroid	CO 55381	Develop mud testing stand with 370°C and 20,000 psi capability.
1-3-3	Temperature Limits of Drilling Fluids	Oklahoma University	SO 55218	Build test stand to measure effects of temperatures to 290°C on mud components.

The projects are listed in Table 2A.

Area 1-3: Drilling Fluids

This area consists of three projects whose common goal is the identification of drilling mud constituents and formulations that retain desired properties for extended times at geothermal drilling temperatures.

The projects are listed in Table 2B.

Area 1-4: Well Logging Instruments

This area consists of seven projects aimed at developing logging sondes or sonde components that can survive geothermal downhole temperatures. While available sondes are advertised to survive 260°C, sondes frequently fail at this temperature. Near term goals are to extend the useful life of many sondes to 275°C. Longer-term goals are targetted at a 350°C goal.

The projects are listed in Table 3.

Area 1-5: Measurements for Drilling and Down-Hole Pumps

The three projects in this area are developing devices for measuring the performance of drilling bits and downhole pumps. Two of the projects are developing downhole instrumentation and telemetry systems. The third is developing a downhole pump testing rig. Projects to develop downhole pumps are included in the Utilization Technology Program (See Volume III).

The projects are listed in Table 3A.

Area 1-6: Descaling Systems

This area contains a single project, which is developing a device

TABLE 3

TECHNICAL AREA 1-4: WELL LOGGING INSTRUMENTS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-4-1	Improved Geo- thermal Logging Tools	Systems, Science, Software	CO 31315	Develop sonde to measure shut-in pressure and temperature to 275°C with- out active electronics down-hole.
1-4-2	Neutron Acti- vation Analysis	IRT	CO 30936	Develop device to measure fractures, fluid flow, porosity, dissolved solids, lithology, formation temperature.
1-4-3	Improved Log- ging Tools & Components	Westing- house	CO 24082	Develop high temperature (275°C) acous- tic sensor for geothermal logging.
1-4-4	Heat Flux Tran- ducer and Thermal Probe	Geosciences	CO 31318	Develop instrument to measure geothermal heat flux and thermal conductivity.
1-4-5	Mechanical Refrigerator	Mechanics Research, Inc.	CO 31309	Develop device to cool logging sondes by mechanical refrigeration.
1-4-6	Electromagne- tic Signal Transmission	Raytheon	CO 22816	Develop electromagnetic borehole tele- metry system.
1-4-7	Improved Temperature Measurement	Spectro Systems	CO 14008	Use materials of selected melting points to measure well temperature while bit is downhole.

that uses cavitating water jets to remove scale rapidly from piping in geothermal power systems. The project is described in Table 3B.

TABLE 3A

TECHNICAL AREA 1-5: MEASUREMENTS FOR DRILLING AND DOWNHOLE PUMPS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-5-1	Downwell Instrumentation for Drilling	Sperry	CO 22817	Define signal collection and transmission requirements for an acoustical telemetry system that can measure well and bit parameters while drilling.
1-5-2	Downwell Instrumentation for pumping	Sperry	CO 22750	Develop instruments and acoustic telemetry system for reporting downhole pump speed, fluid pressure and temperature.
1-5-3	Environmental Simulating Pump Test Rig	Barber-Nichols	2923715	Build test rig for simulating down-hole conditions for pumps.

TABLE 3B

TECHNICAL AREA 1-6: DESCALING SYSTEMS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-6-1	Cavitation Descaling System	Daedalean Associates	CO 12289	Develop a self-contained system for removing scale from pipes.

3.0 METHOD OF ANALYSIS

3.1 Identification of Anticipated Impacts of the R&D Projects on Geothermal Energy Systems

Each R&D project was reviewed to determine which components and processes of geothermal well drilling it might impact. The initial emphasis of this effort was on detecting such impacts and finding appropriate ways to link the impacts to costs of drilling and completing geothermal wells.

Both "positive" and "negative" impacts were sought. For example, a novel drilling bit might promise an increased rate of penetration (positive impact) combined with an increased rate of fuel use due to extra mud flow needed to clean the bit (negative impact). At this stage of the analysis, quantitative estimates of impacts were ignored, except insofar as they indicated relative effects of projects.

Information on impacts was gathered from the following sources:

- A review of the DGE project documentation, especially proposals, progress reports, and available test results.
- Responses to a letter sent to the R&D contractors requesting them to describe and estimate likely impacts of their projects.
- Additional contacts with the R&D contractors by telephone.
- Discussion with the Geothermal Drilling Technology Program Manager at DGE headquarters, and other DGE R&D program managers.
- Surveys of many papers and reports in the open literature on drilling technology and practice.

TABLE 4

EXPECTED IMPACTS OF WELL-DRILLING R&D PROJECTS
ON WELL COST PARAMETERS

R&D PROJECTS	DRILLING OPERATION & COST PARAMETERS																			
	1. BIT LIFETIME	2. RATE OF PENETRATION	3. BIT COST	4. MECHANICAL FAILURE RATE OF BITS	5. TEMPERATURE ON BIT LIFETIME	6. SEAL LIFETIME	7. BIT TESTING COSTS	8. FUEL COSTS WHILE DRILLING	9. SURFACE SUPPORT EQUIPMENT	10. DRILL PIPE COSTS	11. MISHAP RATES AND COSTS	12. SPECIAL SAFETY EQUIPMENT	13. DOWNHOLE MOTOR LIFE	14. DOWNHOLE MOTOR COSTS	15. DIRECTIONAL DRILLING CAPABILITY	16. MUD COST	17. EFFECTS OF MUD ON BITS, ETC.	18. MUD TEMPERATURE LIMITS	19. BOTTOM HOLE TEMPERATURE	20. RIG AUTOMATION
1-1-1. Continuous Chain Bit	X	X	X	X	X															
1-1-2. COMPAX Drill Bit	X	X	X		X															
1-1-3. TERRA TEK Bit	X		X	X	X	X	X													
1-1-4. ERODRILL Concept	X	X	X					X	X											
1-1-5. Water Jet Coring	X	X	X					X	X	X		X								
1-1-6. Water Jet Drilling	X	X	X					X	X	X		X								
1-1-7. CAVIJET	X	X	X					X												
1-1-8. SUBTERRENE	X	X	X	X	X			X	X	X	X									
1-2-1. Down-Hole Drill Motors	X	X		X						X		X	X	X						X
1-2-2. Electro Drill	X	X		X						X		X	X	X						X
1-3-1. HT Drilling Fluids		X									X					X	X	X		
1-3-2. Mud Test Rig		X									X						X	X	X	
1-3-3. Mud Temperature Limits		X									X						X	X	X	
1-4-7. Improved Temp. Measure.																	X	X	X	X
1-5-1. Down Well Instrumentation	X	X									X	X	X							X

This survey indicated that the anticipated impacts fell into three fairly distinct categories:

- (1) Impacts on drilling operations,
- (2) Impacts on well-logging capabilities, and
- (3) Impacts on well-completion operations and well productivity.

Table 4 shows the expected impacts of R&D projects on drilling operations. Note that these projects are drawn from more than one Standard Technical Area. Table 5 provides additional explanation of the impacts cited in Table 4. It should be noted that some of the identified impacts are almost directly relatable to drilling costs, while other impacts (e.g., Directional Drilling Capability) are many technical or economic steps removed from a direct cost impact.

Table 6 shows the expected impacts of R&D projects on well-logging operations. Impacts numbered 22 through 30 all imply the development of a logging sonde (tool) which can (a) provide the indicated type of measurement and (b) survive "geothermal" conditions. Some of these projects are targetted at 275°C survivability goal, others at a 350°C goal. Other development goals are described more explicitly in Appendix B.

It should be noted that a few more years of direct experience in logging geothermal wells and in interpreting those logs will be needed before accurate and precise standards for these sondes can be specified closely. At present, the emphasis is developing tools that can survive high temperatures.

TABLE 5
DESCRIPTION OF WELL COST PARAMETERS FROM TABLE 5

PARAMETER	DESCRIPTION
1. Bit Lifetime	Lifetime (hours) of bit or other penetration device, as a function of rock hardness, drilling fluid type, and bit temperature.
2. Rate of Penetration (ROP)	Instantaneous rate at which bit or other penetrator makes hole in rock (feet/hour), as a function of rock hardness, drilling depth, and drilling fluid used. The assigned rate assumes that the bit is "on bottom" and making hole at the economically optimum rate.
3. Bit Cost	Cost (less salvage value, 1978 \$) of bit or other expendable downhole part of penetration system.
4. Mechanical Failure Rate of Bits	Percentage of nominal bit lifetime (Item 1, above) expected for mechanically complex penetration devices.
5. Effect of Temperature on Bit Lifetime	Percentage of nominal (normal geothermal gradient) lifetime expected at elevated drilling temperatures.
6. Seal Lifetime	Percent of nominal lifetime of mechanical seals used in bits and down-hole motors.
7. Bit Testing Costs	Costs (1978 \$) of laboratory and down-hole tests needed to develop a new bit.
8. Fuel Costs While Drilling	Fuel costs (1978 \$) associated with drilling, including petroleum fuels, electricity, or chemical charges for novel penetration devices.

(Continued)

TABLE 5 (Continued)

DESCRIPTION OF WELL COST PARAMETERS FROM TABLE 5

PARAMETER	DESCRIPTION
9. Surface Support Equipment	Cost (1978 \$/Day) of surface devices (e.g., pumps, generators, compressors) required for drilling.
10. Drill Pipe Costs	Cost changes (1978 \$/foot drilled) due to different modes of use of drill pipe.
11. Mishap Rates and Costs	Rate of incidence and costs of various drilling incidents and accidents, (e.g., doglegs, twistoffs, lost circulation episodes).
12. Special Safety Equipment	Costs of special safety equipment needed for certain novel drilling techniques (e.g., for very high pressure water erosion drilling).
13. Downhole Motor Lifetime	Nominal lifetime of downhole drilling motors (hours), given various rock types, temperatures, and modes of drilling (straight, directional).
14. Downhole Motor Costs	Capital cost and operation expenses for downhole drilling motors (1978 \$).
15. Directional Drilling Capability	Range of drilling conditions (hardness, depth, temperature) under which directional drilling is economically feasible.
16. Mud Cost	Cost of mud (1978 \$/well) during normal drilling and under special conditions.
17. Effects of Mud on Bits and Drill String	Effects of mud characteristics on performance and lifetime of bits, drill string, and mishap rates.

(Continued)

TABLE 5 (Concluded)

DESCRIPTION OF WELL COST PARAMETERS FROM TABLE 5

PARAMETER	DESCRIPTION
18. Mud Temperature Limits	Nominal temperatures below which mud components and formulations retain required characteristics.
19. Bottom Hole Temperature While Drilling	Ability to measure maximum temperature seen by mud and bits while drilling.
20. Rig Automation Capability	Potential for increased ROP, bit life, etc., if drill rig control could be highly automated.

TABLE 6

EXPECTED IMPACTS OF LOGGING INSTRUMENTATION
R&D PROJECTS ON WELL-LOGGING CAPABILITIES

R&D PROJECTS	WELL LOGGING CAPABILITY PARAMETERS ¹											
	21. TEMPERATURE LIMIT ON SONDE	22. TEMPERATURE MEASUREMENT	23. PRESSURE MEASUREMENT	24. FRACTURE MEASUREMENT	25. FLUID FLOW MEASUREMENT	26. POROSITY MEASUREMENT	27. TOTAL DISSOLVED SOLIDS MEASUREMENT	28. LITHOLOGY MEASUREMENT	29. CALIPER MEASUREMENT	30. HEAT FLOW MEASUREMENT	31. SIGNAL TRANSMISSION, LOGGING	32. SIGNAL TRANSMISSION, DRILLING
1-4-1. S ³ Improved Tools	X	X	X									
1-4-2. Neutron Activation	X	X		X	X	X	X	X				
1-4-3. Acoustic Probe	X			X					X	X		
1-4-4. Heat Flux/Conductivity	X										X	
1-4-5. Mechanical Refrig.	X	X	X	X	X	X	X	X	X			
1-4-6. Electromag. Signal	X										X	X
1-4-7. Borehole Temperature	(See Table 5)											

¹ Numbering continued from Table 4.

Table 7 provides fuller descriptions of the impacts listed in Table 6 for logging instruments.

The expected impacts of R&D projects on well-completion and well-productivity parameters are shown in Table 8. Descriptions of the impact parameters are given in Table 9.

It should be noted that the Utilization Technology Branch sponsors R&D projects that (a) affect well costs and productivity and (b) are not shown in Tables 4-9 because they are managed from other programs. The reader should refer to Volume III of this report (Utilization Technology) for R&D projects on downhole pump development and well-flow stimulation, and to Volume IV (Geochemical and Materials Engineering) for projects that impact on drill bit materials, casing materials, and control of scaling and corrosion in geothermal wells.

3.2 Approaches Used to Relate R&D Project Impacts to Geothermal System Parameters

3.2.1 Impacts on Well-Drilling Parameters

Consideration of the impacts listed in Table 4 indicated that either of two approaches to relating R&D-induced changes in technology would be feasible.

First, a "typical geothermal well" could be postulated, based on recent U.S. drilling experience, and economic impacts could then be hand-calculated against that well. This offered the promise of relative simplicity, speed of analysis, and ease of interpretation of results.

TABLE 7
DEFINITIONS OF WELL INFORMATION PARAMETERS

PARAMETER ¹	DESCRIPTION
21. Temperature and Pressure Limits on Logging Tools	Temperature (°C) and pressure (psi) to which sonde can be exposed for say 5 trips of 24 hour duration each before requiring laboratory repairs. (Or other definitions for specific sondes.)
22. Temperature Log	Ability to log down hole temperature.
23. Pressure Log	Ability to log downhole pressure.
24. Fracture Log	Ability to detect presence and location of fractures in borehole wall.
25. Flow Log	Ability to measure velocity of fluid in borehole at specific depths.
26. Porosity Log	Ability to measure formation porosity at specific depths.
27. Total Dissolved Solids Log	Ability to measure TDS in formation fluid at specific depths.
28. Lithology Log	Ability to determine rock type in strata at specific depths.
29. Caliper Log	Ability to measure borehole diameter at all depths.
30. Heat Flow in Exploratory Holes	Ability to measure heat flux and thermal conductivity in exploratory geothermal wells.

(Continued)

TABLE 7 (Concluded)

DEFINITIONS OF WELL INFORMATION PARAMETERS

PARAMETER ¹	DESCRIPTION
31. Signal Transmission While Logging	Ability to transmit signals from logging sonde to the surface. Band requirements may vary for different sondes.
32. Signal Transmission While Drilling	Ability to transmit signals from drill bit instrumentation sub to surface while drilling.

¹ Numbering continued from Table 4.

TABLE 8

EXPECTED IMPACTS OF R&D PROJECTS ON WELL-
COMPLETION AND WELL-PERFORMANCE PARAMETERS

		WELL-COMPLETION AND PRODUCTIVITY PARAMETERS ¹						
R&D PRODUCTS		33. DOWNHOLE PUMP LIFE	34. PUMP O&M COSTS	35. PLANT O&M COSTS	36. PLANT CAPACITY FACTOR	37. GATHERING SYSTEM O&M COSTS	38. WELL O&M COSTS	39. DOWNHOLE PUMP DEVELOPMENT COSTS
1-5-1. Instrumentation, Drilling		(See Table 4)						
1-5-2. Instrumentation, Pumps		X	X	X	X			
1-5-3. Pump Test Rig							X	
1-6-1. Cavitation Descaling		X	X	X				

¹ Numbering continued from Table 6.

TABLE 9

DEFINITION OF WELL PERFORMANCE PARAMETERS

PARAMETER ¹	DESCRIPTION
33. Downhole Pump Life	Nominal lifetime of downhole pump for fluid production.
34. Downhole Pump O&M Costs	Operation and maintenance costs for downhole pumps.
35. Plant O&M Costs	Operation and maintenance costs for geothermal power plant.
36. Plant Capacity Factor	Proportion of year in which plant is producing power.
37. Gathering System O&M Costs	Operation and maintenance costs for fluid gathering pipes.
38. Well O&M Costs	Operation and maintenance costs for geothermal wells.
39. Downhole Pump R&D Costs	Total cost to develop useful downhole pumps for fluid production.

¹ Numbering continued from Table 6.

Second, a computer code could be written that took into account the known variability in some of the most important characteristics of the 27 U.S. geothermal prospects of interest. While this would be a more complex understanding, it offered some important advantages:

- Drilling condition parameters could closely mimic experience at given sites,
- Relationships between site characteristics and drilling technology and tactics could be made more explicit, and
- The computer code approach would allow more accurate analyses of sensitivity relationships between R&D impacts and prospect characteristics.

The second approach was finally selected because it offered the possibility of much more accurate estimates of R&D project benefit impacts on specific prospects.

The approach resulted in the preparation of a FORTRAN code, "WELCST", that calculates the cost of geothermal wells at each of 27 prospects, given either current technology or technology expected to result from R&D projects. WELCST is documented in a separate report (2), and is discussed here only briefly.

WELCST accepts as primary inputs: (a) Characteristics of each of the 27 prospects, (b) Geothermal well designs, and (c) Estimated changes in drilling performances and/or cost parameters expected to result from one or more R&D projects. The output from WELCST is an estimated cost for a geothermal production well at each of the 27 prospects, under the assumption from that the anticipated products of R&D have replaced, or compete with on economic grounds) selected

FIGURE 1
STRATEGY FOR ESTIMATING BENEFITS FROM
GEOTHERMAL DRILLING TECHNOLOGY PROJECTS

portions of conventional technology. WELCST also can compute the expected costs of wells at each prospect assuming that only current technology is available (this is called the "baseline" case.)

The well cost outputs from WELCST are used as input to the GEOBEN program to calculate the cost savings benefit of the R&D impacts at the 27 prospects.

Figure 1 diagrams this strategy for estimating benefits of the Geothermal Drilling Technology projects. Table 11 presents some of the major variables to which the calculations performed by WELCST are sensitive.

The reader who desires further details on WELCST algorithms and logical flow should consult Reference 1. Details on how WELCST was used to evaluate benefits of specific R&D projects are presented in Appendix A, "Project Benefit/Cost Analyses".

3.2.2 Impacts on Well-Logging Capabilities

The well-logging instrumentation R&D, projects described in Tables 4 and 6 have technical objectives and performances goals that impact on improved logging sondes. Estimating benefits for the projects or sondes presented a formidable problem since many variables intervene between the existence of an information gathering instrument and its impacts on well cost or cost of power production.

For these projects it was decided that the most valid approach to benefit/cost evaluation would be to identify the most important intervening variables, and trace the relationships between

TABLE 10

MAJOR PARAMETERS OF WELCST CODE

PARAMETER CATEGORY	SPECIFIC PARAMETERS AND RELATIONSHIPS
Geothermal Prospect Characteristics	Well Depth, Rock Hardness, Formation Temperature, Well Design
Geothermal Well Designs	Borehole Diameter and Depth Intervals, Drilling Fluid, Casing Plan, Open or Cased Hole Bottoms, Multiple Step Outs
Drill Bit Parameters	Bit Type, Diameter, Rate of Penetration, Bit Life, Bit Cost, Effect of Drilling Fluid on ROP, Effect of Rock Hardness and Drilling Depth on ROP, Effect of Drilling Temperature on Bit Life
Footage Costs	Rate of Penetration, Bit Life and Cost, Hole Diameter, Drilling Depth, Tripping Cost, Rig Rent Rate
Other Cost Accounts	Downhole Motor, Mud, Fuel, Site Preparation, Rig Up and Down, Water, Waste Disposal, Surface Equipment, Well Head, Casing, Cement and Services, Mishaps, Miscellaneous Transportation, Logging Services, Supervision and Overhead, Miscellaneous
Drilling Mishaps	Frequency of Mishaps as Functions of Well Depth and Rock Hardness, Cost to Recover from Mishaps: Doglegs, Lost Circulation, Fishing for Junk, Fishing and Recovering Drill Stem, Fishing but not Recovering Drill Stem, Sidetracking when first Bottom is Dry
Engineering Variables	86 Engineering Performance and Cost Relationships that can be Affected by R&D projects

technology improvements and expected benefits through cross-impact matrices containing those variables. The strategy shown in Figure 2 was designed in collaboration with the manager of the Geothermal Well-Logging Instrumentation Program, Sandia Laboratories.

The main steps of the analysis were:

- (1) Estimate the probable impacts of each R&D project upon each of about 10 specific logging capabilities deemed desirable in geothermal wells. This resulted in Matrix 1 of Figure 2.
- (2) Estimate the probable impacts of each logging capability on each of 10 drilling, completion, or production operations in geothermal prospects. This resulted in Matrix 2 of Figure 2.
- (3) Estimate the degree to which the impacts identified in Step 2 would alter the technical and cost parameters of each operation.
- (4) Convert the estimates from Step 3 to input variables for WELCST, GEOBEN, or both, to calculate an expected economic benefit for the anticipated improvement in each of the drilling and completion operations.
- (5) Carry the expected benefits backward through Matrix 2 to assign benefits to specific logging capabilities in proportion to the impacts of each capability on specific drilling operations.
- (6) Finally, carry the calculated benefits backward through Matrix 1 to assign benefit to specific R&D projects in proportion to the impacts of each project on specific logging capabilities.

The details of the analysis are presented in Appendix B of this report. The analysis incorporated much current knowledge of how logging results are used, and provides a very useful structure for continued input from geothermal drillers and operators on how this subprogram can best meet their needs for improved geothermal logging

FIGURE 2
STRATEGY FOR ESTIMATING BENEFITS FROM
WELL LOGGING INSTRUMENTATION PROJECTS

sondes.

3.2.3 Impacts on Well-Completion and Well-Productivity Parameters

The R&D projects that affect these parameters (see Table 8) were evaluated on an individual basis, and did not require the formulation of any new disaggregated models of technical performance or costs.

The analyses are included in Appendix A.

3.3 Grouping of Projects into R&D Subelements

In most instances the projects in this program could be evaluated on an individual basis. But in a few cases, R&D subelements were formulated as consisting of more than one project.

- (1) Three projects on erosion drilling (1-1-5, 1-1-6, and 1-1-7) were grouped together into Subelement 1-1-E.
- (2) The two projects in the Downhole Drilling Motors area were treated as a single subelement.
- (3) The three projects in the Drilling Fluids area were treated as a single subelement.
- (4) The seven projects in the Well-Logging Instruments area are reported as a single subelement. These projects were analyzed as a group, but in a way that allowed estimating a benefit/cost ratio for each project. The individual benefit/cost ratios are reported in Section 10.0 of Appendix A.

3.4 Identification of Subelement Goal

The goal of the subelement was interpreted from the objectives of the projects contained in the subelement. The developed goal had to:

- Represent and include the R&D results that the projects are intended to achieve.
- Be a method, process, technology or piece of hardware which is able to be commercialized and, therefore, would produce an identifiable cost-reducing impact in geothermal electricity production systems.

3.5 Subelement Costs

Subelement costs are the total R&D costs of all the projects contained in the subelement. These costs include sunk and planned costs. The sunk costs (Prior to FY1978) and the planned cost for FY1978 were taken from the DGE Management Information System (MIS) sheets. Costs planned for Fiscal years 1979-1983 were provided by DOE/DGE. Since costs for a fiscal year were provided in current year dollars, costs were discounted to 1978 dollars. A discount rate of 10% per year was used.

3.6 Estimation of the Magnitude of Impacts on System Parameters

"System Parameters" here are the input variables of the GEOBEN benefit model. The impacts on system parameters were estimated by comparing the costs or performance of current technology with those of the new technology to be developed by the R&D subelement.

Since the analysis is primarily an estimate of future impacts, establishment of absolute magnitudes was impossible. It was deemed appropriate to postulate a range of changes rather than a single-valued change. The range limits are called pessimistic and optimistic estimates. The pessimistic and optimistic estimates are used to reflect the uncertainty inherent in these future oriented analyses.

As stated above, the estimates of the magnitude of impacts relied heavily on discussions with the R&D contractors and DGE Program Managers, and on published and unpublished conceptual analyses and R&D test results.

3.7 Impact Year

The impact year of the subelement is the year when the results of the subelement can be used and commercialized. It was determined from the reported contractor's schedule.

The GEOBEN benefits model assumes that an engineering/technology improvement must be available for two years prior to the "on-line" date for a geothermal power plant in order to be incorporated into and reduce the cost of the plant. Thus, an improved heat exchanger available at the start of 1985 (impact year) would be incorporated only into plants going into service at the end of 1986 (on-line year) and later.

In the cases where developmental refinements are required after the year of commercialization, the year of impact was selected by a balanced consideration of contractor's schedule and estimated impacts on system parameters.

3.8 Degree of Success

The impacts on system parameters of the subelement were estimated by assuming that:

- The R&D activities will be successfully completed and their objectives are achieved.
- Other projects or subelements which impact the same system parameters will not affect the use of the new technology developed in the subelement under consideration.

Thus the benefit estimated for each subelement is idealistic. It neglects partial success or lack of success during R&D efforts, and assumed that the product of R&D will in fact be used in all plants where it could be used. To account for losses between R&D goals and commercial use of R&D products, a "degree of success" was estimated for each subelement.

The Degree of Success of a subelement is defined as a factor that includes the possibility of partial success in R&D and partial use of the subelement results. It was estimated by examining the R&D approach, and by estimating the share of market of the resulting technology relative to existing technology and technology currently being developed. The estimate also considered market factors which are not considered in the GEOBEN benefits model.

Estimating the Degree of Success was facilitated by dividing the required R&D work into six different (often sequential) types of R&D activities. These types of work are based in part on the Department of Defense Categories for describing defense R&D projects,

with modifications to match special characteristics of DGE program policies (1).

The six types of work are:

- (i) Preliminary Study - Initial analysis and R&D technical planning efforts to determine the general merit of new R&D concepts. This may include literature searches, gathering of expert opinion, technology forecasting, etc. The product of such studies is advice about what, if any, R&D efforts should be undertaken to develop the concept into a commercially useful product.
- (ii) Basic Research - Scientific study and experimentation directed toward increasing knowledge and understanding in those fields of science related to long-term geothermal energy production needs. It provides fundamental knowledge for the solution of identified technical and engineering problems. It also provides part of the base for exploration and development of advanced technology and new or improved functional capabilities.
- (iii) Exploratory Development - The dominant characteristic of this type of effort is that it is pointed toward specific geothermal technology problem areas and opportunities to develop proposed solutions, determining their parameters, and evaluating their feasibility and practicality. Such efforts vary from fairly fundamental applied research to quite sophisticated broad-based hardware, study, programming, and planning efforts. Such efforts thus may include minor engineering and development work to prove the feasibility of technical components of a proposed solution if carried out to assess the value of the system as a whole. The main output of such efforts are paper reports of designs and analyses of designs of new or improved technology for producing or utilizing geothermal energy. Evaluation of the value of these outputs relies on expert review and development of consensus within the technical branches of the Division of Geothermal Energy.
- (iv) Advanced Development - Includes all projects which have moved into the development of hardware for experimental and engineering tests. These projects result in hardware devices that are viewed as engineering prototypes whose size of performance scale falls short of that of products designed to be components of geothermal energy extraction

or production systems. Evaluation of these prototype devices will typically be based on expert review of engineering performance data provided by the contractor who develops the device.

- (v) Engineering Development - These projects develop hardware devices with characteristics and performance on a scale deemed to be appropriate for components of commercial geothermal energy systems. Evaluation of these devices will be based on operational tests conducted by contractors other than the developing contractor. The emphasis is on achieving performance that significantly reduces the overall cost of producing and utilizing geothermal energy.
- (vi) Demonstration and Commercialization - Activities and projects intended to induce the commercial sector to utilize new technology with proven performance/cost improvements. Evaluation of these activities is based on a combination of expert opinion and technology utilization assessment.

The stage or stages into which each subelement fell at the start of F.Y.1978 was estimated, and indicated in the analysis. The likelihood of technical success was assumed, in general, to increase as a subelement moved through the stages.

By the time a subelement reaches stage v, there has usually been accumulated enough test data to allow fairly good estimates of the technical impact of the subelement on future electric power systems. The likelihood of technical success is then high, and market penetration factors then begin to dominate the estimated Degree of Success.

3.9 Final Calculations

The procedure up to the point generated four quantitative estimates: R&D costs, impacts on system parameters, year of impacts and degree of success. In the subsequent steps of the

procedure, the impacts on system parameters and year of impact were used as inputs to the GEOBEN computer model to calculate the estimated (idealistic) benefit. Pessimistic and optimistic estimates were made separately, corresponding to the pessimistic and optimistic estimates of technical impacts on system parameters.

Each estimated benefit was then multiplied by Degree of Success to find the expected benefit, the cost reduction actually anticipated to occur.

The final benefit/cost ratios were calculated by dividing the expected benefit by estimated R&D costs. Two estimates of R&D cost were made for different purposes. For purposes of inputs to decisions about project selection, only current (F.Y.78) plus future R&D costs are placed in the demoninator of the benefit/cost ratio. This forward-looking benefit/cost ratio is called the "Figure of Merit". It does not consider sunk costs, specifically to steer away from any tendency to throw good money after bad.

The second estimate of R&D costs included sunk costs as well as current plus future costs. The benefit/cost ratio based on these total costs is called the "Historical Figure of Merit" to emphasize the relative merit of each subelement through its entire history, from actual beginning to predicted conclusions.

Thus the analysis culminates in four estimates of benefit/cost ratio which indicate the influence of pessimistic and optimistic estimates of impact, and the absence or presence of consideration of sunk costs.

4.0 RESULTS OF THE BENEFIT/COST ANALYSES

The results of the analyses are presented here. The details of the analyses are in Appendix A.

The following definitions are offered as aids to interpretation of the tables of results.

- Sunk Costs - R&D costs incurred through FY1977, inflated at 10%/year to 1978 dollars.
- Planned Costs - Expected future (including FY1978) R&D costs to the Federal program. These include costs planned by DGE, and in many cases "additional" costs estimated by MITRE to be required to bring the anticipated products of the subelement to commercialization.
- Date of Commercialization - Year in which the product of the subelement is expected to be available for commercial incorporation into geothermal wells or electric plants.
- Estimated Benefit - Savings in the costs of electricity production in the years 1979-2000 at the 27 U.S. liquid-dominated geothermal prospects included in the hydrothermal electricity development scenario. This benefit is based on technical considerations only, and is the modelled consequence of either a pessimistic or optimistic estimate of the degree to which the R&D subelement activities will alter technology performance and/or costs. Expressed in 1978 dollars; assumed discount rate is 10% per year.
- Degree of Success - A scaling factor between 0.0 and 1.0 that reflects MITRE's estimate of the degree to which the possible (estimated) benefit will be delivered commercially. The estimate of degree of success includes such considerations as probability of technical success in the R&D activities, competition between subelement products for shares of the same market, and sundry factors that could affect commercial use of the R&D product.
- Expected Benefit - Product of the estimated benefit and degree of success: final estimate of how much

savings in the cost of electricity production is most likely to result from the R&D subelement. While this value does not appear in the tables in this section, it is reported elsewhere. (Appendix A, and Vol. I)

- Figure of Merit - Expected benefit divided by planned R&D costs. This is the benefit/cost ratio for the R&D subelement. It disregards sunk costs, to provide a forward look of the relative merit of continued investment in the R&D subelement.
- Historical Figure of Merit - Expected benefit divided by sum of sunk plus planned costs. This value provides an estimate of the relative value of each subelement throughout its entire life-span. While this value generally does not appear in the tables in this Section, it is reported elsewhere (Appendix A, and Volume I).

The results the Drilling Bit technical areas are shown in Table 11. The reader should note that the benefits estimated for subelement 1-1-F, SUBTERRENE System derive from potential use of this drilling system at geopressured and hot dry rock geothermal prospects, and do not reduce potential costs at liquid-dominated geothermal electric plants.

The results for all other technical areas in this program are shown in Table 12.

TABLE 11
RESULTS OF THE BENEFIT/COST ANALYSIS FOR STANDARD TECHNICAL AREA 1-1: DRILLING BITS

SUB-ELEMENT ID CODE	SUBELEMENT TITLE (CONTRACTORS)	COST (\$ 10 ³)		DATE OF COMM.	ESTIMATED IMPACTS		ESTIMATED BENEFIT (\$ 10 ⁶)		DEGREE OF SUCCESS	FIGURE OF MERIT ²	
		SUNK +FY77	PLANNED FY78+ 1		ON ENGINEERING AND ECONOMIC VARIABLES	ON HYDROTHERMAL ELECTRIC SYSTEM PARAMETERS	PESSI- MISTIC	OPTI- MISTIC		PESSI- MISTIC	OPTI- MISTIC
1-1-A	Continuous Chain Bit (Sandia)	1302	755	1984	<ul style="list-style-type: none"> • Bit life=9.4x to 12.8x nominal. • Bit cost=12x nominal. 	<ul style="list-style-type: none"> • Replaces conventional diamond bit to save 2.4% to 3.6% of well cost. 	76.4	112.3	0.80	81	119
1-1-B	COMPAX Bit (General Electric)	207	727	1981	<ul style="list-style-type: none"> • ROP=1.5x to 2.0x nominal. • Bit life=3.0x to 4.0x nominal. • Higher bit cost. 	<ul style="list-style-type: none"> • Could save 14.3% to 20.5% of cost of typical well, when used. 	447.3	642.7	0.50	492	707
1-1-C	Improved Geothermal Bits (Terra Tek)	829	470	1981	<ul style="list-style-type: none"> • Bit life=2.0x to 3.0x while air drilling. • Bit cost=30% higher. 	<ul style="list-style-type: none"> • Could save 7%-12% of cost of air-drilled wells. 	132.3	108.4	1.00	282	443
1-1-D	ERODRILL Concept Study (Physics International)	64	0	(1985)	<ul style="list-style-type: none"> • Uncertain trade off between increased ROP and great cost of propellant charges. 	<ul style="list-style-type: none"> • Not expected to be developed. 	0.0	223.1	0.00	0	0

(Continued)

TABLE 11 (Concluded)

1-1-E	Erosion Drilling (Flow Ind., U. Missouri, Hydronautics)	831	655	1982	<ul style="list-style-type: none"> • High pressure erosion drilling probably not economical for hydrothermal sites. • CAVIJET bit might increase ROP by 10% to 20%; bit cost might be about 1.3x nominal. 	<ul style="list-style-type: none"> • CAVIJET might save 0.6% to 2.0% of cost of well drilled entirely in mud. 	8.9	30.4	0.80	11	37
1-1-F	SUBTERRENE System (LASL)	2193	6053	(1990)	<ul style="list-style-type: none"> • Not economical for hydrothermal sites in scenario. • Not currently under development by DGE or other Federal agency. 	<ul style="list-style-type: none"> • Might save 10% to 20% of deep geopressed or hot dry rock wells. 	500.0	1100.0	0.30	25	55

(1) Includes DGE planned costs plus MITRE estimates of additional R&D costs needed to bring the subelement to completion.

(2) FIGURE OF MERIT = (ESTIMATED BENEFIT x DEGREE OF SUCCESS)/(PLANNED R&D COST)

TABLE 12

RESULTS OF BENEFIT/COST ANALYSES FOR STANDARD TECHNICAL AREAS 1-2: DOWNHOLE DRILLING MOTORS,
 1-3: DRILLING FLUIDS, 1-4: WELL LOGGING INSTRUMENTS,
 1-5: MEASUREMENTS FOR DRILLING AND DOWNHOLE PUMPS, AND 1-6: DESCALING SYSTEMS

SUB-ELEMENT ID CODE	SUBELEMENT TITLE (CONTRACTORS)	COST (\$ 10 ³)		DATE OF COMM.	ESTIMATED IMPACTS		ESTIMATED BENEFIT (\$ 10 ⁶)		DEGREE OF SUCCESS	FIGURE OF MERIT ²	
		SUNK +1977	PLANNED 1978+1		ON ENGINEERING AND ECONOMIC VARIABLES	ON HYDROTHERMAL ELECTRIC SYSTEM PARAMETERS	PESSI- MISTIC	OPTI- MISTIC		PESSI- MISTIC	OPTI- MISTIC
1-2-A	Downhole Drilling Motors (Terra Tek, General Electric)	1304	3139	1985	<ul style="list-style-type: none"> • Make directional drilling feasible at hydrothermal prospects at reasonable cost. • Increase ROP by 25% to 50% in straight hole drilling; reduce motor use costs by 30%. 	<ul style="list-style-type: none"> • 50% increase in flow per well. • 10% to 20% increase in cost per well. • Reduce cost per well by 3.8% to 9.3%. 	255.5	592.5	0.80	65	151
1-3-A	Drilling Fluids (Maurer, Baroid, and Oklahoma University)	494	3239	1983	<ul style="list-style-type: none"> • Mud cost per well reduced by 20% to 50%. • Decrease of 20% to 40% in lost circulation incidents. • 25%-50% decrease in twist-off frequency. • Increased air drilling, if H.T. foam is developed. 	<ul style="list-style-type: none"> • 5% to 10.5% reduction in cost per typical well. 	242.0	496.5	0.50	37	77
1-4-A	Well-Logging Instruments (7 contracts; see Appendix B for analyses.)	805	1490	1983	<ul style="list-style-type: none"> • Multiple impacts on diverse drilling and completion operations. 	<ul style="list-style-type: none"> • 1.9% to 5.6% reduction in average cost per well. 	89.7	261.7	0.74	63	192

(Continued)

TABLE 12 (Concluded)

1-5-A	Downhole Instrumentation for Drilling (Sperry)	417	1459	1985	<ul style="list-style-type: none"> • 15% increase in effective ROP. • 15% decrease in twist-off frequency. • 20% reduction in dogleg frequency. • Reduced wireline running time. • Added cost of \$2K to \$3K per day. 	<ul style="list-style-type: none"> • 0.7% to 3.0% decrease in average cost per well. 	31.9	144.0	0.50	11	49
1-5-B	Downhole Instrumentation for Pumps (Sperry)	427	0	1982	<ul style="list-style-type: none"> • 10%-20% reduction in downhole pump O&M costs. • 0.5% to 1.0% increased pumping efficiency. 	<ul style="list-style-type: none"> • Same as engineering/economic impacts. 	85.0	170.0	0.50	100 ³	199 ³
1-5-C	Environmental Simulating Downhole Pump Test Rig (Barker-Nichols)	24	165	1980	<ul style="list-style-type: none"> • Reduced R&D costs for development of downhole pumps. 	<ul style="list-style-type: none"> • Direct cost saving assumed transferrable to overall electricity production costs. 	1.5	3.0	1.00	8	16
1-6-A	Cavitation Descaling System (Daedalean)	227	100	1980	<ul style="list-style-type: none"> • 10%-20% lower capital cost for heat exchangers. • 20%-50% lower O&M cost for heat exchanger. 	<ul style="list-style-type: none"> • 10%-20% reduction in heat exchanger capital cost. • 12%-30% lower utility Process Mechanical O&M Costs. 	35.4	73.3	0.80	283	586

(1) Includes DGE planned costs plus MITRE estimates of additional R&D costs needed to bring the R&D subelement to completion.

(2) FIGURE OF MERIT = (ESTIMATED BENEFIT X DEGREE OF SUCCESS)/(PLANNED R&D COST)

(3) Since subelement activities are completed, there are no planned or additional Federal R&D costs. Therefore the Figure of Merit is infinite. The listed values are for the "Historical Figure of Merit" based on total R&D costs, in this case, sunk costs only.

5.0 DISCUSSION

5.1 Projects in the Context of the Program

To summarize the merit of the R&D activities in the Geothermal Drilling Technology program, Table 13 lists the costs and benefits of the R&D subelements in decreasing order of optimistic Figure of Merit (Benefit/Cost Ratio). The subelements are split into three groups in Table 13 because they impact variously on:

- (a) Drilling Costs at Hydrothermal Electric Plant Sites,
- (b) Other Costs at Hydrothermal Electric Plant Sites,
and
- (c) Drilling Costs at geopressured and hot dry rock sites.

The trade off between planned R&D costs and expected benefits are shown in Figure 3 for the impacts of R&D on drilling costs at hydrothermal electric plant sites.

The overall benefit/cost ratio for all subelements in the program, as it is tentatively planned out during and after FY78 is between 65 and 126 (bottom line of Table 13). If sunk costs are included (Historical Figure of Merit), the benefit/cost ratio is between 43 and 84.

With respect to 1979-2000 developments at the 27 U.S. liquid-dominated geothermal prospects, these R&D efforts, if completed are estimated to offer potential savings of between \$965. million and \$1,823. million due to impacts on drilling costs, and savings of between \$72. million and \$146. million due to impacts on other costs.

TABLE 13

BENEFITS AND PLANNED COSTS OF THE GEOTHERMAL DRILLING TECHNOLOGY R&D PROGRAM SUBELEMENTS

SUB-ELEMENT ID CODE	SUBELEMENT TITLE	EXPECTED BENEFIT ¹ (\$ 10 ⁶ , 1978)				PLANNED COST ² (\$10 ⁶ , 1978)		FIGURE OF MERIT			
		BY SUBELEMENT		CUMMULATIVE				(PLANNED COSTS)		(PLANNED & SUNK COSTS)	
		PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC	BY SUM- ELEMENT	CUMMU- LATIVE	PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC
A. SUBELEMENTS WITH IMPACTS ON DRILLING COSTS AT HYDROTHERMAL ELECTRIC PLANT SITES:											
1-1-B	COMPAX Drill Bit	357.8	514.2	357.8	514.2	0.727	0.727	492.0	707.0	359.0	516.0
1-1-C	Terra Tek Bits	132.3	208.4	490.1	722.6	0.470	1.197	282.0	443.0	102.0	160.0
1-2-A	Downhole Motors	204.4	474.0	694.5	1196.6	3.139	4.336	65.1	151.0	46.0	107.0
1-4-A	Logging Sonde Components	65.3	192.4	759.8	1389.0	1.490	5.826	43.8	129.0	28.5	83.8
1-1-A	Continuous Chain Bit	61.1	89.8	820.9	1478.8	0.755	6.581	81.0	119.0	29.7	43.7
1-3-A	High-Temperature Drill Fluids	121.0	248.2	941.9	1727.0	3.239	9.820	37.4	76.6	32.4	66.5
1-5-A	D.H. Instru. for Drilling	16.0	72.0	957.9	1799.0	1.459	11.279	11.0	49.3	8.5	38.4
1-1-E	Erosion Drilling	7.1	24.3	965.0	1823.3	0.655	11.934	10.9	37.1	4.8	16.4
1-1-D	ERODRILL Concept	0.0	0.0	965.0	1823.3	0.000	11.934	0.0	0.0	0.0	0.0
	SUBTOTAL	965.0	1823.3	965.0	1823.3	11.934	11.934	80.9	153.0	52.9	99.9

(Continued)

TABLE 13 (Concluded)

B. SUBELEMENTS WITH IMPACTS ON OTHER COMPONENTS OF HYDROTHERMAL ELECTRIC PLANT SITES:											
1-5-B	D.H. Instru. for Pumps	42.5	85.0	1007.5	1908.3	0.000	11.934	-----	-----	99.5	199.0
1-6-A	Cavitation Descaling	28.3	58.6	1035.8	1966.9	0.100	12.034	283.0	586.0	86.5	179.0
1-5-C	Pump Test Rig	1.5	3.0	1037.3	1969.9	0.165	12.199	9.1	18.2	7.9	15.9
	SUBTOTAL	72.3	146.6	1037.3	1969.9	0.265	12.199	273.0	553.0	76.7	155.0
C. SUBELEMENT WITH BENEFIT AT GEOPRESSURED AND HOT DRY ROCK SITES, BUT NOT HYDROTHERMAL SITES:											
1-1-F	SUBTERRENE System	150.0	330.0	1187.3	2299.9	6.035	18.234	24.9	54.7	18.2	40.1
	OVERALL TOTAL	-----	-----	1187.3	2299.9	-----	18.234	65.1	126.0	43.3	83.9

(1) Product of calculated benefit and degree of success.

(2) Includes MITRE estimates of costs required beyond current DGE plans.

FIGURE 3
EXPECTED BENEFIT VS. PLANNED PLUS ADDITIONAL R&D COST
FOR THE WELL DRILLING AND COMPLETION SUBELEMENTS OF THE
GEOHERMAL DRILLING TECHNOLOGY R&D PROGRAM

The largest contributions to these savings are expected to be the development of the COMPAX drilling bits (\$358-\$514 million), Terra Tek drilling bits (\$132-\$208 million), Downhole Motors (\$204-\$474 million), and High-Temperature Drilling Fluids (\$121-\$248 million). The first two of these subelements are nearing completion with field tests of hardware. The latter two require substantial future R&D activities.

5.2 Benefit/Cost Ratios of Technical Areas

The subelements within each of the six Technical Areas of this program were grouped, and an overall benefit/cost ratio was estimated for each area, as shown in Table 14. Definitions of values are as described in Section 4.0.

With the exception of the Descaling area, which consists of a single excellent project, the optimistic figure of merit does not vary markedly across the technical areas. This is true whether benefit/cost ratios are based on either planned costs only or on total R&D costs. The Downhole Motor area generally appears to be the most advantageous, while Drilling Fluids and Measurements for Drilling and Pumps fall at the lowest end of the spectrum.

When the SUBTERRENE estimates are removed from the Drill Bits area in Table 14, the values for that area are changed to \$3296K sunk costs, \$2607K planned costs, \$558.3 million pessimistic expected benefit, \$836.7 million optimistic expected benefit, Figure of Merit ranging from 214 to 321, and Historical Figure of Merit ranging from 94.6 to 142. Thus, with respect to potential cost saving impacts at

TABLE 14
BENEFIT/COST RATIOS OF STANDARD TECHNICAL AREAS
IN THE GEOTHERMAL DRILLING TECHNOLOGY R&D PROGRAM

STANDARD TECHNICAL AREA	COST (\$1000, 1978)		EXPECTED BENEFIT ¹ (\$ MILLIONS, 1978)		FIGURE OF MERIT ²		HISTORICAL FIGURE OF MERIT ³	
	SUNK ←FY77	PLANNED FY78→	PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC	PESSI- MISTIC	OPTI- MISTIC
Drill Bits	5,489	8,642	708.3	1,166.7	82.0	135.0	50.1	82.6
Downhole Motors	1,304	3,139	204.4	474.0	65.1	151.0	46.0	107.0
Drilling Fluids	494	3,239	121.0	248.2	37.4	76.6	32.4	66.5
Logging Sondes	805	1,490	65.3	192.4	43.8	129.0	28.5	38.8
Measurements for Drilling & Pumps	868	1,624	60.0	160.0	36.9	98.5	24.1	64.2
Descaling	227	100	28.3	58.6	283.0	586.0	86.5	179.0
ENTIRE PROGRAM	9,187	18,234	1,187.3	2,299.9	65.1	126.0	43.3	83.9

(1) Product of calculated benefit and degree of success.

(2) Includes planned and additional costs only.

(3) Includes sunk, planned, and additional costs.

liquid-dominated geothermal electric sites, to which SUBTERRENE is expected to make no contribution, the Drill Bit area provides both the largest expected benefits and the highest benefit cost ratios.

5.3 Potential Impacts of Program on Costs of Hydrothermal Geothermal Electric Plants

Looking back at Table 13 the expected benefit at hydrothermal electric plants is estimated to be \$965. to \$1823. million for drilling costs, and \$72. to \$147. million for other costs. (This excludes benefits from the SUBTERRENE subelement). These sum to $\$965. + 72. = \$1037.$ million (pessimistic) and $\$1823. + 147. = \$1970.$ million (optimistic), present value in 1978 dollars. This benefit is the total saving of electricity production costs for power plants expected by DGE to be installed in the years 1979 to 2000 at 27 U.S. liquid-dominated geothermal prospects.

If current technology only (no impacts from R&D) is assumed, the total electricity production cost (capital and O&M costs) for the hydrothermal scenario, as estimated by the GEOBEN model, is \$10.928 billion (present value, 1978 \$). Approximately \$4.700 billion of this is due to the capital (drilling) costs of the wells needed for the plants.

Thus the Geothermal Drilling Technology Program, most of whose technological impacts are expected to be commercialized by 1985, promises benefits that could reduce the cost of geothermal electricity by $(100 \times 1.037/10.928) = 9.5\%$ to $(100 \times 1.970/10.928) = 18.0\%$. Considering geothermal well capital costs alone, the impacts of the

program could reduce drilling and completion costs by $(100 \times 0.965/4.700) = 20.5\%$ to $(100 \times 1.823/4.700) = 38.8\%$.

In recent DGE drilling R&D program plans, it has been estimated that continuing research could reduce the cost of geothermal wells by 25% (in constant dollars) by 1985. The present analysis supports this estimate, and suggests the savings may be even greater.

5.4 Major Conclusions of This Analysis

The following major conclusions are drawn from the benefit/cost analysis of the Geothermal Drilling Technology R&D Program:

- As an average across the U.S. scenario for geothermal electricity development, the program activities could reduce electricity costs by 9.5% to 18.0%.
- The cost of geothermal wells at these sites could be reduced by 20% to 39% by 1985.
- There is good balance of funds distribution across the six technical areas of this program, as evidenced by fairly uniform benefit/cost ratios across the spectrum of areas.
- The largest share of the expected benefits come from R&D activities in the Drilling Bits area.
- Continued R&D activity is needed to realize potentially large cost savings in the areas of Downhole Motors and Geothermal Drilling Fluids.
- The overall benefit/cost ratio for the program falls between 65 and 126, based on FY78 plus anticipated future R&D costs.

LIST OF REFERENCES

1. Dhillon, H.S. and D. J. Entingh, "An R&D Project Management and Selection System for the Utilization Technology Branch, Division of Geothermal Energy, Volume III - Project Selection Procedure and Benefit/Cost Analysis", Report MTR-7694, The MITRE Corporation/Metrek Division, May 1978.
2. Entingh, D.J. and A. Lopez, "WELCST: Engineering Cost Model of Geothermal Wells", Report M-78-86, The MITRE Corporation/Metrek Division, December 1978.

APPENDIX A

GEOTHERMAL DRILLING TECHNOLOGY
R&D PROJECT BENEFIT/COST ANALYSES

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1.0 INTRODUCTION

1.1 General Introduction

This section presents details of the benefit/cost analyses of R&D Subelements of the DGE Geothermal Drilling Technology R&D Programs. Each subsequent section describes the analysis for a single subelement, using a more-or-less uniform format.

The approach for the analyses is described in the body of the report. As mentioned there, these analyses required the preparation of a computerized engineering/economic model of the cost of geothermal wells, "WELCST," which is documented in MITRE Report M-78-86. The documentation of the first few analyses presented below illustrate explicitly how technological impacts expected from R&D projects were translated into inputs to the WELCST model.

1.2 "Mud-Drilled" and "Air-Drilled" Scenarios

One of the difficult problems in this analysis was to estimate the relative amounts of geothermal footage that might be drilled using air or using water as the principal component of the drilling fluid. Here, "air" is taken to mean air or foam, while "water" is taken to mean fairly clean water or water-based mud of various compositions and densities. Oil-based drilling fluids were excluded from the analysis because of the commonly held opinion (although the evidence is uncertain) that oil-based muds are likely to damage geothermal formations, reducing the production per well of hot water or steam.

Mud is used as the drilling fluid in most holes because its weight counterbalances formation pressures, it suspends and lifts cuttings efficiently, it cools the drill bit, and lubricates the drill string. Air can be used when the formation is underpressured, or when formation fluids do not enter the borehole. When air can be used, rates of penetration can be two to four times higher than that in mud.

From a historical perspective, most of U.S. geothermal drilling has been done either at the Geysers field or the Imperial Valley field, both in California. Air drilling must be used within the live steam formation at the Geysers because mud overpressures the formation, leading to both lost circulation and potential formation damage. On the other hand, Imperial Valley wells are drilled in mainly soft sedimentary rock, where conventional oil-field mud formulation practices are generally effective.

To distinguish between air and mud drilled footage is essential in the present analysis because the fluids have quite different effects on drilling equipment and certain engineering-economic trade-offs. For example, today, diamond bits and journal-bearing tricone insert bits are uneconomical in geothermal air drilling because air circulation does not cool the bits enough to prevent diamonds from carburizing ("burning") or to prevent the elastomer seals needed for journal bearings from disintegrating. On the other hand, rate of penetration is usually higher in air, especially in rock whose

compressive strength is increased markedly when pressurized by mud columns.

Since some of the R&D projects that were analyzed here involve drill bit improvements that are in some cases relatively specific to use in air or mud, a distinction had to be drawn between mud and air footage for wells in the hydrothermal electricity production scenario.

Across the currently active U.S. geothermal liquid-dominated prospects, perhaps 90% or more of the footage appears to be drilled in mud, today. Even if good geothermal drilling foams are developed, which could combine good lifting of cuttings with minimal rock compression, it seems unlikely that by 2000, more than perhaps 40% of geothermal footage will be drilled with air. It also seems likely, as at the Geysers, that surface hole will be drilled with mud, and that air drilling will be used mainly in the bottom portions of the holes when air is used.

It was convenient to transform these assumptions into a mud-drilled and an air-drilled scenario. The mud-drilled scenario was assumed to apply to two-thirds of the wells required by the 1978-2000 hydrothermal electricity scenario, and assumed that these wells would be drilled to total depth in mud. The air-drilled scenario was assumed to apply to the remaining third of the required wells, and assumed that these wells would have their upper 30% drilled in mud, and their lower 70% drilled in air.

These two scenarios are consistent with a gradual increase in the percentage total footage drilled in air from about 10% in 1978 to about 40% in 2000. (The Geysers steam wells are excluded from these percentages because the Geysers falls outside of the scope of the present analysis.)

2.0 SUBELEMENT 1-1-A

CONTINUOUS CHAIN BIT

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-1-A	CONTRACT NUMBER(S) CO 40789
TITLE Continuous Chain Drill Bit	
CONTRACTOR Sandia Laboratories, Albuquerque, New Mexico	
RELATED PROJECTS None, but the COMPAX bit project (Subelement 1-1-B) might produce a bit that would drill the same formations for which the continuous chain bit has been designed.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
			✓	✓	
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)											
F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:	1108										1108
2. DGE Planned:		300									300
3. Additional:			500	0							500
Total:	1108										1908

Discounted Total of Planned and Additional: \$2,057 K (1978 \$)

EXPECTED YEAR OF COMMERCIALIZATION 1984 for full-sized bits
EXPECTED DEGREE OF SUCCESS 0.80

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$ 76.4
	PESSIMISTIC	\$112.3
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	119.0
	PESSIMISTIC	81.0
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	43.7
	PESSIMISTIC	29.7

SEE ATTACHED PAGES FOR RATIONALE

2.1 Objective

The objective of this initiative is to develop, test, demonstrate and transfer to industry, a new concept in hard-rock diamond bit drilling. The primary goal of this activity is to reduce the costs per foot of hard-rock drilling by increasing both the instantaneous penetration rate and the downhole life of the bit.

The rock cutting mechanism in the continuous chain drill bit is by drag action due to the rotation of the rotary table and drill pipe as in normal rotary drilling. The bit cutting surface is formed by diamond pads on a long continuous chain. By cycling the chain, worn out surfaces can be replaced by new cutting surfaces.

2.2 Relationship to Other R&D Projects

The performance of the continuous chain bit is expected to differ from that of conventional diamond bits mainly with respect to increased lifetime and cost. This bit will be used mainly in the hard dense formations where conventional diamond bits are used. The only other R&D project likely to produce a bit that would be used in that type of drilling is the COMPAX bit (Subelement 1-1-B), but the degree to which the bits might compete is difficult to determine.

2.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78 →	TOTAL
1-1-1	758	350	1108	300						300	1408
PLANNED					500					500	500
TOTAL	758	350	1108	300	500					800	1908
(1978 \$)	917	385	1302	300	455					755	2057

R&D costs planned by DGE cover development of a 4-3/4 inch diameter version of this bit. At end of FY 1978, this device had been laboratory tested but not tested downhole. It is estimated that \$500 K will be required in FY 1979 for downhole tests and refinements.

It is assumed that development of full-sized bits (8-3/4 inches to 12-1/4 inches) will be undertaken by a commercial drilling bit company.

Full-sized bits are estimated to be available in commercial quantities at the beginning of calendar 1984.

2.4 Impacts on Engineering and Economic Variables

The expected impacts of the continuous chain bit (hereafter called "chain bit") are based on laboratory tests of a 4-3/4 inch diameter version of the device. The important results cover tests conducted in 1976 (January 18, 1977 letter from M. M. Newsom of Sandia to ERDA/DGE managers

on "Economics of the Sandia Chain Drill") and in November of 1977 (as published in The Oil and Gas Journal, January 30, 1978). Estimated costs for the 4-3/4 inch version were updated in a July 3, 1978 letter on the economics of the chain bit from SANDIA to DGE.

a. Technical Objectives of the Project:

The objective of this project is to provide a new drill bit that will result in a reduced drilling footage cost in hard, abrasive rock by reducing total trip time and cost through increased bit life, while maintaining an adequate penetration rate. The system utilizes a cutting surface that can be replaced while the bit is still in the hole, i.e., a new cutting surface can be cycled into position without the need for a round trip. The system utilizes diamond cutting surfaces fabricated on the links of a continuous chain. Five links provide one complete cutting surface, and a total of 75 links can be accommodated in the present design. Thus, 15 bit changes can be made before it is necessary to trip out of the hole.

b. Performance of Current Technologies:

Both 1977 and 1978 reports on tests of the chain bit included comparative tests of a Christensen MD-24 conventional diamond bit drilling in Sierra White granite. The 1977 and 1978 tests were conducted in different manners, and suggested quite different performance values for the MD-24 bit in this rock.

In the 1977 test, the MD-24 bit was weighted constantly at an 11,000 lb load, and cumulative feet drilled during the course of 68

rotating hours was reported. The preparation of this type of curve allows estimation of the optimum number of hours to rotate the bit to reduce total average footage costs to a minimum. If it is assumed that the MD-24 bit is drilling at 6000 ft at rig rent of \$200 per hour, then the performance curve dated January 18, 1977 indicates that this bit should be run 20 hours, to make a total footage of 29.2 feet, at a cost of \$432 per foot. (This calculation assumes an 8-3/4 bit with the same life and ROP as a 4-3/4 bit, but with an after-salvage cost of \$7425.)

In the 1978 test, the MD-24 bit was weighted variably to give an ROP maintained at a constant 4.0 ft/hr. The bit drilled at total of about 11.5 feet in 2.88 hours. At this point, the weight on bit was 18,000 lbs. The bit was weighted above 11,000 lb for approximately half of the test duration. Using the same assumptions for this bit (8-3/4 inch diameter, drilling at 6000 ft, rig at \$200/hr, 2.88 hr bit life, 11.5 feet made), the cost is equal to \$800 per foot.

Thus, the conditions used in the 1977 test lead to a more economical use of the conventional bit. The performance of the MD-24 bit under the 1977 conditions are therefore assumed for this analysis.

c. Performance of the Product of this R&D Project:

In the 1977 test, the chain bit was run at reduced weight (6500 lb load) to optimize the lifetime of the nose of the bit. At this weight, the total footage costs (assuming 6000 ft, 8-3/4 inch bit, \$200/hr rig rent, 15 link sets per bit, and bit cost as estimated

below) for the chain bit were optimized at \$379 per foot, with a life of 15 hours footage total of 21.2 feet per link set. Note that this \$379 per foot is somewhat more economical than the \$432 per foot for the MD-24 tested at the same time.

Between the 1977 and the 1978 tests, the design of the chain bit was significantly improved by the insertion of STRATAPAX ((C)-General Electric Company) man-made diamond cutters in the nose of the link set, and by an improved hydraulic design that promoted better nose cleaning. Four links were tested under conditions that fixed the ROP at 4 feet per hour. The SANDIA report conservatively averaged the lives of all four links at 4.75 hours, which would set the footage cost for this bit at about \$315 per foot, for an 8-3/4 inch bit, under the same assumptions as above.

A close reading of the 1978 report, however, indicates that a reasonable lower bound for lifetime of each link set is probably best set at 6.0 hours (the life of link set 2), and that the optimistic estimate of performance should be set at 8.25 hours (the life of link set 4, the latest tested version). A life of 6.0 hours per link set implies a footage cost of \$260 per foot, and the 8.25 hour life implies \$203 per foot. These are very significant improvements over the \$315 per foot implied by the results reported for the chain bit in 1977.

d. Cost of Current Technology:

Cost per bit -- (less salvage value) - \$2650 (1978 \$), 4-3/4 inches.

Basis -- Quote from Christensen Diamond Products, June, 1978.

e. Cost of Improved Technology:

Cost per bit -- (less salvage value) - \$30,000 (1978 \$).

Basis -- Prepared by SANDIA for this estimate. Assumes production quantities bits per year by 1982, 4-3/4 inch bit.

f. Date When Product Is Expected To Be Commercially Available:

Date -- No sooner than 1981. 4-3/4 inch bit will probably be first produced in 1982. The analysis assumes that full-sized bits (8-3/4 - 12-1/4 inch) will be commercially available at the start of 1984.

g. Additional Devices Needed to Support the Use of This New Device at a Typical Geothermal Installation:

Additional Devices -- None.

h. Scaling Factors for Costs of Bits Larger Than 4-3/4 Inch Diameter:

Since most geothermal drilling is done with bit diameters ranging from 8-3/4 to 12-1/4 inch, bit costs must be scaled to useful diameters.

Sandia's rough estimates of the production costs of the chain bit are:

<u>Bit Diameter</u>	<u>Cost</u>
4.75 inch	\$26 K
8.75 inch	\$84 K
12.5 inch	\$164 K

(Letter from SANDIA to MITRE, October 18, 1978).

For the conventional diamond bit, MD-24 prices from the Christensen April 1978 catalog were used. Assuming 40% recovery of diamonds as salvage value, an 8.75 inch conventional bit costs about \$7425, and a 12.5 inch bit costs about \$13,050.

Thus, the ratio of estimated cost of chain bit to conventional bit is $84,000/7425 = 11.3$ for 8.75 inches and $164,000/13,050 = 12.6$ for 12.5 inch bits. Thus, for the present analysis it is convenient to assume that the chain bit with 15 link sets costs approximately 12.0 times a conventional bit of the same diameter.

i. Reliability of Mechanical System:

The key feature of this bit is the mechanical system that allows replacement of the cutting faces while the bit is downhole. This obviates the need to trip the bit to renew the cutting faces.

The mechanical system is not simple, and to date (September 1978) has neither worked perfectly in laboratory tests, nor been tested downhole. It is assumed that this system may not work perfectly downhole under actual drilling conditions.

Under the optimistic estimate of benefits, the cutter cycling system is assumed to work perfectly, thus allowing full use of all 15 cutter sets. Under the pessimistic estimate of benefits, the cutter cycling system is assumed to fail to operate about 20% of the time. The failure is assumed to occur 50% through the lifetime of the bit. Thus on the average, $15 \times 0.80 + 7.5 \times 0.20 = 13.5$ of the cutting faces of each bit will be used.

2.5 Rationale for Impact on System Parameters

The economic impact of the Continuous Chain bit was evaluated using the WELCST cost of geothermal wells model.

There is no simple way of estimating how much diamond bits will be used in geothermal drilling. Diamond bits are used in strata of specific types of dense and relatively hard rock that are difficult to crush using roller cone bits. The extent to which diamond bits might be used in a specific geothermal prospects cannot be estimated in the absence of detailed stratigraphic data and drilling experience in the prospect. This information does not exist for most of the 27 prospects included in this analysis.

The WELCST model was designed, with this problem in mind, to allow some provisions for use of diamond bits. The model selects diamond bits for use when the ROP of insert tricone bits is less than or equal to 4.0 feet per hour. This condition occurs in 9 of the 27 prospects, in the lower parts of holes being drilled in medium-hard or hard rock.

The nominal parameters assumed in WELCST for a conventional diamond bit, based on typical field experience, are:

- Rate of penetration = 3.0 ft/hr
- Bit lifetime = 25 hr
- Bit cost = \$1500 x Diameter (inches) - \$5000.

It should be noted that the conventional bit drills about 75 feet under typical field conditions, which is considerably greater than

the 11.5 feet drilled by the conventional bit in SANDIA's 1978 laboratory test. Therefore, the SANDIA test results were scaled in proportion to total footage made per bit (or link set) to bring the comparison of the bits more in line with typical field performance.

For the MD-24 bit (1977 test results), the total reported footage was 29.2 feet. Thus the scaling factor used here is $75/29.2 = 2.57$ times the reported footage. For the chain bit (1978 test results), the optimistic estimate of footage per link set becomes $33 \times 2.57 = 84.8$ feet per link set (ROP = 4.0 ft/hr, life = 21.2 hr) and the pessimistic estimate becomes $24 \times 2.57 = 61.7$ ft (ROP = 4.0 ft/hr, life = 15.4 hr).

The time required to cycle the links was assumed to be 3 hours for 14 cycling operations. This was entered as a 3 hour addition to bit life, coupled with a slight reduction in effective ROP to account for the portion of the bit life spent not rotating.

The parameters for the chain bit were entered to the WELCST model as follows:

Parameter	Pessimistic Estimate	Optimistic Estimate
● Rate of Penetration (ft/hr)	3.95	3.96
● Life per Link Set (hr)	15.4	21.2
● No. of Usable Links	13.5	15.0
● Total Bit Life (hr)	234	321
● Bit Cost	12 x nominal	12 x nominal

The results from WELCST and GEOBEN indicated a benefit of $\$114.7 \times 10^6$ (pessimistic) to 168.4×10^6 (optimistic). The drilling fluid scenario used to estimate this benefit was "mud-based," which MITRE expects to account for about two-thirds of the geothermal drilling at U.S. hydrothermal prospects between 1978-2000. Thus the initial estimate of benefits is reduced by one-third (lost to the "air-drilled" scenario) to produce a net benefit of \$76.4 million (pessimistic) to \$112.3 million (optimistic).

2.6 Expected Degree of Success

This project (subelement) is expected to be essentially a complete technical success because laboratory tests, as described above, indicate proven technical feasibility. The remaining uncertainty about the ultimate mechanical reliability of the link-cycling mechanism has been included in the pessimistic estimate of benefits. The uncertainty that is most likely to detract from total success for this project is the degree to which the chain bit will be used in holes for which it is economic. It is assumed that the bit will be used for about 80% of the holes in which it "should" be used. The overall degree of success is thus equal to 0.80.

2.7 Adjustment of Benefit to Avoid Overlap With Other DGE Bit Projects

No adjustment was necessary because the (modeled) footage drilled by this bit was not drilled by any other bit examined in this analysis.

2.8 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$112.3	119.0	43.7
Pessimistic	\$ 76.4	81.0	29.7

¹ Figure of Merit = $\frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$

3.0 SUBELEMENT 1-1-B

COMPAX DRILL BIT

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-1-2	CONTRACT NUMBER(S)	CO 12360
TITLE Geothermal COMPAX ^R Drill Bit Development			
CONTRACTOR General Electric Company, Schenectady, N.Y.			
RELATED PROJECTS All other bit improvement projects might have benefits that overlap the benefits of this project.			

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
				✓	✓
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)											
F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:	241										241
2. DGE Planned:		400	177								577
3. Additional:				200							200
Total:	241	400	177	200							1018

Discounted Total of Planned and Additional: \$727 K (1978 \$)

EXPECTED YEAR OF COMMERCIALIZATION	1981
EXPECTED DEGREE OF SUCCESS	0.50

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$447.3
	PESSIMISTIC	\$642.7
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	703
	PESSIMISTIC	492
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	516
	PESSIMISTIC	359

SEE ATTACHED PAGES FOR RATIONALE

3.1 Objective

The objective of this subelement (a single project) is to develop a drag-type bit with man-made diamond cutters. Drag bits remove rock by a scraping action, rather than the crushing actions of roller bits. The COMPAX (G.E. Copyright) bit, in its present design, is a solid-body drag bit with sintered polycrystalline diamond compacts (inserts) providing the cutting edges. Its body structure is similar to that of a conventional diamond bit.

3.2 Relationship to Other Projects

This subelement consists of a single project and contract with General Electric.

This bit is expected to compete directly with both conventional tricone rock bits and diamond bits. Therefore benefits of this project could overlap directly with benefits from most of the other drill bit R&D projects of DGE. As discussed below, an adjustment was made in the estimated benefit to account for such overlaps.

3.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
1-1-2	41	200	241	400						400	641
PLANNED					177					177	177
ADDI- TIONAL						200				200	200
TOTAL	41	200	241	400	177	200				777	1018
(1978 \$)	50	220	270	400	161	166				727	997

The DGE planned funds of \$177 K for FY 1979 appear to be adequate for further work on improved metals for the bit body. Any needed support of commercialization efforts could be met by additional funding of about \$200 K in FY 1980.

General Electric intends to manufacture and sell cutters, but not manufacture entire bits. G.E. is working with a number of bit manufacturers to develop commercial bits containing COMPAX (R) (for soft rock) and STRATAPAX (R) (for harder rock) cutter inserts. Since successful downhole tests have already been conducted using 8-3/4 inch bits, there is every reason to believe that this bit will be available in commercial quantities by the end of 1980.

3.4 Rationale for Impact on Engineering and Economic Variables

The expected impacts of the COMPAX bit are based on results of STRATAPAX^T/rock bit comparisons in 5 oil/gas wells reported by letter from L. E. Hibbs and D. G. Flom of G.E. to J. V. Walker, DGE. The technical portions of that letter are reproduced here (Items a.-g.).

a. Technical Objective of Project

To develop and demonstrate the performance of a new geothermal drill bit for increased penetration rates and/or longer bit life utilizing sintered polycrystalline diamond compacts for the cutting edges. These compacts are available from the General Electric

Company as COMPAX^{R*}, or, when designated for rock cutting as STRATAPAX^{T**}.

b. Performance of Current Technology

Penetration Rate: Typically 10 to 50 ft/hr in the Valles Caldera region for rock bits depending on exact rock formation and depth of hole.

Bit Life: Extremely variable but a typical average is 18 hours at a depth of ~6000 feet.

Basis: Survey by Maurer Engineering, Inc., under subcontract to General Electric Company.

c. Performance of Product of This R&D Project

Penetration Rate: Twice that of conventional rock bits in similar rock formations and similar depths, consistent with adequate bit life.

Bit Life: Three times that of conventional rock bits in similar rock formations, and similar depths, consistent with adequate penetration rate. For example, a typical average life might be 36 hours at a depth of ~6000 feet.

Basis: Results of STRATAPAX^T/rock bit comparisons in drilling 5 oil/gas wells in Netherlands, North Sea, and Persian Gulf showed an increase of 4X in bit life and 2.5X in penetration rate.

*Registered trademark, General Electric Company, U.S.A.

**Trademark, General Electric Company, U.S.A.

Geothermal drilling is generally considered more severe than oil/gas drilling.

d. Cost of Current Technology

Cost per bit: \$2500.

Basis: Catalog price for 8-3/4 inch rock bit.

e. Cost of Improved Technology

Cost per bit: \$15,000.

Basis: Actual price not yet established but will be set later by bit fabricators. The \$15,000 figure for an 8-3/4 inch bit has been used as an estimate for calculations of cost-effectiveness. When STRATAPAX bits are available routinely on a commercial basis, the cost may be lower.

f. Date When Product Is Expected To Be Commercially Available

STRATAPAX^T cutters are available now. First geothermal bits using these cutters should be available commercially by late 1979 or early 1980.

g. Additional Devices Needed to Support the Use of This New Device at a Typical Geothermal Installation

None required but downhole motors for geothermal should enhance performance through RPM and torque control.

h. Costs of Larger Bits

Costs of larger bits are estimated on the following basis:

- (1) The 8-3/4 inch bit is assumed to cost \$15,000. This cost is assumed to be evenly split between (a) cost

of inserts and (b) cost of fabricating bit body plus setting inserts.

(2) The cost of inserts is assumed to scale in proportion to the area of the bit (diameter squared). The fabrication and setting cost is assumed to scale in proportion to the diameter of the bit.

(3) Therefore, the cost C is related to the bit diameter D (inches) by:

$$C = 7500 (D/8.75) + 7500 (D/8.75)^2.$$

This simplifies to:

$$C = 857. D + 98.0 D^2$$

Because marketing negotiations between G.E. and bit manufacturers are very current, no one queried was willing to provide price estimates firmer than the rough assumptions used above. The bit prices could be 5 to 15 percent lower than indicated.

3.5 Rationale for Impact on System Parameters

The economic impact of the COMPAX bit was evaluated using the WELCST model.

The assumed characteristics of the COMPAX bit were assigned to the "Advanced Bit" feature of the model. The model uses the Advanced Bit to drill the hole whenever the footage costs for that bit are less than those of other bits available in the model.

The following characteristics were assumed for the COMPAX bit:

1. Rock hardness in which bit can be used: All.
2. Depths at which bit can be used: All.
3. Diameter of available bits: 8-3/4 and 12-1/4 inch.
4. Temperature range in which bit can be used: 10°C-500°C.
5. Rate of Penetration:

Optimistic case: 2.0 X that of conventional bits.

Pessimistic case: 1.5 X that of conventional bits.

6. Bit Life:

Optimistic case: 4.0 X that of conventional bits.

Pessimistic case: 3.0 X that of conventional bits.

7. Bit Cost: \$15,000 for 8-3/4 inch bit, \$25,200 for 12-3/4 inch bit. Entered into the "Advanced Bit" parameters of WELCST by the equation given in Section 3.4.h.
8. Additional Time and Footage Charges: None.

The results from WELCST and GEOBEN indicated a benefit of \$670.9 million (pessimistic) and \$964.1 million (optimistic). The drilling fluid scenario used to estimate this benefit was "mud-based," which MITRE expects to account for about two-thirds of the drilling at U.S. geothermal prospects between 1979-2000. Thus the initial estimate of benefits is reduced by one-third (lost to the "air-drilled" scenario, in which the COMPAX bit is not expected to drill much) to produce a net benefit of \$447.3 million (pessimistic) to \$642.7 million. This requires one further reduction (see Section 3.7) to account for competition with other DGE drill bit R&D projects.

3.6 Expected Degree of Success

This project is expected to be a nearly complete technical success, since geothermal and oil field tests indicate proven success for 8-3/4 inch bits. There is some uncertainty remaining about the ability of the metallic materials of the bit body to withstand geothermal temperature and rock fracture conditions. This uncertainty is expected to be resolved by a small amount of further R&D.

There is, however, a major factor that could reduce the frequency with which the COMPAX bit is used, even in cases where it would be economic. Drag bits require more skill to operate than roller bits because excessive weight-on-bit can force a drag bit to dig itself into the formation quickly, causing a locked bit and twist-off. Roller bits require less operator skill because they have much less tendency to lock into the formation.

It is assumed that the current shortage of highly skilled operators will be a continuing problem, and make it impossible to use drag bits in more than half of the drilling for which they would be economical. Therefore, the degree of success for this R&D subelement has been set at 0.50.

3.7 Adjustment of Calculated Benefit to Avoid Overlap With Other DGE Drill Bit R&D Projects

Three bits were found to compete for footage in the "mud-drilled scenario": COMPAX, CAVIJET, and ERODRILL. ERODRILL is assumed to be a dead project because of its low Figure of Merit, and is assumed to not compete. COMPAX will be limited to less than its full market share due to lack

of trained drilling crews, not by competition from CAVIJET, which promises fewer savings per hole if it works. Thus, the estimated benefit for COMPAX is not reduced, and remains \$447.3 million - \$642.7 million.

3.7 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$642.7	703.3	515.7
Pessimistic	\$447.3	492.2	358.9

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

4.0 SUBELEMENT 1-1-C

TERRA TEK IMPROVED GEOTHERMAL DRILL BIT

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-1-3	CONTRACT NUMBER(S) CO 71546
TITLE Geothermal Drill Bit Improvement	
CONTRACTOR(S) Terra Tek, Inc., Salt Lake City, Utah	
RELATED PROJECTS The drilling bits being developed here will find most of their use in air-drilled boreholes. They will not compete against other DGE-supported bit developments for water and mud-based drilling.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
				✓	✓
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)											
F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:	717										717
2. DGE Planned:		370	110								480
3. Additional:				0							0
Total:	717	370	110								1197

Discounted Total of Planned and Additional: \$470 K (1978 \$)

EXPECTED YEAR OF COMMERCIALIZATION	1981-1983
EXPECTED DEGREE OF SUCCESS	1.00

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$208.4
	PESSIMISTIC	\$132.3
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	443
	PESSIMISTIC	282
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	160
	PESSIMISTIC	102

SEE ATTACHED PAGES FOR RATIONALE

4.1 Objective

The Terra Tek project consists of three objectives and related activities:

- (1) Alteration of Terra Tek's existing drill bit test stand to encompass geothermal ranges of temperature and pressure. This task is completed. The device can now test the drilling performance of bits at temperatures up to 427°C (800°F) and pressures up to 35 MPa (5000 psi).
- (2) Development of an unsealed roller bearing tricone insert bit with materials selected to increase the bearing lifetimes at high temperature. This bit, hereinafter called the Terra Tek bit, is in an advanced state of development. The first downhole test test was conducted in 1978.
- (3) Development of a seal for bits that can withstand temperatures much greater than 200°C for 100 hours or longer. This would allow sealed journal bearing bits to operate at drilling fluid temperatures in the 200-300°C range. This task has included the development of a sophisticated seal testing device.

The three tasks are interrelated. For example, the drill bit test stand has been used extensively in developing the Terra Tek bit. Similarly, development of a high temperature elastomeric seal

for bit bearings could reduce the geothermal well footage in which the Terra Tek bit (unsealed) would be used. Nonetheless, the three tasks have distinct technological impacts, and therefore the benefits have been analyzed separately.

4.2 Relationship to Other R&D Projects

As this analysis was in progress, it became apparent that the benefits to be derived from the Terra Tek bit-development activities will be derived in the main from air-drilled footage in geothermal wells. No other DGE R&D bit projects appear to be able to produce significant benefits in air-drilled boreholes.

The drill bit test stand is credited for R&D cost savings across a number of drill-bit development projects.

4.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
1-1-3	358	359	717	370						370	1087
PLANNED					110	0				110	110
TOTAL	358	359	717	370	110	0				480	1197
(1978 \$)	434	395	829	370	100					470	1299

The drilling bit test stand is in operation. The various drill bit improvements expected from this Subelement should all be commercially available starting in the years 1981-1983.

4.4 Impacts on Engineering/Economic Variables

The expected technological impacts of Terra Tek's work on improved geothermal drill bits are discussed separately for three areas: elastomeric seals, heterogeneous seals; and bit bearing materials. All information presented here was derived from discussion with Terra Tek's Geothermal Bit Program Manager, Mr. Robert Hendrickson; his associate, Mr. Richard Wizenried; and the various R&D reports from Terra Tek to DGE.

4.4.1 Status of Current Technology

The bit of choice for most geothermal drilling is a sealed journal-bearing tungsten carbide insert bit. Of available bearings, journal bearings can take the highest loads (weight on bit), and thus maximize rate of penetration (ROP). The journal bearing must, however, be sealed to retain its lubricant and prevent grit from drill cuttings from penetrating the bearing.

If the temperature of the seal exceeds a certain limit (estimated by Terra Tek to be about 100°C for the seals in current bits), the seal fails, grit penetrates the bearings, and the bearings fail within a few hours. Thus journal bearing bits must be replaced with roller bearing bits when seals get too hot. Roller bearing bits are inferior to journal bearing bits with respect to both bit lifetime, and how much weight can be borne by the bit.

For the analyses here, it is assumed that journal bearing bits have a nominal lifetime of 90 hours, and can be used only if the

seal temperature stays below a critical temperature (assumed to be 100°C for currently used elastomers). Roller bearing bits are assumed to have a lifetime of 30 hours in mud and 18 hours in air, and cost about 70% as much as a journal bearing bit of equivalent diameter.

The most difficult thing to analyze is the temperature to which the seals are exposed. This is treated analytically in the WELCST geothermal well engineering cost model prepared for the present analysis. The reader is encouraged to consult Section 4.0 of the User's Guide to WELCST for details. Simply put, various exercises with the WELCST model have indicated for most liquid-dominated (hydrothermal) prospects in the U.S. that if the prospects are mud-drilled, the seal temperature will tend to be close to the bottom hole mud circulating temperature, which will rarely exceed 100°C. Thus, the seals currently available will survive most mud-drilling at U.S. geothermal prospects. However, if the holes are air drilled, seal temperatures will frequently exceed 100°C. Thus, improvement in seal temperature limits could increase the footage in which journal bearing bits could be used.

4.4.2 Impacts of Improved Elastomers

Terra Tek has tested a number of elastomers of advanced composition for favorable properties when used in drill bit bearings. They are finding that improved bit-bearing lubricants increase the temperatures that seals can withstand. Terra Tek

estimates that by the end of FY 1979 they will have demonstrated that specific lubricant and seal material combinations will have increased the seal temperature limit to 175°C (rotating) and to 250°C (30-minute soaking, non-rotating). The nominal values for currently available seal and lubricant combinations are 100°C (rotating) and 200°C (soaking). Terra Tek's estimates are accepted here as the optimistic estimate of technical performance improvement. The pessimistic estimates are assumed to be 150°C (rotating) and 225°C (soaking). The improvement requires only negligible changes in bit fabrication cost, because only an inexpensive materials substitution is required.

4.4.3 Impacts of Heterogeneous Seals

Above certain temperatures, (about 200°C), elastomers simply cannot go. In these higher ranges, seal designs must incorporate combinations of elastomers, metals, and composites to attain all of the required properties. These "heterogeneous" seals have the technical disadvantage of being mechanically complex, perhaps more difficult to fabricate, and certainly physically larger. This latter difference will necessitate redesign of bits that incorporate heterogeneous seals, thus raising bit costs.

Terra Tek estimates that within two years a heterogeneous seal can be fabricated that will have a temperature limit while rotating of 250°C and while soaking of 275°C. This is accepted as the optimistic estimate of improvement in technology performance. The

pessimistic limits are assumed to be somewhat lower: 200°C rotating, and 250°C soaking.

In either case, it is likely that the bits containing heterogeneous seals will have to be priced 30% higher than identical bits with conventional seals. It is the current consensus that heterogeneous seals will probably have different dimensions from equivalent elastomeric seals. Thus, use of the former will require expensive redesign and alteration of drill bits in which they are used. Bit manufacturers are deemed more likely to use improved elastomers than they are to redesign bits to accommodate conditions suitable for geothermal drilling, which constitutes a relatively small proportion of the market for bits compared to oil and gas drilling.

4.4.4 Improved Bearing Materials

When seals fail, the strength of roller bearing and bearing races become important. Terra Tek has been working to develop an unsealed roller bearing tricone insert bit whose bearings have increased lifetimes compared to existing bits when used in air drilling at formation rock temperatures of 200°C to 300°C.

Two conditions in current geothermal drilling technology and practice motivate this goal. First, when formation temperatures at the Geysers, CA field exceed about 200°C (usually while air is used as the fluid for drilling in steam zones), the elastomeric seals on journal bearing bits fail. Journal bearing bits are then replaced by roller-bearing bits for further drilling, because these

latter bearings are not as sensitive to erosion by grit in the drilling fluid. Second, in this use at the Geysers, unsealed bits give about one-fifth of the lifetime expected for similar rock and depth in cool (non-geothermal) boreholes. The dominant failure mode for these bits is bearing failure.

The R&D approach for this task assumes that use of better steels and improved fabrications methods can result in bearings (and other bit components) that have much better hardness retention and thus wear resistance characteristics at elevated temperatures. The approach appears to be succeeding and has resulted in decreased bearing wear or increased bearing lifetime in a number of laboratory tests and a series of downhole tests in mid-1978.

The test of six Terra Tek experimental unsealed bits at the Geysers in August/September 1978 indicated that gage wear and the consequent reaming to recover full gage in the borehole is a dominant mode of bit wear when drilling medium-hard rock with air as the drilling fluid.

For conventional bits, gage wear seems to result mainly from cone wobble as the bit bearings begin to wear. The undergage portion of the hole then has to be reamed by the next bit before that bit reaches bottom and begins to dull. The bit bearings are not designed to withstand the lateral thrust encountered while reaming, and they wear much during reaming. In fact, the conventional bits used in the test appeared to have lives of about 10 hours if used

exclusively for reaming compared to about 20 hours if used exclusively for drilling on bottom.

The Terra Tek bits lost gage much less rapidly than the conventional bits to which they were compared. The average gage wear for 13 bits (mix of experimental and conventional bits) was 0.23 inch during a total of 65 hours spent reaming and 173 hours spent drilling (rotating on bottom). Bits appeared to wear about twice as fast while reaming as while drilling. If we postulate a lifetime for bits in "use" hours, where one actual hour spent reaming = 2 use hours and one actual hour spent drilling = 1 use hour, then:

- The total use hours for all bits was $2 \times 65 + 173 = 303$ h,
- Six conventional bits (Reed Y-73JA) showed an average gage wear of 0.34 inch for an average of 23 use hours, and
- Four Terra Tek experimental bits showed an average gage wear of 0.19 inch for an average of 29 use hours.

Let us assume that all bits will be run to a gage wear of 0.23 inch. Then the "effective life" of the conventional bits in use hours is:

$$E_c = \frac{0.23}{0.34} \times 23 = 15.6 \text{ hr},$$

and the effective life of the Terra Tek bits in use hours is:

$$E_T = \frac{0.23}{0.19} \times 29 = 35.1 \text{ hr}.$$

If we assume that the typical on-bottom rate of penetration (ROP) of both bits was 15 ft/hr, as it was in this test, then we can calculate effective lives and ROPs for both bits. We assume that the required reaming time (actual) is $65/13 = 5.0$ hours per

bit if the gage wear is held to 0.23 inch. This would consume 10.0 hr of the effective life of both types of bit, leaving the conventional bit 5.3 hr for drilling on bottom and the Terra Tek bit 25.1 hr for drilling on bottom. The bits would make $5.3 \times 10 = 80$ ft and $25.1 \times 15 = 376$ ft of new hole respectively, for respective actual lifetimes of $5 + 5.3 = 10.3$ hr and $5 + 25.1 = 30.1$ hr, and respective effective ROP's of $80/10.3 = 7.8$ ft/hr and $376/30.1 = 12.5$ ft/hr.

Thus the effective lifetime of the Terra Tek bit is $30.1/10.3 = 2.92$ times that of the conventional bit and the effective ROP of the Terra Tek bit is $15.3/7.8 = 1.96$ times that of the conventional bit.

These factors of 2.92 the nominal lifetime and 1.96 the nominal ROP, coupled with a 30% price premium on the Terra Tek bit were evaluated using the WELCST model.

	<u>Pessimistic</u>	<u>Optimistic</u>
Life	2.00	3.00
Cost	1.30	1.30

The bit also holds promise of increasing the effective ROP, but any gains here are difficult to evaluate given the existing test data. This could easily double the benefit from extension of bit life, especially if stronger thrust bearing designs are incorporated into the bits and either stronger gage teeth or stabilizing collars become available to allow more weight on bit while avoiding hole direction problems.

4.5 Impacts on System Parameters, and Benefits

4.5.1 Impacts on Mud-Drilled Boreholes

The technical improvements estimated in seals and bearings, described in Section 4.4, were evaluated for their impact on mud drilling costs using the WELCST and GEOBEN models. The "mud-drilling scenario" used for this assumes that two-thirds of the wells at each of the 27 prospects in the hydrothermal development scenario will be drilled entirely with mud.

The postulated improvements in seals and bearings materials were found to have essentially no cost-saving impact for mud drilling. If the technology improvements are grouped together (under the assumption that all three are available starting in 1982), the pessimistic benefit is \$0., and the optimistic benefit is \$0.9 million.

While this result seems counter-intuitive, it occurs because, under the assumptions in the WELCST model, it is exceptionally unusual for the bottom-hole circulating mud temperature to exceed 100°C. Thus mud has a very strong effect in cooling bits to temperatures where seals can survive. Only in the deepest and hottest prospects contained in the hydrothermal development scenario is there any cost savings due to improved temperature characteristics of seals, or improved lifetime of unsealed bits.

4.5.2 Impacts on Air-Drilled Boreholes

The postulated improvements in seals and bearing materials were found to have significant cost-saving impacts when air is used as the drilling fluid, when evaluated using the WELCST and GEOBEN models. The evaluation included premiums on prices, where appropriate. The "air-drilling scenario" assumes that for one-third of the wells drilled at each of the 27 prospects in the hydrothermal development scenario, the bottom 70% of the hole will be drilled using air as the drilling fluid.

The cost-saving benefits from the three technological improvements, evaluated both separately and as if all three are available, are shown in Table 4-1. It is noteworthy that the heterogeneous seal improvements promote the greatest cost saving when considered alone. It is also noteworthy that the separate benefits do not sum. Each of the improvements competes, as it were, for the same cost-saving effect - increased bit life, at a price - across the same total footage. The result is useful redundancy of improved capability. (It is conceivable, although it has not been evaluated here, that the elastomer improvement and bearing improvement together might possibly deliver most of the maximum benefit (\$74.5 million) in the absence of an effective heterogeneous seal.)

4.5.3 Impacts at the Geysers, CA, Field

Since the improvements in bit bearing materials were originally motivated by the desire to improve the performance of unsealed bits

TABLE 4-1
BENEFITS IN AIR DRILLED BOREHOLES

IMPROVEMENT	IMPACT YEAR	BENEFIT FROM NOTED DEVELOPMENT (\$ MILLION, 1978 \$)	
		PESSIMISTIC	OPTIMISTIC
1. ELEASTOMERIC SEAL	1980	\$29.2	\$51.5
2. HETEROGENEOUS SEAL	1982	56.7	70.3
3. IMPROVED BEARING	1980	40.2	57.4
4. ALL THREE IMPROVE- MENTS AT SAME TIME	1982	\$63.0	\$74.5

in air drilling at the Geysers (vapor-dominated) field, benefits that would be gained from use of this novel bit there are estimated.

At a discount rate of 10%, the present value (1978 \$ in 1978) of the wells expected to be drilled at the Geysers for steam production in the years 1980-2000 inclusive is approximately \$300 million (1). The WELCST model was configured to cost-estimate a well designed and drilled according to 1977 practice at the Geysers. Then the effect of the improved Terra Tek unsealed bit (the bearing materials) was estimated.

The pessimistic technology improvement estimate (from Section 4.4.4 above) indicated that 2.6% of the cost per well would be saved. The optimistic estimate indicated a 5.0% saving per well. This translates into a total benefit at the Geysers ranging from \$7.8 million to \$15.0 million.

4.5.4 Impacts Due to ROP Increases

The benefits in bit life were evaluated in the absence of consideration of concomitant changes in rate of penetration. If the Terra Tek projects are successful, the resulting improved drill bits should be able to tolerate more weight on bit. This is true for both improved roller bearing bits, and for situations where better seals allow use of journal bearings rather than roller bearings.

1. H. S. Dhillon and D. J. Entingh, "An R&D Project Management and Selection System for the Utilization Technology Branch, Division of Geothermal Energy, Volume III," MTR-7694, MITRE/Metrek, May 1978, Table A-VII, p. A-19.

tion rate should result in savings of \$50 million to \$115 million in one air-drilled portion of the hydrothermal development scenario.

4.5.5 Benefits Expected From Drill Bit Test Stand

About \$500,000 of the contract funds have been used to modify an existing drill bit test stand to include geothermal-like conditions of temperature and pressure. The test stand was required for Terra Tek's work on improving geothermal bits, but has benefits in addition to the Terra Tek bit development work. It will be, and is already being used, to test other improved geothermal bits during their development.

The benefit due to test stand accrues because use of the stand replaces more expensive downhole tests required during bit development. The size of the benefit is estimated as follows:

- (1) Assume that the test stand has a 10-year life.
- (2) Assume that for each new bit type being developed, 20 tests using the stand would replace 10 downhole tests otherwise required.
- (3) Assume that the cost per test on the stand is \$1000 for materials, scientist and technician time, etc.
- (4) Assume that the costs of a downhole test, chargeable to the drill bit developer are:
 - (a) Travel to well site: \$2000.
 - (b) Idle drill rig time due to tests, including extra tripping time; 48 hours @ \$200/hr: \$9600.

(c) Development opportunity time lost per test.

Assume one month is lost per test, and that during the month two scientists are 50% idle (\$2500). Assume \$500,000 investment in bit, at 15% interest rate, is tied up for the month (\$6250). Total cost = \$8750.

(d) Cost of fishing for pieces of bit lost, assume infrequent occurrence, with most costs borne by driller, \$500.

(e) Total of (a) - (d): \$20,850.

This total for item (4) assumes that the drill rig operator will absorb any other costs or savings due to altered bit performance or hole damage.

(5) The test stand will provide superior knowledge about bit performance because bit operation can be monitored more closely. Assume that this effect saves six months of development time on a \$500,000 investment @ 15%: \$37,500.

The differential cost per bit type, assuming use of the stand is then:

(a) 10 downhole tests @ \$20,850:	\$208,500
(b) Value of test stand information:	+ 37,500
(c) 20 tests with stand @ \$1000:	<u>- 20,000</u>
Savings total:	\$226,000.

If this savings per bit type is distributed over a 10-year period,

its present value at a 10% discount rate is $0.676 \times \$226,000 = \$153,000$.
 $\$153,000$.

An optimistic estimate of stand utilization is that 20 new types of bits will be developed using the stand. A pessimistic estimate is that the stand will be used on the development of only 10 types of bits. Under these assumptions, the optimistic benefit for the stand is $\$153,000 \times 20 = \$3,060,000$, and the pessimistic benefit is $\$153,000 \times 10 = \$1,530,000$.

Note that the test stand cannot substitute for the final down-hole tests needed to prove the capability of a new bit. These final tests are assumed to be required whether or not the stand exists.

4.5.6 Sum of Benefits

The sum of the benefits from the sources discussed above are shown here.

<u>Source</u>	<u>Benefit, \$ Millions, 1978</u>	
	<u>Pessimistic Estimate</u>	<u>Optimistic Estimate</u>
1. Mud Drilling	\$ 0.0	\$ 0.9
2. Air Drilling	63.0	74.5
3. Geysers Steam Field	7.8	15.0
4. Increased ROP	60.0	115.0
5. Test Stand	<u>1.5</u>	<u>3.0</u>
Total	\$132.3	\$208.4

4.6 Expected Degree of Success

This project (subelement) is expected to be essentially a complete technical success because of the redundancy of technical impacts from the improvements in seals and the improvements in bearings. It is assumed that the better bits will find use in almost all of the holes in which they would be advantageous. Therefore, the degree of success is set at 1.0.

4.7 Adjustment of Benefit to Avoid Overlap With Other DGE Bit Projects

No adjustment was necessary because the (modeled) footage drilled to evaluate the benefits from this project was not drilled by any other bit examined in this analysis.

4.8 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$208.4	443	160
Pessimistic	132.3	282	102

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

5.0 SUBELEMENT 1-1-D

ERODRILL CONCEPT

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-1-D	CONTRACT NUMBER(S)	CO 31312
TITLE	Study of ERODRILL Concept		
CONTRACTOR	Physics International		
RELATED PROJECTS	Competes with Subelements 1-1-B and 1-1-E for borehole footage and benefits.		

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
✓					
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		58										58
2. DGE Planned:			0									
3. Additional:			0									
Total:		58	0									58

Discounted Total of Planned and Additional: 0.0

EXPECTED YEAR OF COMMERCIALIZATION	1985
EXPECTED DEGREE OF SUCCESS	0.0

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$223.1
	PESSIMISTIC	\$ 0.0
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	0.0
	PESSIMISTIC	0.0
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	0.0
	PESSIMISTIC	0.0

SEE ATTACHED PAGES FOR RATIONALE

5.1 Objective

The objective of the ERODRILL concept is to develop a water erosion assisted drilling system wherein the required pressure is developed by the ignition of propellant charges downhole. The study by Physics International was a feasibility study of a hybrid system using erosion drilling to cut a kerf for the conventional rotary tricone drill bit to break into. The mud circulation carries a stream of propellant capsules to a combustion chamber mounted just above the drill bit. Ignition of the propellant provides an erosive fluid jet on the rock face.

The study was published in June 1977 (Physics International Report No. PIFR-984), and forms the basis of this analysis.

5.2 Relationship to Other R&D Projects

If the development of this device were undertaken and was successful, the resulting drilling system would compete for footage in mud drilled boreholes with the COMPAX bit (Subelement 1-1-B) and the Water Jet bit (Subelement 1-1-E).

5.3 Estimated R&D Costs and Year of Commercialization

PROJECT	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
SUNK		58	58								58
ADDI- TIONAL		0	0	0	150	250	400	400	300	1500	1500
TOTAL		58	58	0	150	250	400	400	300	1500	1588
(1978 \$)		64	64	0	137	208	300	272	186	1103	1167

The R&D costs estimated above assume a five-year project that would complete technical developments in 1983 and produce a drilling system commercialization at the start of 1983. DGE does not plan to undertake this effort. Therefore, only sunk costs are shown elsewhere for this project.

5.4 Impact on Engineering and Economic Variables

The expected impacts of the ERODRILL bit are based on "A Feasibility study of a Hybrid Erosion Drilling Concept," PIFR-984, Vane, 1977, Physics International, 2700 Merced Street, San Leandro, CA 94577, and a summary of this report by letter to D. Entingh from R. F. Flagg of Physics International (10 August 1978).

a. Technical Objective of Project - ERODRILL is a combination rotary-bit and erosion-drilling technique. It uses chemical propellant capsules carried to the bottom of the drill hole by the drilling fluid to generate high pressure fluid jets. These cut a kerf in the rock immediately ahead of the bit. The presence of the kerf facilitates the rate at which the tricone cutters of the bit can remove rock.

b. Performance of Current Technology - Rates of penetration and bit costs as specified in the WELCST model.

c. Performance of ERODRILL - Development goal is 2.0 times the normal rate of penetration. Expected performance has been theoretically evaluated for only one rock type in which the ROP was assumed to be 10 ft/hr. This does not take into account actual variations

of ROP with rock hardness and depth. Nonetheless, this increase in ROP is the only technical benefit expected from this project.

This goal and the technical features of the ERODRILL are translated into an optimistic estimate of performance as follows. If it is assumed that the erosion function of the drill sets the limiting factor on ROP, then the ROP probably could be designed to the 20 ft/hr rate if enough propellant charges were fired per hour. If each charge cuts a 4.2 inch kerf, as estimated by Physics International, then $240/4.2 = 57$ charges would have to be ignited per hour to attain ROP = 20 ft/hr.

A pessimistic estimate assumes that the presence of a key merely doubles the rate of penetration of the tricone insert portion of the bit. In this case ROP would be 2.0 x nominal, say for 120 charges fired per hour.

d. Cost of Current Technology - Assumed to be as specified in the WELCST model.

e. Cost of ERODRILL - The device is estimated to cost \$4400 (1978 \$) for an 8-3/4 inch version, and \$6160 for a 12-1/4 inch version. This is cost after salvage. This includes the cost of the novel downhole propellant handling system and the cost of the bit body with special jets and standard cutters.

There are two additional costs for this device: (1) Propellant charge costs and (2) Propellant insertion system costs.

Propellant Charge Costs are estimated by Physics International to be about \$4.00 per charge when in full production, based on a cost of \$2.05 per charge from the raw propellant. Under the optimistic estimate, this adds a cost of $\$4 \times 57 = \228 per active rotating hour. Under the pessimistic estimate, this adds a cost of \$480 per hour.

Propellant Insertion System costs are estimated by MITRE to be about \$100 per day, or about \$5 per hour of rotating time. Thus the total per hour additional extraordinary expense is \$231 or \$485 for the optimistic or pessimistic cases, respectively.

It should be noted that the rig rental for typical geothermal wells is currently about \$200 per hour. Given an almost one-to-one trade-off between rig rent and an extra cost of \$485 per hour for faster ROP, the ROP would have to be 3 x to 4 x nominal values to make this device economical. This might occur if the ERODRILL could drill at 20 ft/hr in the deeper portions of hard and medium-hard rock holes.

5.5 Impact on System Parameters

The economic impact of the ERODRILL was evaluated using the WELCST model.

The assumed characteristics of the ERODRILL were assigned to the "Advanced Bit" feature of the model. (See Project 1-1-2, this Appendix, for further explanation.)

The following characteristics were assumed:

ENGINEERING/ECONOMIC PARAMETER	OPTIMISTIC CASE	PESSIMISTIC CASE
1. Rate of Penetration	20 ft/hr	2.0 x Nominal
2. Bit life	Nominal	Nominal
(Failure of seals and bit bearings continue to be the determining factor here.)		
3. Bit diameter	8.75 in, to 12.25 in	8.75 in only
4. Bit cost (\$503/inch diameter)	\$4400-\$6160	\$4400-\$6160
5. Depth range of use	150-20,000 ft	150-20,000 ft
6. Rock hardness drilled	1-4	2-4
7. Temperature effects on bit	Nominal	Nominal
8. Time charge per hour	\$231	\$485

It should be noted that the above estimates assume that the bit-per-se portion of the ERODRILL will have lifetime equivalent to that of corresponding sealed or unsealed bits. In the WELCST model bit lifetime ranges from 80 hours to about 5 hours (in very hot rock). The 1977 Physics International feasibility study assumed a lifetime of 100 hours for both conventional bits and the ERODRILL.

The assumed technical characteristics were evaluated using the WELCST and GEOBEN models in the "mud-drilled scenario" for

hydrothermal geothermal prospects. The benefit under the pessimistic assumptions is zero. This is because the propellant cost exceeds the typical rig rental rate by much more than is economic for only a two-fold increase in ROP. The optimistic benefit was estimated to be \$353.3 million. Thus, it is reasonable to assume that the economic impact of this system could be large, provided that (a) propellant costs can be kept low and that (b) ROP's will at times reach 3 times nominal rates.

5.6 Expected Degree of Success

It is assumed that this is a toss-up. The technical parts of the system would appear to present no major development problems. However, since only a conceptual design study and economic analysis have been completed, without further evidence of DGE interest in pursuing the concept, R&D activity on this device will probably continue only if picked up on by private industry. This is deemed unlikely, so the degree of success is estimated to be 0.0.

5.7 Results

	Benefit \$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$223.1	0.0	0.0
Pessimistic	\$ 0.0	0.0	0.0

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

6.0 SUBELEMENT 1-1-E

EROSION DRILLING

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-1-E	CONTRACT NUMBER(S)	4S 12325 SO 22677
TITLE Erosion Drilling			
CONTRACTOR(S) Flow Industries; University of Missouri; Hydronautics, Inc.			
RELATED PROJECTS Erosion-assisted bits would compete with any other bits for mud-drilled footage.			

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
		✓		✓	
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		719										719
2. DGE Planned:			291									291
3. Additional:				400								400
Total:		719	291	400								1407
Discounted Total of Planned and Additional: \$655 K (1978 \$)												

EXPECTED YEAR OF COMMERCIALIZATION	1982
EXPECTED DEGREE OF SUCCESS	0.80

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$30.4
	PESSIMISTIC	\$ 8.9
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	37.1
	PESSIMISTIC	10.9
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	16.4
	PESSIMISTIC	4.8

SEE ATTACHED PAGES FOR RATIONALE

6.1 Objective

The objective of the three projects in this subelement is to define the conditions under which water erosion drilling might be made economical for geothermal drilling. Oil field rock bits will transmit only a limited amount of power to the rock. It has long been known, on the basis of laboratory tests and field experiments (e.g., by EXXON) that high pressure jets added to conventional bits can increase penetration rates, but that the extra pumping required is expensive and the high pressure equipment is dangerous. Therefore this subelement has been developing information to determine if significant economies might be gained by erosion drilling.

6.2 Projects in Subelement and Relationship to Other R&D Projects

This subelement consists of three R&D contracts:

<u>Code</u>	<u>Contractor</u>	<u>Title</u>
1-1-5	Flow Industries	"Water Jet Coring Bit"
1-1-6	University of Missouri	"Design of a Water Jet Drill for Development of Geothermal Resources"
1-1-7	Hydronautics, Inc.	"CAVIJET Bit Development"

The studies of project 1-1-6 are oriented to research in the interactions of erosion jets and rock, and optimizing nozzles for hybrid (mechanical plus erosion) bits. Project 1-1-7 is developing cavitating jets for incorporation into low to medium pressure mechanical bits.

Any erosion-based or -assisted bit to result from this R&D subelement would compete for footage with other bits in mud-drilled-boreholes, specifically the COMPAX bit and ERODRILL. Appropriate adjustments are made in Section 6.6.

6.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST \$(1000) BY FISCAL YEAR									
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78 → TOTAL
1-1-5	162	19	189	0						0 189
1-1-6	307	220	527	116						116 643
1-1-7	0	0	0	175						175 175
ADDI- TIONAL					400					400 400
TOTAL	469	239	716	291	400					691 1407
(1978 \$)	568	263	831	291	364					655 1486

Funds on the order of \$10 million during 1980-1984 would be required to bring a high-pressure erosion-assisted drilling system to the field for tests. Such funds are not considered here because the economics of the high pressured system appear to be unfavorable for geothermal wells at U.S. liquid-dominated prospects.

The CAVIJET cavitation assisted bit should be commercially available by about 1982.

6.4 Impacts on Engineering and Economic Variables

6.4.1 High-Pressure Erosion Drilling

The economic impacts of high-pressure erosion drilling hinge on the trade off between increased rate of penetration (ROP) and additional costs for high pressure operations. In his 1977 report on "Near-Term Needs in Drilling Technology," Dr. William C. Maurer estimated on the basis of much field experience that ROP's could be increased by 100% to 200% above conventional procedures (page 13), (1). He stated "this is the only new drilling system to come along in the last 50 years which has demonstrated that it can double and triple drilling rates."

In another article, Maurer described various strategies for using high pressure pumps to generate the required downhole pressures (2). He estimated that the additional rig cost for pumps and fuel would be on the order of \$3000 (1973 \$) per day. Inflated to 1978 \$, this is equivalent to about \$4000 per day, or \$167/hr.

The WELCST cost of geothermal wells model was used to evaluate the economics of erosion drilling in the "mud-drilled scenario," with the following assumptions.

¹Presentation to the U.S. House of Representatives Fossil and Nuclear Energy Research, Development and Demonstration Subcommittee of the Committee on Science and Technology, March 1, 1977.

²Journal of Petroleum Technology, July 1973, pp. 851-859.

- The extra cost of \$4000 per day is assumed to be split between pump fuel cost (\$30/hr) and pump and equipment rental cost (\$140/hr). The fuel cost is applied only when the erosion device is operating. The equipment cost is assumed to apply during the entire time the rig is on site. Bit costs are assumed to be 20% higher than nominal because of the special nozzles. Permissible hole diameters ranged from 8.75 to 12.25 inches.

- Three hypothetical cases were run, differing only with regard to assumption about the effect of erosion on the rate of penetration: 2 times nominal, 3 times nominal, or 4 times nominal. None of the runs indicated any benefit. If the added costs run at \$4000 per day, even a 3X increase in ROP does not prove economical, given current land-based geothermal drilling costs.

6.4.2 Split Drill Pipe

The Flow Industries study has made the observations that most of the flow is required to remove cuttings. Only a small fraction of the flow must be high pressured. If a double tubing drill pipe system were to be developed, only 250 additional horsepower would be needed (instead of the 2500 hp additional when the entire mud column is subjected to the extra-high pressure). There would, of

course, be significant economic penalties due to higher drill pipe costs and probably longer connection times during tripping.

The following assumptions were made. (1) Drill pipe charges are increased to 5 times nominal. (2) Connection time is increased to 5 times nominal (5 minutes per 90 ft stand instead of 1 minute) - this changes round tripping rate from 1000 ft/hr (nominal) to 405 ft/hr. (3) The equipment charge is reduced to 1/8 of that of the fully pressured single pipe system (\$17.50/hr) and the fuel charge to 1/10 that of the fully pressured system (\$3.00/hr). (4) The rig must be able to handle heavier drill pipe, 65 lb/ft instead of about 25 lb/ft (Flow Report). This will make drill-string total weight heavier than the casing total weight, the determining factor for hook load requirements (casings weights fall in the range of 30 to 60 lb/ft). This is assumed to raise the basic rig rental rate by 30% (\$260/hr instead of \$200/hr).

These assumptions were evaluated for cost saving impacts using the WELCST model, given three hypothetical cases that assumed ROP would be increased to 2X, 3X, or 4X the nominal values. None of the WELCST runs indicated any benefit. The extra drill pipe and rig rent charges, and decreased tripping rate outweigh the ROP advantages.

6.4.3 The Cavijet Bit

This device seems to be the R&D product from this subelement that is most likely to produce economic benefits in geothermal drilling.

The CAVIJET bit is basically an insert bit with cavitating nozzles. It might cost on the order of 30% more than conventional bits and drill at rates 10% (pessimistic) to 20% (optimistic) faster than conventional bits, without changes in mud pump operation.

These assumptions, evaluated by the WELCST and GEOBEN models in the "mud-drilled scenario" (assumes 70% of the wells in the hydrothermal scenario are drilled with mud), indicate the CAVIJET bit would save between 0.6% and 2.1% of the total well cost. The economic benefit of this is \$17.8 million to \$60.7 million (1978 \$).

6.4.4 Sum of Benefits

The benefit from the CAVIJET bit is the only benefit expected to result directly from this R&D subelement. Therefore, the estimated benefit of the subelement is \$17.8 million (pessimistic) to \$60.7 million (optimistic).

6.5 Expected Degree of Success

There are no complex factors in bringing this device to completion. The degree of success is estimated to be 0.80.

6.6 Adjustment of Calculated Benefit to Avoid Overlap With Other DGE Drill Bit R&D Projects

Three bits were found to compete for footage in the "mud-drilled scenario": COMPAX, CAVIJET, and ERODRILL. ERODRILL is estimated to be a dead project, and will not compete.

COMPAX is expected to capture half of CAVIJET's potential market, but not lose any of its expected market to CAVIJET. The reasoning is as follows.

In any given hole, COMPAX promises much better economics than CAVIJET. Therefore, COMPAX would take all of CAVIJET's market if applied to all holes. However, because of lack of skilled drilling crews, COMPAX is expected to be used in only half the holes in which it could be used. Therefore, half of the market is still open to CAVIJET.

The Adjusted Estimated Benefits are shown below.

Bit	Raw Benefit (\$Millions, 1978)		% of Market Lost to Other Bit	Adjusted Benefit (\$ Millions, 1978)	
	Pess.	Opti.		Pess.	Opti.
COMPAX	\$447.3	\$632.7	0%	\$447.3	\$632.7
CAVIJET	\$ 17.8	\$ 60.7	50%	\$ 8.9	\$ 30.4

6.7 Results

	Benefit \$10 ⁶ , 1978	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned & Sunk)
Optimistic	\$30.4	37.1	16.4
Pessimistic	\$ 8.9	10.9	4.8

¹ Figure of Merit = $\frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$

7.0 SUBELEMENT 1-1-F
SUBTERRENCE DRILLING SYSTEM

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-1-F	CONTRACT NUMBER(S) 05 ENG 36
TITLE SUBTERRENE	
CONTRACTOR(S) Los Alamos Scientific Laboratories	
RELATED PROJECTS None. This project will have little impact on hydrothermal developments. Benefits shown are for geopressured and hot dry rock developments.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
	✓	✓			
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		1812										1,812
2. DGE Planned:			0	0	0	0						0
3. Additional:					500	1000	1500	2000	2000	2000	1000	10,000
Total:		1812	0	0	500	1000	1500	2000	2000	2000	1000	11,812

Discounted Total of Planned and Additional: \$6,035 K (1978 \$)

EXPECTED YEAR OF COMMERCIALIZATION 1990
EXPECTED DEGREE OF SUCCESS 0.30

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$1,100 Million
	PESSIMISTIC	\$ 500 Million
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	54.7
	PESSIMISTIC	24.9
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	40.1
	PESSIMISTIC	18.2

SEE ATTACHED PAGES FOR RATIONALE

7.0 SUBELEMENT 1-1-F. SUBTERRENE DRILLING SYSTEM

7.1 Objective

The goal of the R&D on "SUBTERRENE" is to develop a system that makes hole by melting rock through the electrical resistance heating of a drilling point. This is deemed by many to be attractive in geothermal drilling because the heat of the rock should synergize with heat delivered by the point. Current will be delivered to the drilling point by special coaxial drill pipe. The melt will be removed from the hole bottom by air circulation.

One potentially valuable side effect of SUBTERRENE is that when rock is sufficiently porous, much of the melted rock will solidify behind the bit into a solid glass liner. This liner might substitute for casing in some cases, and would always reduce the amount of rock that would have to be transported up the borehole.

7.2 Relationship to Other R&D Projects

A recent analysis of SUBTERRENE economics by LASL staff suggests that the system will probably not reduce costs, relative to rotary drilling technology, unless well depth is greater than about 10,000 feet (1). If this is the case, SUBTERRENE will probably not be used in the 27 prospects carried in the current hydrothermal development

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1. J. H. Altseimer, "Technical and Cost Analysis of Rock-Melting Systems for Producing Geothermal Wells," LASL Report No. LA-6555 MS, Los Alamos Scientific Laboratories, Los Alamos, New Mexico. November 1976.

scenario, since almost all of the wells for those prospects have depths less than 10,000 feet.

Thus, it is assumed in this analysis that SUBTERRENE will not compete directly with the geothermal drilling bit R&D projects. Rather, it is postulated that SUBTERRENE is much more likely to be used in deep boreholes, and thus be much more applicable to geopressured geothermal and hot dry rock geothermal energy system development. For this project alone, illustrative benefits are postulated on a development base other than hydrothermal geothermal electricity plants.

7.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000 BY FISCAL YEAR)										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78 →	TOTAL
1-1-8	1812	0	1812								1812
ADDI- TIONAL						500	1000	1500	7000	10,000	10,000
TOTAL	1812	0	1812	0	0	500	1000	1500	7000	10,000	11,812
(1978 \$)	2193	0	2193	0	0	415	750	1020	3850	6,035	8,228

Significant applied R&D is required to develop a rock-melting point with an economically attractive rate of penetration. Demonstration of economic attractiveness will require extensive downhole tests. It is assumed that the latter phases of development will be

cost-shared between DGE and a commercial firm, but even so, a long range Federal commitment seems necessary.

This system is sufficiently novel, yet reasonably well understood. It seems most likely that the system would see commercial application starting in the late 1980's. This is sufficiently soon for the device to be employed in the majority of geopressured and hot dry rock development expected between now and 2000 A.D. The expected commercialization date for SUBTERRENE is therefore set at 1990.

7.4 Impacts on Well Costs

The analysis here is drawn entirely from the 1976 economic analysis of SUBTERRENE performance by John H. Altseimer¹.

The economics of SUBTERRENE are most sensitive to the trade-offs between rig rental rates and the devices rate of penetration. For the present purposes we assume that land-based rig rental rates apply.

At the time the LASL report was written, the R&D goal for rate of penetration (ROP) was 1.0 mm/sec. The laboratory performance indicated ROP's on the order of 0.2 mm/sec, with the main limitation on ROP being problems with heat transfer rates from the tip of the bit to the rock immediately ahead of it. It is reasonable to assume that the result of this R&D project will be a rock-melting bit with an ROP probably midway between 0.2 and 1.0 mm/sec = 0.6 mm/sec.

It is further assumed that the wells to be drilled for geopressured and hot dry rock geothermal energy systems will fall in the depth range of 5000 to 7000 meters (16,400 to 23,000 feet). Working from Altseimer's cost curve (his Figure 40, p. 33), SUBTERRENE would, compared to conventional rotary drilling, save 17% of the costs on a 5000 m well and 22% of the costs on a 7000 m well. It is thus reasonable to expect that if SUBTERRENE achieves 0.6 mm/sec, it will reduce the costs of geopressured and hot dry rock wells by about 20%. Although Altseimer did not provide cost curves for 0.4 mm/sec, we estimate here that ROP would save about 10% of the cost per well. (An ROP of 0.2 mm/sec - the achieved laboratory performance - produces little cost saving.)

Thus the cost impact of SUBTERRENE is estimated to be a reduction of 18% (pessimistic) to 20% (optimistic) in the cost per well.

7.5 Economic Benefits of Cost Impacts

The impacts of a 10% - 20% reduction in cost per well on the capital outlay for geopressured and hot dry rock applications are developed in Table 7-1. The anticipated present value of the benefit is estimated to be in the range of $\$500 \times 10^6$ to $\$1,100 \times 10^6$ 1978 \$. The reader is encouraged to recognize that the uncertainties associated with this estimate are both enormous and intrinsically not subject to quantification.

7.6 Expected Degree of Success

The project is on hold, but has already produced promising test results in horizontally drilled holes. As of late 1976, the rate of penetration observed was about 30% - 60% of that needed to deliver the engineering process impacts described in Section 7.5.

Nonetheless, the time horizon is long. The degree of success is estimated to be 0.3, on the assumptions that technical success is uncertain and that if the device reaches commercialization its very novelty will interfere with its acceptance by drillers.

7.7 Results

	Benefit \$10 ⁶ , 1978)	Figure of Merit	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$1,100	54.7	40.1
Pessimistic	\$ 500	24.9	18.2

TABLE 7-1

ECONOMIC IMPACTS OF SUBTERRENE ON GEOPRESSURED
GEOTHERMAL AND HOT DRY ROCK COSTS

FACTOR	GEOPRESSURED	HOT DRY ROCK	UNITS
1. Expected Energy by 2000 A.D.	2-4 ⁽¹⁾	0.1 - 0.5 ⁽²⁾	Quads ⁽³⁾
2. Typical Cost/Well	\$4 x 10 ⁶⁽⁴⁾	\$5.6 x 10 ⁶⁽⁵⁾	(1978 \$)
3. Wells/Quad	770 ⁽¹⁾	10,000 ⁽⁵⁾	
4. Total Well Investments	6-12	6-28	(\$ Billion, Current Year)
5. Discount Factor (1995 to 1978 @ 10%/year)	0.17	0.17	None
6. Present Value of Investment	1-2	1-4.8	(\$ Billion, 1978)
7. Potential Cost Savings @ 10% Reduction	100-200	100-480	(\$10 ⁶ , 1978)
@ 20% Reduction	200-400	200-960	(\$10 ⁶ , 1978)
8. Interquartile Range	175-325	315-745	(\$10 ⁶ , 1978)
9. Sum of Savings (Rounded)	--	500-1100	(\$10 ⁶ , 1978)

NOTES FOR TABLE 7-1

- (1) "A Study of a Phase '0' Plan for the Production of Electrical Power from U.S. Gulf Coast Geopressured Geothermal Waters," The University of Texas/The Dow Chemical Company, February 1976.
- (2) "Hot Dry Rock Reserach and Development Plan," Los Alamos Scientific Laboratory/Department of Energy, 1978.
- (3) One Quad equal 10^{15} Btu.
- (4) R. E. Snyder, "Geothermal Well Completions," SANDIA Report 78-7010, January 1978.
- (5) R. B. Duffield, et al., "Hot Dry Rock Geothermal Energy Development Project, Annual Report Fiscal Year 1977," LASL Report LA-7109PR, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, February 1978. Hot dry rock cost and number of wells are for pairs of wells.

8.0 SUBELEMENT 1-2-A

DOWNHOLE MOTORS FOR DRILLING

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-2-A	CONTRACT NUMBER(S)	CO 71581 CO 24033
TITLE Downhole Motors for Drilling			
CONTRACTOR(S) Terra Tek, General Electric			
RELATED PROJECTS The results from this subelement could interact with all drill bit R&D projects, and with downhole instrumentation for drilling.			

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
		✓	✓		
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		1158										1158
2. DGE Planned:			500									500
3. Additional:				500	500	1000	1500	0				3500
Total:		1158	500	500	500	1000	1500	0				5158

Discounted Total of Planned and Additional: \$3,139 K (1978 \$)

EXPECTED YEAR OF COMMERCIALIZATION	1985
EXPECTED DEGREE OF SUCCESS	0.80

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$592.5
	PESSIMISTIC	\$255.5
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	151.0
	PESSIMISTIC	65.1
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	106.7
	PESSIMISTIC	46.0

SEE ATTACHED PAGES FOR RATIONALE

8.0 SUBELEMENT 1-2-A. DOWNHOLE MOTORS FOR DRILLING

8.1 Objective

The goal of this subelement is to develop downhole drilling motors that can (1) survive geothermal drilling conditions and (2) are optimized to produce maximum penetration rates from bits. The technical details of the required improvements in currently available motors are beyond the scope of this analysis. The reader is referred to two recent reports for more information (1, 2).

8.2 Relationship to Other Projects

This subelement is comprised of a number of existing and planned activities over a long time span. Identified contractors include Terra Tek, Inc. (turbodrill), and General Electric Company (Electro-drill).

It should be noted that the results of this subelement, reduced directional drilling costs and improved rate of penetration in straight hole drilling may overlap to an unquantified extent with benefits expected from projects seeking to increase the rate of

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1. W. C. Maurer, J. C. Rowley, and C. Carwile, "Advanced Turbodrill for Geothermal Wells," TRANSACTIONS of the Geothermal Resources Council, Volume 2, July 1978, pp. 411-414.
 2. W. C. Maurer, "Program to Develop Improved Downhole Drilling Motors," Terra Tek, Inc., Report TID-28687, Salt Lake City, November 1976.

penetration of drilling bits. This is because cost savings due to increased rates of penetration do not sum linearly.

On the other hand, interactions of downhole motors and downhole instrumentation packages (Subelement 1-5-A) are likely to be highly synergistic with respect to optimizing both bit performance and directional control.

It has been estimated by DGE program officials that electric downhole motors cannot be readily adapted to geothermal conditions. Therefore the contract with General Electric is treated here only as a sunk cost in this R&D subelement.

8.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST \$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
1-2-1	271	504	775	500						500	1275
1-2-2	0	383	383	0						0	383
ADDI- TIONAL					500	500	1000	1500	0	3,500	3,500
TOTAL	271	887	1158	500	500	500	1000	1500	0	4,000	5,518
(1978 \$)	328	976	1304	500	455	414	750	1020	0	3,139	4,443

Notes: 1-2-1 is Terra Tek contract. 1-2-2 is G.E. contract.

The additional costs are MITRE's estimate of Federal funds needed to bring the development of downhole motors for geothermal

drilling to a point where further RD&D would be co-opted by private industry. The expected year of commercialization is approximately 1985 for most of the developmental goals.

8.4 Impacts on Engineering, Economic, and System Variables

8.4.1 Directional Drilling

While a downhole motor for directional drilling could impact in a number of cost-saving ways (e.g., repair of dog-legs, multiple wells drilled from the same path), it is assumed here, without proof, that the major economic benefit from a downhole motor suited to downhole conditions will come from use of the motor for multiple completions similar to the recently reported triple completion in well number RRGE-3 at Raft River, Idaho (1).

The best estimate from the Raft River group is that, on the average, substituting triple completions for single completions will increase the flow rate per well by 50% for a 20% increase in drilling and completion costs (1). We assume here that this strategy could be adopted for one-half of the wells in the hydrothermal development scenario.

A substantial fraction of the extra cost is due to the difficulty of the directional drilling needed to start the two step-outs

¹Kunze, J. F. and P. A. Witherspoon, "Energy Extraction and Reservoir Management of a Moderate Temperature Hydrothermal System," Proceedings, American Nuclear Society, Energy and Mineral Resource Recovery Conference, April 12-14, 1977, pp. 68-76.

or kickouts from the initial borehole. Improved downhole motors could provide a substantial cost saving in this regard. It is assumed that with improved motors, the additional cost to attain the increased flow rate would be 15% (pessimistic) or as little as 10% (optimistic).

The value of adopting this completion strategy, in terms of cost reduction per unit flow needed for each power plant is given by:

$$(0.5) \left(1 - \frac{1.20}{1.50}\right) (100) = 10.0\% \text{ cost}$$

savings per unit of flow. (The 0.5 factor reflects the assumption that only half of the wells or prospects could be treated this way.)

If the cost addition is 15% instead of 20%, the cost saving is

$$(0.5) \left(1 - \frac{1.15}{1.50}\right) (100) = 11.67\%, \text{ a contribution of } 1.67\% \text{ from the}$$

downhole motor. If the cost addition is only 10%, the cost saving

$$\text{is } (0.5) \left(1 - \frac{1.10}{1.50}\right) (100) = 13.33\%, \text{ a contribution of } 3.33\% \text{ from}$$

the downhole motor. Since each one percent reduction in well cost is worth about \$47 million, the resulting benefit is \$78.5 million (pessimistic) to \$156.5 million (optimistic).

8.4.2 Straight Hole Drilling

The principal technical benefit of using downhole motors for straight drilling is that the motor will deliver more power and torque to the bit, thus increasing the rate of penetration (ROP). Without firm basis, it is assumed that the increase in ROP would range from 25% (pessimistic) to 50% (optimistic).

The economic effects of these assumptions were estimated using the WELCST (and GEOBEN) model, which contains provision for drilling most boreholes with downhole motors. The assumed cost added by the use of the motor was \$2000 per day, a typical cost for directional drilling in the Geysers field.

At current use costs, a downhole motor that increased ROP by 25% would save \$87 million, and a motor that increased ROP by 50% would save \$361.1 million. If the motor use charges were reduced by 30%, a not unreasonable goal for this R&D subelement, there would be an additional cost saving of \$90 million in the first case, and \$75 million in the second case.

Thus, the pessimistic benefit is estimated to be $\$87 + \$90 = \$177$ million, and the optimistic benefit is estimated to be $\$361 + \$75 = \$436$ million.

8.4.3 Sum of Benefits

When benefits from directional and straighthole drilling are combined, the pessimistic benefit is $\$78.5 \text{ million} + \$177 \text{ million} = \$255.5 \text{ million}$ and the optimistic benefit is $\$156.5 \text{ million} + \$436 = \$592.2 \text{ million}$.

8.5 Expected Degree of Success

While the payoff for this subelement is well in the future, there is no reason to believe that the improvement goals could not be attained, and that the motors could come to dominate much of

geothermal drilling. The degree of success is therefore estimated to be 0.80.

8.6 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$592.5	151.0	106.7
Pessimistic	\$255.5	65.1	46.0

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

9.0 SUBELEMENT 1-3-A
HIGH-TEMPERATURE DRILLING FLUIDS

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-3-A	CONTRACT NUMBER(S)	SO 55218, CO 71603, EG 77-C-05-5381
TITLE High Temperature Drilling Fluids			
CONTRACTOR(S) Maurer, NL Baroid, Oklahoma University			
RELATED PROJECTS None			

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
	✓	✓		✓	
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	86	TOTAL
1. Sunk:		427										427
2. DGE Planned:			248	293	60							601
3. Additional:					540	700	800	600	600	600	300	4140
Total:		427	248	293	600	700	800	600	600	600	300	5168
Discounted Total of Planned and Additional: \$3239 (1978 \$)												

EXPECTED YEAR OF COMMERCIALIZATION	1983 (assumed)
EXPECTED DEGREE OF SUCCESS	0.50

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$496.5
	PESSIMISTIC	\$242.0
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	76.6
	PESSIMISTIC	37.4
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	66.4
	PESSIMISTIC	32.4

SEE ATTACHED PAGES FOR RATIONALE

9.0 SUBELEMENT 1-3-A. HIGH-TEMPERATURE DRILLING FLUIDS

9.1 Objective

The objective of this subelement is to develop drilling fluids (e.g., mud and foam) that retain advantageous physics-chemical properties when exposed to the elevated temperatures, saline waters, and acid gases encountered in geothermal drilling. As described by Maurer et al. (1), these conditions induce rheological problems because the clay colloids in mud flocculate at high temperature (starting at 150°C, giving rise to high shear strength and gel strength. Ensuing drilling problems include: mud solidification, stuck pipe and twist-offs; lost circulation, slowed drilling to recover circulation, or blowouts; corrosion and erosion; and poor filtration control, causing damage to potential producing formations.

9.2 Relationships to Other Projects

The benefits to be derived from improved muds are essentially independent from benefits derived from the other R&D subelements analyzed here.

In the past two years to present this subelement has consisted of three major projects: 1-3-1. (Contract No. CO 71603) Maurer Engineering, to measure characteristics of available muds at elevated temperature and pressure. 1-3-2 (Contract No. EG-77-C-05-05381)

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1. McDonald, W. J., L. J. Remont, and C. Carwile, "Improved Geothermal Drilling Fluids," Transactions of the Geothermal Resources Council, Volume 2, July 1978, pp. 419-422.

NL Baroid, to develop a mud testing stand with 370°C and 20,000 psi capability, and 1-3-3 (Contract No. SO 55218), Oklahoma University, to build a test stand to measure effects of temperatures up to 290°C on mud components.

Much work to develop improved mud components will be necessary over a number of years in various unspecified projects.

9.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83- 86	TOTAL 78→	TOTAL
1-3-1	20	115	135	62	100					162	297
1-3-2	0	0	0	65	125	60				250	250
1-3-3	202	90	292	121	68					189	481
ADDI- TIONAL						540	700	800	2100	4140	4140
TOTAL	222	205	427	248	293	600	700	800	2100	4741	5168
(1978 \$)	269	225	494	248	267	498	525	544	1157	3239	3733

It is assumed that the benefits will start being commercialized before all of the R&D is completed. 1983 is set as the year of commercialization for analysis purposes.

9.4 Impacts on Engineering/Economic Variables

Five types of impacts were examined using the WELCST and GEOBEN models. The impact types and their consequent cost saving benefits are shown in Table 9-1, and discussed briefly here.

- (a) Mud cost per well. This could be reduced if thickening due to high temperature were reduced. Replacement of unusable mud would be required at slower rate.
- (b) Lost circulation frequency. Improved filtration properties could reduce the rate of occurrence of (and consequent costs to recover from) lost circulation episodes. It is assumed that improvement here would pertain mainly to lost circulation which can be recovered by the use of lost-circulation materials. In those cases where cementing is required to recover circulation, it is assumed that thick fissures have been penetrated and that mud, however good, does not do much to prevent this type of mishap.
- (c) Stuck pipe and twist-off. Thickened mud can cause either drill pipe or bits to become stuck. The drilling records used to tabulate frequencies of twist-off were for the most part labeled "Fishing for pipe," without indication of how the pipe had become lost downhole. Maurer et al. (See footnote above) indicate that most such episodes in geothermal

TABLE 9-1

EXPECTED IMPACTS FROM IMPROVED DRILLING FLUIDS

ENGINEERING/ECONOMIC IMPACT	% Change		Benefit (\$Million, 1978)	
	Pessimistic	Optimistic	Pessimistic	Optimistic
1. Mud cost per well. Reduced due to decreased thickening at high temperatures.	-20%	-50%	\$ 22.6M	\$ 56.5M
2. Frequency of lost circulation episodes in soft & medium hardnesses formation. Reduced by better filtration properties.	-20%	-40%	\$ 0.6M	\$ 1.3M
3. Stuck pipe & twist-off frequency. Reduced due to decreased thickening.	-25%	-50%	\$133.8M	\$267.7M
4. Switch to air drilling at % of prospects. Caused by development of improved foams.	20%	40%	\$ 83. M	\$166. M
5. R&D savings due to test stand availability.	NA	NA	\$ 2. M	\$ 5. M
TOTAL	NA	NA	\$242.0M	\$496.5M

NA - Not Applicable

drilling can be attributed to mud problems. It is assumed here, however, that some large part of twist-offs in geothermal holes are due to bits jammed in rock, especially because of drilling in under-gage holes. Thus the maximum improvement attributed to muds is assumed to be a 50% reduction in twist-off frequency.

- (d) Switch to air drilling. The subelement activities are likely to develop foams for geothermal drilling that would allow many holes to be drilled with most of the increased ROP advantages of air drilling. The WELCST model indicates that, if the bottom 70% of all holes in the hydrothermal development scenario could be drilled with air, there would be a total net savings of about \$416 million. If new foams allow the switch of between 20% and 40% of these holes to air drilling, the benefit would be on the order of \$83 million to \$166 million.
- (e) Test stands. The value of this R&D cost appears mainly in form of R&D cost savings. Following lines of analysis similar to that for the drill bit test stand (See Section 4.5.5, this Appendix), the potential benefit is estimated to lie roughly in the range of \$2 million to \$5 million.

9.5 Impacts on System Variables

As shown in Table 9-1, the total benefit is estimated to fall in the range of \$242 million to \$496.5 million.

9.6 Estimated Degree of Success

It is not unlikely that success in this program of R&D activities depends on the discovery of certain relatively inexpensive but exotic materials that possess all the good qualities but none of the bad qualities of bentonite clays, the principal constituent of most drilling fluids. Success is not assured. In the absence of any firm basis for estimation, the degree of success is assumed to be 0.5.

9.7 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned and Sunk)
Optimistic	\$496.5	76.6	66.5
Pessimistic	242.0	37.4	32.4

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

10.0 SUBELEMENT 1-4-A
GEOTHERMAL LOGGING SONDE COMPONENTS

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-4-A	CONTRACT NUMBER(S) See analysis
TITLE GEOTHERMAL LOGGING SONDE COMPONENTS	
CONTRACTOR(S) See analysis, Table 10-1	
RELATED PROJECTS Other DGE R&D projects related to cables for geothermal logging and interpretation of geothermal well logs. See Appendix B, this volume.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
		✓	✓		
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)											
F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:	709										709
2. DGE Planned:		724									724
3. Additional:			450	250	200						900
Total:	709	724	450	250	200						2333

Discounted Total of Planned and Additional: \$ 1.490 million (1978\$)

EXPECTED YEAR OF COMMERCIALIZATION	Circa 1980-1983
EXPECTED DEGREE OF SUCCESS	0.74

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$ 261.7
	PESSIMISTIC	\$ 89.7
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	129.
	PESSIMISTIC	43.8
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	83.8
	PESSIMISTIC	28.5

SEE ATTACHED PAGES FOR RATIONALE

TABLE 10-1

GEOTHERMAL LOGGING SONDE COMPONENTS R&D PROJECTS

MITRE CODE	PROJECT TITLE	CONTRACTOR	DGE CONTRACT #	TECHNICAL OBJECTIVE
1-4-1	Improved Geo- thermal Logging Tools	Systems, Science, Software	CO 31315	Develop sonde to measure shut-in pressure and temperature to 275°C without active electronics down-hole.
1-4-2	Neutron Acti- vation Analysis	IRT	CO 30936	Develop device to measure fractures, fluid flow, porosity, dissolved solids, lithology formation temperature.
1-4-3	Improved Log- ging Tools & Components	Westinghouse	CO 24082	Develop high temperature (275°C) acoustic sensor for geothermal logging.
1-4-4	Heat Flux Tran- ducer and Thermal Probe	Geosciences	CO 31318	Develop instrument to measure geothermal heat flux and thermal conductivity.
1-4-5	Mechanical Refrigerator	Mechanics Research, Inc.	CO 31309	Develop device to cool logging sondes by mechanical refrigeration.
1-4-6	Electromagnetic Signal Transmission	Raytheon	CO 22816	Develop electromagnetic borehole telemetry system.
1-4-7	Improved Temperature Measurement	Spectro Systems	CO 14008	Use materials of selected melting points to measure well temperature while bit is downhole.

10.0 SUBELEMENT 1-4-A. GEOTHERMAL LOGGING SONDE COMPONENTS

10.1 Objective

The objective of the seven R&D projects analyzed in this subelement is to develop certain components for well logging sondes that can withstand the high temperatures and corrosive fluids of geothermal wells.

10.2 Approach to Analysis and Relationships to Other R&D Projects

The titles and specific objectives of the seven R&D projects are listed in Table 10-1.

The projects were reviewed and found to have multiple and overlapping potential impacts on a number of data collection capabilities and a number of geothermal well drilling and completion operations. A major integrated analysis of the economic benefits of these seven R&D projects was made; it is reported in Appendix B of this volume. The expected benefits reported here are taken from Appendix B.

The benefits estimates for the sondes are based on estimates of impacts of the sondes on the economics of well drilling and completion operations. The analyses took account of the relative contributions of sondes and other aspects of drilling technology in a way that makes the estimate of benefit from seven sonde R&D projects independent of other DGE R&D projects.

It should be noted, however, that the benefits predicted for each specific sonde R&D project are not necessarily independent of each other. In some cases, more than one sonde impacts on a given

data-gathering capability. In these cases, a benefit derived for the data-gathering capability was distributed between the sondes in proportion to estimates of how much each sonde might be used to collect the particular type of data. Thus there is some redundancy between the projects in their capability to deliver economic benefits. Therefore, if a particular R&D project were to be unsuccessful, some of its estimated economic benefit would still be captured by the remaining sondes component R&D projects.

10.3 Estimated Costs and Year of Commercialization

COSTS (Current year, Non-Discounted)

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
1-4-1		86	86	102						102	188
1-4-2		86	86	45						45	131
1-4-3		105	105	97	100					197	302
1-4-4		79	79	79						79	158
1-4-5		121	121	145	150	150	200			645	766
1-4-6		131	131	200	200	100				500	631
1-4-7		101	101	56						56	157
TOTAL		709	709	724	450	250	200			1624	2333

COSTS (Discounted at 10%/Year to 1978 \$)

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→	TOTAL
1-4-1		95	95	102						102	197
1-4-2		95	95	45						45	140
1-4-3		116	116	97	91					188	304
1-4-4		87	87	79						79	166
1-4-5		146	146	145	136	124	150			555	701
1-4-6		144	144	200	182	83				465	609
1-4-7		122	122	56						56	178
TOTAL		805	805	724	409	207	150			1490	2295

Costs beyond 1978 were estimated by MITRE.

The expected year of commercialization varies between 1980 and 1983. All benefits were calculated under the assumption that the devices would be commercially available in 1983 and beyond.

10.4 Expected Degree of Success

The projects were examined with respect to the stipulated R&D activities and the technological complexity of the sonde being developed by each. A (necessarily arbitrary) degree of success was estimated for each project. The degree of success was set high if the desired objective seemed attainable within budget, and lower in

TABLE 10-2
BENEFIT/COST RESULTS FOR LOGGING SONDE
COMPONENTS R&D PROJECTS

MITRE CODE	PROJECT TITLE	Estimated Benefit, (\$Millions, 1978) ¹		Degree of Success	Expected Benefit, (\$Millions, 1978) ²		Figure of Merit			
		Pessimistic	Optimistic		Pessimistic	Optimistic	FY78 to Completion		Historical (Sunk & Planned)	
							Pessimistic	Optimistic	Pessimistic	Optimistic
1-4-1	Improved Geo-thermal Logging Tools	10.8	37.5	1.00	10.8	37.5	106.	368.	54.8	190.
1-4-2	Neutron Acti- vation Analysis	17.7	51.0	0.30	5.3	15.3	118.	340.	37.9	109.
1-4-3	Improved Log- ging Tools & Components	3.5	6.5	0.80	2.8	5.2	14.9	27.7	9.2	17.1
1-4-4	Heat Flux Tran- ducer and Thermal Probe	1.8	5.2	1.00	1.8	5.2	22.8	65.8	10.8	31.3
1-4-5	Mechanical Refrigerator	38.3	112.2	0.80	30.6	89.8	55.1	162.	43.7	128.1
1-4-6	Electromag- netic Signal Transmission	15.8	44.8	0.80	12.6	35.8	27.1	77.0	20.7	58.8
1-4-7	Improved Temperature Measurement	1.8	4.5	0.80	1.4	3.6	25.0	64.3	7.9	20.2
	TOTAL	\$ 89.7M	\$261.7M	0.74 ³	65.3	192.4	43.8	129.1	28.5	83.8

¹ Discount rate = 10%.

² Expected Benefit = Estimated Benefit x Degree of Success.

³ Weighted average.

proportion to the degree that substantial R&D would be required in the private sector to bring the specific sonde into use.

The estimated degree of success for each project is included in Table 10-2.

10.5 Results

The results are shown in Table 10-2. The summed benefit for the seven projects is estimated to be \$89.7 million to \$261.7 million. Optimistic figures of merit for the seven projects range from 27.7 to 368 (based on FY 1978 and future outlays). The overall current figure of merit for the seven projects, combined, ranges from 43.8 (pessimistic) to 129.1 (optimistic).

11.0 SUBELEMENT 1-5-A

DOWNHOLE INSTRUMENTATION FOR DRILLING

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-5-A	CONTRACT NUMBER(S) CO 22812
TITLE Downhole Instrumentation for Drilling	
CONTRACTOR(S) Sperry Research Center	
RELATED PROJECTS None. But benefits from this Subelement could synergize with benefits expected from downhole motor development (Subelement 1-2-A).	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
		✓			
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		352										352
2. DGE Planned:			0	0								0
3. Additional:					500	600	600	300	0			2000
Total:		352	0	0	500	600	600	300	0			2352

Discounted Total of Planned and Additional: \$1.459 million (1978\$)

EXPECTED YEAR OF COMMERCIALIZATION 1985
EXPECTED DEGREE OF SUCCESS 0.50

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$144.0
	PESSIMISTIC	\$ 31.9
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	49.3
	PESSIMISTIC	11.0
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	38.4
	PESSIMISTIC	8.5

SEE ATTACHED PAGES FOR RATIONALE

11.0 SUBELEMENT 1-5-A. DOWNHOLE INSTRUMENTATION FOR DRILLING

11.1 Objective

The objective of this subelement (project) is to explore and develop methods of telemetry for use during geothermal drilling which could be used as the basis of a Measurements-While-Drilling (MWD) system. The emphasis has been on acoustic and electromagnetic methods which employ the drill pipe, casing, and/or the surrounding formation as the transmission medium.

11.2 Relationship to Other Projects

This subelement consists of a single R&D project (Contract Number C022812) at Sperry Research Center. Some of the technical work on Subelement 1-5-B, Geothermal Downwell Instrumentation for Pumping, by the same contractor, contributed to the R&D on the mud-pulse telemetry studied here. But the benefits of the two subelements are not expected to overlap.

11.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR										
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78 →	TOTAL
1-5-1	278	74	352	0						0	352
ADDI- TIONAL						500	600	600	300	2000	2352
TOTAL	278	74	352	0	0	500	600	600	300	2000	2352
(1978 \$)	336	81	417	0	0	415	450	408	186	1459	1876

The costs listed here assume that once the acoustic or electromagnetic telemetry system is developed, significant R&D efforts will be required to package, along with the telemetry, appropriate sensors for an integrated downhole drilling instrumentation system that includes directional analysis capabilities.

11.4 Impacts on Engineering/Economic Variables

Much of the discussion here is based on the very comprehensive report "Borehole Measurements While Drilling - Systems and Activities" by Dr. William J. McDonald of Maurer Engineering, Report Number MEI, TR-77-14/IDO/0091, June 1977.

This subelement is one of the most intriguing of those analyzed here because it presents great uncertainties with respect to the technological impacts of the novel device(s) and the operating costs to drill-rig operators of the new device(s).

Everyone contacted is certain that data captured downhole, and quickly fed back to the drilling process could improve drilling techniques a great deal. But, there is no hard information available regarding either the data that would be the most important to capture, or the magnitude of the technological impacts that such data might have. Also, it is very unclear how much, say in terms of dollars per day, a useful instrumentation package, would add to drilling charges.

Now, consider some of the impacts that a downhole instrument (DHI) could have:

- Sensing torque on bit could be used to better match bit RPM and weight on bit to rock characteristics, maximizing energy transfer to the face of the hole, and thus increasing the rate of penetration (ROP).
- Sensing mud pressure in the immediate vicinity of the bit could detect incipient blowouts in plenty of time to flood the hole with dense mud (held in reserve in a storage pit or tank) to counter-balance the detected bottom-hole pressure increase. If so, mud density could be set at much nearer the safety margin, mud pressure at hole bottom would be reduced, and ROP would be further increased.
- Sensing torque on bit could also reduce twist-off frequency. Wireline, mud pulse, or electromagnetic telemetry could signal "stop rotating" much more rapidly than the operator's sensing this condition on the platform.
- Collection of open-hole logging information while drilling. This would reduce the time the rig is idle during wireline logging operations.

The above impacts apply to all drilling. There would be additional impacts for directional drilling. These include:

- Reduced hole deviation and reduction in dogleg frequency and severity.
- Reduced rig time lost due to wire-line surveys during directional drilling.

The reader need not be reminded that directional drilling has gained importance for geothermal drilling in the last few years, due to factors such as the economic advantages of drilling multiple wells from a single drilling pad, multiple bottomhole completions, and the strenuous directional drilling demands that must be met if the "Hot Dry Rock" Concept is to become a practicable energy source.

These positive impacts were translated into the following estimates of technological changes in drilling events:

IMPACT	ASSUMED EFFECT
1. Increased effective ROP due to lightened mud and better bit torque control.	+15% (Industry estimates range from 5% to 35%, according to McDonald.)
2. Reduction in frequency of twist-off incidents.	-15% (But could be much higher.)
3. Reduction in dogleg frequency.	-20% (Greater impacts require and are credited to use of down-hole motors.)
4. Reduced time for wireline logging and directional services.	40% in reduction in miscellaneous time lost while rotating (YAC (5) in WELCST set to 0.60).

These above impacts are economic credits. Economic debits come in the form of costs to raise the DHI package. These costs will depend on:

- The number and types of sensors in the package.
- The type of telemetry used, whether mud-pulse, acoustical, electromagnetic or wire-line.
- The degree to which data might be used immediately downhole - especially when DHI packages are linked to use of downhole motors, compared to the case where data from DHI packages have to reach the drilling platform before they can have effects on operational decisions.

The likely cost/day for use of a DHI system is difficult to estimate. McDonald (reference cited) gathered a number of estimates

of what per-day costs for a DHI package might be. Estimates tended to be either in a high range (\$4K to \$8K for Schlumberger/The Analysts tool for gamma log, temperature log, electric log, bit weight, bit torque and bit condition; \$4K-\$5K for Scientific Drilling Controls "Eye - Electronic Yaw Equipment" for directional drilling) or in a low range (\$1.2K-\$2K for Teleco mud pulse system for directional drilling; \$1K-\$2K for Exploration Research Company system for pressure ahead of the bit, geophysical structure, and other data).

From these estimates, it seems most likely that a DHI system could be priced in the range of \$2K to \$4K per day while delivering information useful both for straight hole and directional drilling.

This range of costs was evaluated using the WELCST model, by assuming that the added cost of the DHI package would be \$1K, \$2K, \$3K or \$4k per day.

11.5 Impacts on System Parameters

The positive technological impacts and the costs estimated in Section 11.4 were used as inputs to the WELCST and GEOBEN models.

The results are shown here.

Rental Cost per day for Use of DHI Package	% Reduction in Cost per Typical Geothermal Well	Benefit (\$ Millions,78)
\$1,000/day	-4.5%	\$286.5
\$2,000/day	-2.3%	\$144.0
\$3,000/day	-0.5%	\$ 31.9
\$4,00/day	-0.0%	\$ 0.0

Since it was estimated above that the cost per day is most likely to fall in the \$2,000 to \$3,000 range, the pessimistic estimate of the benefit of this R&D subelement is set at \$31.9 Million, and the optimistic estimate is \$144.0 Million.

11.6 Expected Degree of Success

The main questions here are: (1) Will the efforts of private industry to develop DHI packages for gas and oil drilling also result in a DHI package suited to most geothermal needs?, and (2) Will drillers adopt DHI packages when available? The general answers to both of these questions are deemed to be positive, particularly if the DGE program continues to fund judiciously the incremental improvements in components needed for both geothermal and deep oil well drilling. Nonetheless, there are many imponderables, so the degree of success is estimated to be 0.50.

11.7 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned & Sunk)
Optimistic	\$144.0	49.3	38.4
Pessimistic	\$ 31.9	11.0	8.5

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

12.0 SUBELEMENT 1-5-B
DOWNHOLE INSTRUMENTATION FOR PUMPS

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-5-B	CONTRACT NUMBER(S) CO 22750
TITLE DOWNHOLE INSTRUMENTATION FOR PUMPS	
CONTRACTOR(S) Sperry Research Center	
RELATED PROJECTS None in this program. But contributes to downhole pump projects in Program II: Utilization Technology R&D.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
			✓	✓	
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		364										364
2. DGE Planned:			0									0
3. Additional:				0								0
Total:		364	0	0								
Discounted Total of Planned and Additional: \$0.0												

EXPECTED YEAR OF COMMERCIALIZATION	1982
EXPECTED DEGREE OF SUCCESS	0.50

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$170 Million
	PESSIMISTIC	\$ 85 Million
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	--
	PESSIMISTIC	--
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	199.0
	PESSIMISTIC	99.5

SEE ATTACHED PAGES FOR RATIONALE

12.1 Objective

Sensing and telemetry (over existing structures without any additional cables or tubes) of parameters such as fluid pressures and temperatures and pump shaft speed from a down-well pump site to the surface during pump operation.

12.2 Relationship to Other R&D Projects

This instrumentation system is an adjunct to the Sperry down-well pumping system, discussed in Volume III of this report. The project was managed under the Geothermal Drilling Technology Program because the work on this contract with Sperry Research Center followed from the work on Subelement 1-5-A, Downhole Intrumentation for Drilling.

12.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR									
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→
1-5-3	249	115	364	0						0
ADDI- TIONAL				0	0					0
TOTAL	249	115	364	0	0					0
(1978\$)	301	126	427	0						0

Down-well tests of this system in 1976 were judged successful with respect to the acoustic telemetry. Sperry will continue work on this system, and expects that prototypes will be used with early

downhole pumping systems in calendar 1980. The year of commercialization is therefore estimated to be 1981.

12.4 Impacts in Engineering/Economic Variables

The sensors and acoustic telemetry system developed in this contract were tested downhole. Acoustic signal was transmitted on the pump's pipe strings in the 1976 down-well test (see Final Reports, Contract No. EY-76-C-02-2750, April 1977). Based on those tests, it is believed to be practical to transmit acoustically on the pipe string up to 100 bits/second of data from 2,000-foot depth at temperatures up to 360 degrees F. Higher temperatures would require use of advanced electronic components now the subject of DOE-sponsored research.

The currently available bubble tube technique measures fluid pressure only and requires a dedicated capillary tube which is difficult to install and vulnerable to damage. (Two such tubes used in 1976 down-well pump tests never worked.) A separate electric logging cable severely complicates pump installation and is limited to about 350 degrees F operation.

Cost of the entire instrumentation system (sensors, power supply, acoustic modulator and transmitter, wellhead receiver, and indicators and recorders) for more than eight different parameter measurements is estimated to be less than \$20,000 in production.

The impacts of the system lie in the areas of (a) reduced maintenance costs for downhole pumps and (b) increases in fluid production efficiency.

O&M cost savings for downhole pumps are estimated to be in the range of 10% to 20%, after the cost of instrumentation system is taken into account. This was evaluated using the GEOBEN model, via input ROMF(6) and found to produce a benefit of \$57. Million to \$115. Million.

Improved pumping efficiency is estimated to improve overall plant efficiency by about 0.5% to 1.0%, thus reducing the overall cost of electricity from pumped (mainly binary-cycle) plants by about the same percentage. The benefit of this effect ranges from \$28. Million to \$55. Million, assuming that about half of the plants in the hydrothermal electric plant scenario employ downhole pumps.

12.5 Impacts on System Parameters

The calculated benefit is the sum of the two types of savings calculated above. The pessimistic estimate of benefit is (\$57.M + \$28. M) = \$85.0 Million. The optimistic estimate is (\$115.M + \$55.M) = \$170.Million.

12.6 Estimated Degree of Success

Because the test results are promising, and further development is coupled to Sperry's downhole pump development efforts, it is assumed that Sperry will continue to develop this device with its own funds, and that therefore the technical success of this subelement is not in doubt. However, it is likely that Sperry's downhole pump and instrumentation package may not capture more than half of its potential market. Therefore the degree of success is set at 0.50.

12.7 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned & Sunk)
Optimistic	\$170.M	- - 2	199.0
Pessimistic	\$ 85.M	- - 2	99.5

¹ Figure of Merit = $\frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$

² Cannot be calculated because there are no future costs for this Subelement.

13.0 SUBELEMENT 1-5-C
ENVIRONMENTAL SIMULATING PUMP TEST RIG

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER	1-5-C	CONTRACT NUMBER(S)	2923715
TITLE	ENVIRONMENTAL-SIMULATING PUMP TEST RIG		
CONTRACTOR(S)	Barber-Nichol Engineering, Arvada, Colorado		
RELATED PROJECTS	None in this program.		

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
			✓	✓	
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)												
	F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:		20										20
2. DGE Planned:			35	75	75	0						185
3. Additional:			0	0	0	0						0
Total:		20	35	75	75	0						205
Discounted Total of Planned and Additional: \$165 K (1978\$)												

EXPECTED YEAR OF COMMERCIALIZATION	1981
EXPECTED DEGREE OF SUCCESS	0.80

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC	\$ 3.0 Million
	PESSIMISTIC	\$ 1.5 Million
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC	18.2
	PESSIMISTIC	9.1
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC	15.9
	PESSIMISTIC	7.9

SEE ATTACHED PAGES FOR RATIONALE

13.1 Objective

The objective is to provide a test facility to aid the development of downhole pumps for geothermal brine production.

13.2 Relationship to Other R&D Projects

The reader is encouraged to consult Volume III of this report for descriptions of the types of downhole pumps that are being developed, and are likely to be tested on this test rig.

13.3 Estimated R&D Costs and Year of Availability.

PROJECT CODE	COST (\$1000) BY FISCAL YEAR									
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→
1-5-3	0	20	20							0
Planned				35	75	75	0			185
TOTAL	0	20	20	35	75	75	0			185
(1978\$)	0	24	24	35	68	62	0			165

The rig should be ready for use in 1981.

13.4 Cost-Saving Impacts

This project promises to reduce R&D costs associated with downhole pump development. There is no way to predict exactly how much the rig will be used, or how much it will save per test.

MITRE made the following tentative estimates:

- Number of tests: 30, over the 5-year period 1980-1984.
- Economic value of each test: This derives from obviating the need to conduct downhole tests at every stage of pump development. Downhole tests are very expensive because the pump has to be installed and removed perhaps twice (perhaps \$20K per round trip), pump operation requires many personnel

on-site (\$10K to \$20K), and pump operation may damage the well (say a 5% to 10% chance of ruining a \$500,000 well). When these and other factors are considered, each test could have a value on the order of \$50,000 to \$100,000 in saved costs.

- Overall Value: 30 tests, at \$50K to \$100K per test suggest a benefit from this test stand of \$1.5 Million (Pessimistic) to \$3.0 Million (optimistic).

13.5 Expected Degree of Success

Since there is no reason to expect that the stand will not be used as planned, the degree of success is set at 1.00.

13.6 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned & Sunk)
Optimistic	\$ 3.0	18.2	15.9
Pessimistic	\$ 1.5	9.1	7.9

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

14.0 SUBELEMENT 1-6-A
CAVITATION DESCALING SYSTEM

BENEFIT/COST RATIONALE AND RESULTS

SUBELEMENT NUMBER 1-6-A	CONTRACT NUMBER(S) CO 12289
TITLE CAVITATION DESCALING SYSTEM	
CONTRACTOR(S) Daedalean Associates, Inc., Woodbine, Md.	
RELATED PROJECTS None. However, a follow-on to this study will investigate the application of cavitation to the descaling of well-bores.	

CURRENT STATE OF R&D: (CHECK APPROPRIATE STAGES)					
				✓	✓
Preliminary Study	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Demonstration & Commercialization

(\$1000s, CURRENT YEAR)											
F.Y.	To 78	78	79	80	81	82	83	84	85	>85	TOTAL
1. Sunk:	196										196
2. DGE Planned:		100	0								100
3. Additional:		0	0								0
Total:	196	100	0								296
Discounted Total of Planned and Additional: \$100K (1978\$)											

EXPECTED YEAR OF COMMERCIALIZATION	1980
EXPECTED DEGREE OF SUCCESS	0.80

CALCULATED BENEFIT (DISCOUNTED TO \$ MILLIONS, 1978)	OPTIMISTIC \$73.3
	PESSIMISTIC \$34.5
FIGURE OF MERIT (W/O SUNK COSTS)	OPTIMISTIC 586.
	PESSIMISTIC 283.
HISTORICAL FIGURE OF MERIT (W/SUNK COSTS)	OPTIMISTIC 179.
	PESSIMISTIC 86.5

SEE ATTACHED PAGES FOR RATIONALE

14.1 Objective

The objective is to develop a self-contained cavitation cleaning system for removing scale from geothermal heat exchangers and piping. The system pumps water through high pressure cavitating nozzles, producing cavitation bubbles which collapse on the cleaning surface, removing scale, but not damaging the pipe walls.

14.2 Relationship to Other R&D Projects

There may be some overlap of benefits between this R&D project and scale-control R&D projects in the Geochemical and Materials Engineering R&D Program of DGE. See Volume IV of this report.

14.3 Estimated R&D Costs and Year of Commercialization

PROJECT CODE	COST (\$1000) BY FISCAL YEAR									
	PRIOR 76	77	TOTAL	78	79	80	81	82	83	TOTAL 78→
1-6-1	98	98	196	100	0					100
ADDITIONAL					0					0
TOTAL	98	98	196	100	0					100
(1978\$)	119	108	217	100	0					100

The device was demonstrated in the field in 1978. The FY-78 funds are to support commercialization efforts. The device will be ready for commercial use no later than 1980.

14.4 Impacts on Engineering/Economic Variables

This device offers two major improvements over current

water jet scale removal systems: it can clean hard silica scale from pipes, and it removes scale very rapidly.

The economic advantages of the system will be maximized when geothermal electric plant design can be optimized to take advantage of the rapid cleaning rates offered by this system. The heat exchangers can be cleaned more often, reducing the average fouling factor for the heat exchanger tubes, and thus reducing the needed size of heat exchanger. There should also be a direct reduction in the O&M costs for the heat exchanger.

The following impacts were estimated to apply to 60% of the binary-cycle plants in the hydrothermal electric plant development scenario.

Impact	GOEBEN Input Variables	Magnitude of Impact	
		Pessimistic	Optimistic
Capital Cost of Heat Exchanger.	RDFCC(8)	-10%	-20%
O&M Cost for Heat Exchanger.	(60% of Utility Process Mechanical O&M Cost. See next line.)	-20%	-50%
Utility Process Mechanical O&M Cost.	ROMF(11)	-12%	-30%

14.5 Impacts on System Parameters

The GOEBEN model was used to estimate the benefit from the impacts listed above. Assuming that 60% of binary plants will be affected by the impacts, the benefits are:

Impact Factor	Benefit (\$ Millions, 1978)	
	Pessimistic	Optimistic
Reduced Heat Exchanger Capital Cost	30.4	60.7
Reduced Heat Exchanger O&M Cost	5.0	12.6
SUM	\$35.4M	\$73.3M

14.6 Estimated Degree of Success

The descaling system is effective and is being well publicized. The main competition for use lies in the development of effective and inexpensive scaling prevention procedures. The degree of success of this subelement is estimated to be 0.80.

14.7 Results

	Benefit (\$10 ⁶ , 1978)	Figure of Merit ¹	
		FY 78 to Completion	Historical (Planned & Sunk)
Optimistic	\$73.3	586.	179.
Pessimistic	35.4	283.	86.5

$$^1 \text{Figure of Merit} = \frac{\text{Benefit} \times \text{Degree of Success}}{\text{R\&D Cost}}$$

APPENDIX B

BENEFITS FROM WELL-LOGGING
INSTRUMENTATION R&D PROJECTS

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1.0 INTRODUCTION

This appendix describes the approach, methodology and results of an analysis of the potential economic benefits of selected projects of the Geothermal Well Logging Instrumentation R&D Program of the Division of Geothermal Energy (DGE). The analysis was performed by MITRE/Metrek as part of a benefit/cost analysis of the DGE Geothermal Drilling Technology R&D Program.

1.1 The Geothermal Well Logging R&D Program

The Well Logging R&D Program is targeted at developing improved components for geothermal well logging sondes. The overall goal is to facilitate the development of sondes that can withstand the severe physical conditions encountered in geothermal wells.

Much of the technology used in the drilling of geothermal wells was originally developed for the drilling of oil and gas wells. This is as true for logging equipment as it is for drilling hardware. Consequently, little logging is done on geothermal wells, since the existing logging sondes do not survive the higher temperatures and more corrosive environments found in these wells.

The emphasis and R&D directions of the Program have been carefully tailored to the needs of the growing geothermal industry, starting with an in-depth survey of well logging technology and geothermal applications (1). Workshops held in 1975 identified which logging tool capabilities were most important to develop for geothermal applications, and the suitability of various types of

electronic components to be adapted to geothermal working conditions (2). These workshops provided a well-founded set of R&D objectives against which to seek appropriate projects.

By intent and practice, the DGE Geothermal Well Logging Instrumentation R&D Program has sought positive interaction with the well-logging service companies, and avoided competition with their operations and marketplace. The Program's strategy to develop positive relationships with the service companies has been to focus on the development of components in the areas of sensors, active electronics, passive electronics, cables, and packaging. The objective of this strategy is to produce components that sonde manufacturers (who are often synonymous with the logging service companies) can incorporate into their existing oilfield tools, to enable these tools to survive geothermal conditions.

The status of the Program has been recently reviewed by the Measurement Analysis Corporation (3). That report can be consulted for detailed descriptions of the R&D projects analyzed here.

1.2 Scope of the Analysis

The present analysis required that seven R&D projects of the Program be analyzed with respect to cost-saving impacts that logging tools and operations might have on the development of hydrothermal electric plants at 27 United States geothermal prospects. It is clear that information from well logs can affect the cost of power in various ways, i.e., by allowing practices that lower drilling

costs, increasing well flow in some wells, or increasing the productive life of some wells. The central task of this analysis was to be as comprehensive as practicable in identifying probable cost-reducing impacts of new geothermal logging tools, and then ascribing some portion of those impacts to particular R&D projects sponsored by DGE.

Estimating the potential economic benefit of geothermal logging tools requires that the following factors be taken into account:

- The type and quality of information needed from logging operations is not well defined;
- The impact that better information could have on drilling operations is not fully known;
- The economic impact of improved logging on full-scale commercialization of geothermal power is not fully understood.

In the first instance, not only do the sondes often not survive geothermal conditions, but the geology and conditions of interest are sufficiently different from oil-field conditions that techniques developed for logging in oil or gas fields may not prove effective. The geothermal formations tend to be younger, harder, hotter, and more fractured than those encountered in oil and gas fields, and the temperature and fracture conditions are of great significance for productive geothermal wells.

Since current practices in geothermal exploration and development do not rely on extensive information from well logging, the actual value of such information is not known and estimates had

TABLE I
PROJECTS INCLUDES IN THIS ANALYSIS

MITRE Code #	Contractor	DGE Contract #	Project Title	Technical Objective	Estimated Benefits (\$ x 10 ⁶)	
					Pessimistic	Optimistic
1-4-1	Systems, Science and Software (S ²)	CO 31315	Pressure and Temperature Sonde	Develop sonde to measure shut-in pressure and temperature to 275°C without active electronics downhole.	10.8	37.5
1-4-2	IRT	CO 30936	Neutron Activation Analysis Sonde	Develop device to measure fractures, fluid flow, porosity, dissolved solids, lithology, formation temperature.	17.7	51.0
1-4-3	Westinghouse	CO 24082	Sensor for Acoustic Log	Develop high temperature (275°C) acoustic sensor for geothermal logging.	3.5	6.5
1-4-4	Geoscience	CO 31318	Heat Flow Transducer and Thermal Conductivity Probe	Develop instrument to measure geothermal heat flux and thermal conductivity.	1.8	5.2
1-4-5	Raytheon	CO 22816	Electromagnetic Borehole Telemetry System	Develop electromagnetic borehole telemetry system	15.8	44.8
1-4-6	MRI	CO 31309	Mechanical Refrigerator for Sondes	Develop device to cool logging sondes by mechanical refrigeration.	38.3	112.2
1-4-7	Spectro-Systems	CO 14008	Borehole Maximum Temperature while Drilling	Use materials of selected melting points to measure well temperature while bit is downhole.	1.8	4.5
SUBTOTAL FOR ACTIVE PROJECTS					89.7	261.7
1-4-x	?	?	Cables/Connectors	Cables to transmit power to sonde or data from sonde.	30.4	97.7
1-4-x	?	?	Mechanical Caliper Device	Device to measure borehole diameter.	1.1	3.4
1-4-x	?	?	Mud Pulse Telemetry	System for transmitting information from downhole while Drilling.	.2	0.5
1-4-x	?	?	General Purpose Log Interpretation	Overall development of geothermal log interpretation capabilities.	19.0	53.0
SUBTOTAL FOR DUMMY PROJECTS					50.7	154.6
TOTAL FOR ALL PROJECTS					140.4	416.3

to be developed by extrapolating from the limited logging currently practiced and from informed opinion of what the value of such information is likely to be.

1.3 The R&D Projects

Table I lists the seven R&D projects analyzed here. During the development of the analysis, it became appropriate for various reasons to add four R&D activities not originally included in the list of projects to be analyzed. These activities are:

- Cables and Connectors
- Mud Pulse Telemetry
- Mechanical Caliper Device
- General Purpose Log Instrumentation.

These are referred to as "dummy projects" in the text. The first two, Cables and Connectors, and Mud Pulse Telemetry, were added to achieve a reasonable distribution of benefits across various ways of transferring information between sondes and the surface. The Mechanical Caliper was added because it is a conventional source of information about borehole diameter; such information has impacts on cementing operations. General Purpose Log Instrumentation was added to give appropriate credit for "data analysis" benefits to log-interpretation studies beyond those associated directly with the seven R&D projects analyzed here.

1.4 Result for Total Program

Table 1 also shows the benefit estimated for each of the seven actual projects and the four dummy projects, as well as subtotals and totals.

The summed benefit expected from the seven actual projects ranges from \$89.7 Million (pessimistic) to \$261.7 Million (optimistic). The dummy projects (some of which are in fact being pursued by the Division of Geothermal Energy) could add expected benefits ranging from \$50.7 Million to \$154.6 Million.

When these two subtotals are summed, the expected benefit ranges from \$140.4 Million to \$416.3 Million.

2.0 APPROACH

The method used here was to adapt standard procedures of Structural Value Analysis to trace the probable effects of new logging sonde components (the products of the R&D projects) through three levels of multiple impacts on logging, drilling, and reservoir engineering operations. A schematic of the approach and resulting structure is shown in Figure 1.

The impact levels were structured as follows:

- Level I: Impacts of each component R&D project upon the future existence of one or more logging sondes with specific measurement capability (s). This is Matrix 1 in Figure 1.
- Level II: Impacts of specific logging capabilities upon specific reservoir engineering and well drilling operations. This is Matrix 2 in Figure 1.
- Level III: Impacts of the altered reservoir engineering and drilling operations on the costs to develop production and injection wells sufficient to support 50 MW net electricity generating plants in specific geothermal prospects in the United States. This is the right half of Figure 1.

The impact results estimated at Level III were used as inputs to MITRE's GEOBEN computer code.

GEOBEN calculates impacts of altered technology on the total cost to produce forecasted amounts of electricity at selected U.S. geothermal sites. The GEOBEN runs furnished estimates of the economic value of each altered operation, expressed in terms of cost savings (in 1978 dollars, discounted at 10% to 1978 present value) across some 400 plants projected to be developed at 27 prospects between 1979 and 2000.

FIGURE 1
STRATEGY FOR ESTIMATING BENEFITS FROM
WELL LOGGING INSTRUMENTATION PROJECTS

These calculated benefits were then traced back through the matrices of the structured value analysis to arrive at an estimated value for the economic benefit attributable to each of the evaluated R&D projects. The trace-back process is shown by the dotted line in Figure 1. This trace-back of the benefits required formulation of specific assumptions regarding (1) how benefits at each level of the scheme should be distributed across the multiple impacts that generated the benefit, and (2) the degree to which information from sources other than logging operations (e.g., exploration efforts, drilling operations, mud logging, coring, flow tests) should be credited for parallel or prior contributions to some of the calculated operations. How these considerations were treated is discussed below.

To summarize the analysis, return to Figure 1. Starting at top left are seven R&D projects. Their impacts on logging sonde capabilities are contained in Matrix 1. The impacts of these sondes upon field operations are contained in Matrix 2. The impacts from the altered operations are carried forward as inputs to the GEOBEN code. Once the benefits are computed, they are traced back through the two matrices in reverse order, to ultimately distribute the benefits to specific R&D projects.

Benefits were disaggregated in linear proportion to the estimated relative importance of impacts. For example, one calculation showed a potential benefit of nearly \$6 million saved (over all fields, for the lifetime of 400 plants) by using an

optimized mud formulation plan. It was estimated that each of three types of information (derived from three specific sondes) would contribute about one-fifth of the needed information, and a fourth type (from a fourth sonde) would contribute the remaining two-fifths. Thus, savings of about \$1.2 million were credited to each of the first three types of information, and savings of \$2.4 million to the fourth type.

In some cases, sources of information other than logging will contribute to the realization of a better set of well drilling and completion operations. In those cases, the portion of the benefit ascribed to the logging sondes was made proportional to estimates of the value of the information from the sondes relative to the estimated value of information from all other sources. This is intelligible only by example: Both logging operations and exploration technology will contribute to a gradual reduction in the dry hole fraction encountered in drilling producer wells; the estimated benefit of this effect was distributed equally between these two sources of information.

The structure and magnitude of all the impacts described in this analysis are estimates made by MITRE. They are based on discussions with the manager of the DGE well logging instrumentation program, perusal of the very limited open literature available on geothermal logging, and much general information about geothermal drilling technology. As experience accumulates in this field, the

analytical estimates developed here will inevitably have to be refined. The current analytic framework provides a basis for:

- (1) Evaluating the relative economic impacts of various concepts regarding the use of logging sondes in the geothermal industry;
- (2) Identifying the kinds of information that would have to be collected to improve this analysis and its future applications.

R&D PROJECT	VALUE FACTOR	SONDE TYPE					
		Fluid and Forma- tion Temperature			Well Bore Pressure		
		Sonde	Tele- metry	Data Anal- ysis	Sonde	Tele- metry	Data Anal- ysis
1-4-2 Pressure and Temperature Sonde	% Capability	100	0	100	100	0	100
	Benefit, \$ Million	12.0		12.0	10.6		10.6
1-4-2 Neutron Acti- vation Anal- ysis Sonde	% Capability	80	0	80	0	0	0
	Benefit, \$ Million	9.6		9.6			

FIGURE 2
EXAMPLE OF CELLS FROM TABLE II

3.0 IMPACTS OF R&D PROJECTS ON SONDES

This section describes how each R&D project contributes to particular sonde capabilities, and shows the derived economic benefits of these contributions. Subsequent sections show how these benefit values were derived, first by analyzing the impact of sondes on well drilling operations, then by calculating the changes in overall well drilling costs due to changes in particular operations.

3.1 Explanation of Matrix

The device used to identify the project contributions to sonde capabilities was a matrix with the projects as one dimension and the properties measured by logging sondes as the other dimension. Each cell (project X property) was further divided to show the three main aspects of using a sonde: (1) the sonde itself (data element); (2) telemetry (bringing the data to the surface); and (3) analysis of the data. The project entry was divided into two factors, to allow one entry for the percentage of a sonde's capability derived from that project and another entry for dollar benefit ascribed to the project.

Figure 2 provides several example cells to illustrate this procedure. The entry for pressure and temperature sonde (project 1-4-1) indicates that if this project is successful, it could provide 100% of the sonde capability, none of the telemetry requirements, and 100% of the analysis requirements for acquiring Fluid-Formation Temperature. Similarly for Well Bore Pressure. The

other numbers are the derived benefit of the project, and will be discussed below. The second entry, Neutron Activation Analysis Sonde, indicates that if the project is successful, it could account for 80% of the sonde capability, 0% of the telemetry requirements, and 80% of the analysis requirements for measuring fluid-formation temperature. This project could contribute nothing toward measuring Well Bore Pressure, as indicated by the zeroes entered under that column.

When all R&D projects were evaluated against the ten sonde types selected for this analysis, the majority of cases yielded column totals of contributions greater than 100%. Note in Figure 2 that the Fluid Formation Temperature column shows percentage contributions that total 180%. These numbers were used to provide a relative scaling of benefits to each project. In this case, 100/180 of the benefit would be allocated to project 1-4-1 and 80/180 of the benefit to project 1-4-2.

The derived benefit that is reported for each project (the numbers 12, 10.6, and 9.6 in Figure 2) is the value, in millions of dollars, of that project, due to the project's impact on the specific sonde type indicated. Thus, the total benefit of a project is the sum of these values across the project row. These numbers "come up from the bottom" in the sense that a total benefit has been determined for each sonde type, and then distributed to each project according to its percentage fraction of the summed

contribution of all R&D projects to that sonde type, as indicated in the above example. Sections 4.0 and 5.0 describe the procedures used to obtain the total benefit by sonde type.

3.2 The Matrix

The above section describes the structure of the matrix presented here as Table II. The overall matrix consists of 11 project entries (the row elements) and ten sonde types (the column elements), plus the rows and columns for various totals. Table II presents the optimistic (high) estimate of benefits. Totals for the pessimistic (low) estimate are given in Section 3.3, but the table for these numbers is omitted because it is otherwise identical to Table II.

The project entries include the seven R&D projects sponsored by DGE, numbered 1-4-1 through 1-4-7, plus four dummy projects which provide for certain logging functions identified during the analyses that were not covered by the original set of seven projects. These dummy projects permitted a more comprehensive view of the benefits of the logging program, in order to avoid the allocation of the entire benefit to the present program as though it were comprehensive.

The ten sonde types do not represent specific sondes, but rather the categories of information for which the sondes are to collect data. Thus, the percentage figures under each sonde type represent an estimate of the degree to which the product (a practical sonde)

of each R&D project would contribute to capturing specific types and amounts of information needed by geothermal drillers.

The row at the bottom of the table called "Total Benefit" is the derived benefit for each sonde type, the derivation of which is reported in Sections 4.0 and 5.0. The first level of disaggregation of this benefit occurs in the row immediately above, where the benefit is divided into equal thirds, one-third allocated to each of the three aspects of the use of a sonde; sonde, telemetry, and analysis.

The final level of disaggregation occurs by allocating the total benefit in each column to each project in proportion to the project's contribution to the information needs. An example of this procedure is given above in Section 3.1.

One exception to this procedure was made for the distribution of credit to "Analysis." In addition to the interpretive work that would be derived during the development of a sonde, separate log interpretation development work will be needed to fully exploit particular sonde capabilities. This is reflected by a bracketed entry in the row titled "General Purpose Log Interpretation." This entry represents an absolute percentage of the benefit for that column that is credited to Log Interpretation before it is disaggregated and distributed to the specific projects (as described in Section 3.1).

TABLE II
IMPACTS OF R&D PROJECTS ON LOGGING CAPABILITIES
AND BENEFITS ANALYSIS RESULTS FOR PROJECTS

PROJECT TITLE	VALUE FACTOR	TYPE OF MEASUREMENT MADE BY SONDE																												BENEFIT OF PROJECT (\$x10 ⁶)						
		DRILLING TEMPERATURE			FLUID-FORMATION TEMPERATURE			WELL BORE PRESSURE			WELL BORE FLOW			CALIPER			FRACTURES			LITHOLOGY			HEAT FLOW			POROSITY			PERMEABILITY			SONDE	TELE-METRY	ANALYSIS	TOTAL	
		S	T	A	S	T	A	S	T	A	S	T	A	S	T	A	S	T	A	S	T	A	S	T	A	S	T	A								
1-4-1 Pressure and Temperature Sonde	% Capability				100		100	100		100																										
	Benefit, \$x10 ⁶				12.0		9.6	10.6		5.3																						22.6		14.9	37.5	
1-4-2 Neutron Activation Analysis Sonde	% Capability				80		80			50		20				30		30	30		30				100		80									
	Benefit, \$x10 ⁶				9.6		7.7			10.0		6.0				0.8		0.3	5.4		1.8				6.3		3.2						32.1		19.0	51.
1-4-3 Sensor for Acoustic Log	% Capability													80		70	80		70																	
	Benefit, \$x10 ⁶													3.4		4.5	1.2		0.7														4.6		5.2	9.8
1-4-4 Heat Flow Transducer and Thermal Conductivity Probe	% Capability																						100		100											
	Benefit, \$x10 ⁶																						4.3		0.9									4.3		0.9
1-4-5 Electromagnetic Borehole Telemetry System	% Capability		100			80			50			80				80			30							100			50							
	Benefit, \$x10 ⁶				12.0		9.6	10.6		5.3	20.0		18.0	4.2		6.4		1.6		4.2						6.3			2.4				44.8		44.8	
1-4-6 Mechanical Refrigerator for Sondes	% Capability				100		100	100		100	100		60	100		100	100		80	30		30			100		80	50		50						
	Benefit, \$x10 ⁶				12.0		9.6	10.6		5.3	20.0		18.0	4.2		6.4	1.6		0.8	5.4		1.8			6.3		3.2	3.6		3.6			63.7		48.7	112.4
1-4-7 Borehole Maximum Temperature While Drilling	% Capability	100	100	100																																
	Benefit, \$x10 ⁶	2.0	0.5	2.0																													2.0	0.5	2.0	4.5
Cables/Connectors	% Capability		100			100			100			100				100			100				100			100			100							
	Benefit, \$x10 ⁶		0.5			18.7			21.2			20.0			6.0			2.0		13.9				4.3			6.3			4.8				97.7		97.7
Mechanical Caliper Device	% Capability													80																						
	Benefit, \$x10 ⁶													3.4																				3.4		3.4
Mud Pulse Telemetry	% Capability		100																																	
	Benefit, \$x10 ⁶		0.5																														0.5		0.5	
General Purpose Log Interpretation	% Capability						[20]			[50]			[20]					[50]			[80]			[80]			[50]			[50]						
	Benefit, \$x10 ⁶						6.7			10.6			6.0					1.8			14.5			3.5			6.3			3.6					53.0	53.0
Aggregate Capability		100	400	100	280	180	280	200	100	200	150	150	180	260	180	170	230	180	180	60	130	60	100	100	100	200	200	160	50	150	50					
Disaggregate of \$ Benefit (\$x10 ⁶)		2.0	2.0	2.0	33.6	33.6	33.6	21.2	21.2	21.2	29.9	29.9	29.9	10.9	10.9	10.9	3.6	3.6	3.6	18.1	18.8	18.1	4.3	4.3	4.3	12.6	12.6	12.6	7.2	7.2	7.2					
TOTAL BENEFIT (\$x10 ⁶)			5.9			100.9			63.5			89.8			32.7			10.8			54.2			13.0			37.9			21.5			132.7	143.5	143.7	419.9

TABLE II
IMPACTS OF R&D PROJECTS ON LOGGING CAPABILITIES
AND BENEFITS ANALYSIS RESULTS FOR PROJECTS

Once the final disaggregation was completed, the total project benefits were obtained by accumulating the row sums in the far right-hand columns, labeled "Benefit of Project."

3.3 Results

The results of this analysis are summarized in Table I. The derivation of the optimistic and pessimistic estimates is covered in detail in Sections 4.0 and 5.0. The overall value of improved well logging for the entire power-on-line scenario of 400 plants at 27 prospects is seen to range from about \$140 million to \$416 million. The summed value of the seven DGE projects evaluated here ranges from about \$90 million (pessimistic) to about \$262 million (optimistic).

TABLE III
IMPACTS OF DRILLING OPERATIONS FOR PARTICULAR SONDE TYPE

GEOTHERMAL FIELD OPERATIONS		TYPE OF MEASUREMENT MADE BY SONDE										
		DRILLING TEMPERATURE	FLUID FORMATION TEMPERATURE	WELL-BORE PRESSURE	WELL BORE FLOW	CALIPER	FRACTURES	LITHOLOGY	HEAT FLOW	POROSITY	PERMEABILITY	TOTAL \$x10 ⁶
1. Mud Formulation Plan	IMPACT	20%	20%	40%							20%	
	BENEFIT	1.2	1.2	2.4							1.2	5.9
2. Mud Formulation While Drilling	IMPACT	100%										
	BENEFIT	4.7										4.7
3. Preventing Twist-Offs	IMPACT						25%	75%				
	BENEFIT						6.5	19.5				26.1
4. Cement Volume, Time	IMPACT		50%			50%						
	BENEFIT		22.0			22.0						43.9
5. Cement bond, Borehole-to-Casing	IMPACT		25%			25%	10%	20%			20%	
	BENEFIT		10.7			10.7	4.3	8.6			8.6	42.8
6. Decision after Reading Planned Depth	IMPACT		50%	50%								
	BENEFIT		24.5	24.5								49.0
7. Depth to Produce	IMPACT				100%							
	BENEFIT				60.3							60.3
8. Stimulation of Well Flow	IMPACT		10%		50%					20%	20%	
	BENEFIT		5.9		29.5					11.8	11.8	59.1
9. Site and Design for Next Well	IMPACT		25%	25%				25%		25%		
	BENEFIT		26.1	26.1				26.1		26.1		104.5
10. Well Operation Analysis	IMPACT		50%	50%								
	BENEFIT		10.6	10.6								21.2
TOTAL \$		5.9	100.9	63.5	89.8	32.7	10.8	54.2		37.9	21.5	417.5

4.0 IMPACTS OF SONDES ON GEOTHERMAL FIELD OPERATIONS

This section describes how sonde types were linked to specific drilling operations. The evaluation of potential benefits from particular changes in drilling operations is described in Section 5.0.

4.1 Explanation of Matrix

The matrix described in this section, Table III, identifies the impact of particular sonde types on various drilling operations. The vertical dimension is a list of drilling operations that can be affected by logging operations. The horizontal dimension is the properties measured by logging sondes.

Each row corresponds to one drilling operation, with entries corresponding to those sonde types that could contribute toward improving that operation. The entry under each sonde type is two-fold. The upper number is that sonde's percent contribution (compared to other sondes) toward improving a particular well operation. The lower number is that percent of the total benefit derived for the sonde from the improved well drilling operation. Thus, the column sum of dollar benefits is the total benefit to be attributed to the particular sonde type from improvements in all well drilling operations. This total is the number entered at the bottom of Table II (See Section 3.2).

The analysis of well drilling operations, from the point of view of using sondes to improve operations, led to estimates of the relative

TABLE IV
ESTIMATED BENEFITS FOR THE DEVELOPEMNT
OF GEOTHERMAL INFORMATION-COLLECTION
CAPABILITIES (SONDE TYPES)

SONDE TYPE	BENEFIT (\$10 ⁶)	
	PESSIMISTIC	OPTIMISTIC
1. Mud Temperature Downhole While Drilling	2.3	5.9
2. Fluid-Formation Temperature	30.7	100.9
3. Well-Bore Pressure	16.7	63.5
4. Well-Bore Flow Rate	29.1	89.8
5. Caliper (Borehole Diameter)	10.9	32.7
6. Fracture Defection	5.1	10.8
7. Lithology	21.5	54.2
8. Heat Flow > Thermal Conductivity	4.4	13.0
9. Formation Porosity	15.4	37.9
10. Formation Permeability	11.6	21.5
TOTAL	147.7	430.5

value of each sonde type for each operation. These are presented in Table III as a percentage. If only one type of sonde was seen as contributing to the improvement of an operation, that sonde received a value of 100% (e.g., the drilling temperature sonde for operation no. 2, "Mud Formulation While Drilling"). Where more than one sonde could contribute to improving an operation, then the 100% was divided among the sondes according to MITRE's estimate of the relative values of the sondes for that operation.

Once the benefit had been calculated for each operation, it was entered in the right-hand column of Table III, and then distributed across the sonde-type columns in proportion to the estimated percentage contributions of each sonde type. The columns were then totaled to obtain the total benefit of a sonde type, which was then carried to the bottom row of Table I.

4.2 Results

The results of the disaggregation of benefits across geothermal information-collection capabilities (sonde types) are shown in Table IV.

The results suggest that there are four most important sonde types: Fluid formation temperature, Well-bore flow rate, Well-bore pressure, and Lithology. None of the benefits are negligible.

TABLE V
OPERATIONS AFFECTED BY LOGGING INFORMATION
AND ANALYZED FOR THEIR IMPACT

Operation	Section of Text	BENEFIT (\$ x 10 ⁶)	
		Pessimistic	Optimistic
Optimize Mud Formulation Plan	5.3.1	2.9	5.9
Maintain Optimal Mud Formulation While Drilling	5.3.2	1.7	4.7
Preventing Twist-offs	5.3.3	13.1	26.1
Cement Volume and Time	5.3.4	12.6	43.9
Cement Bond, Casing-to Borehole	5.3.5	18.3	42.8
Decisions after Reaching Planned Depth	5.3.6	4.3	49.0
Depth to Produce	5.3.7	10.6	60.3
Stimulation of Well Flow	5.3.8	36.9	59.1
Site and Design for Next Well	5.3.9	32.0	104.5
Well Operations Analysis	5.3.10	10.8	21.2
	TOTAL	143.2	417.5

5.0 IMPACTS OF LOGGING SONDES ON GEOTHERMAL WELL DRILLING, COMPLETION, AND USE OPERATIONS

This section describes the selection of the drilling operations for detailed analysis, including the approach used to select these operations. Also described are the specific operations and the method of analyzing each through the use of MITRE's GEOBEN and WELCST computer codes.

5.1 Operations Affected by Logging

A careful review of the process of drilling geothermal wells identified a number of particular aspects of the process which could potentially benefit from improved down-hole information. Table V lists those drilling operations for which the present analysis was fully developed, and which are treated individually in Section 5.3.

Table VI lists operations which were considered for inclusion, but not analyzed for specific reasons.

The first rejected operation is preventing and recovering from lost circulation incidents. These incidents are very time consuming, and contribute substantially to drilling costs. However, there are no kinds of logging information that would seem to be applicable toward alleviating the incidence or recovery of lost circulation incidents. The loss of circulation fluid is a direct indication of a downhole event which no kind of information or prediction can prevent. Once the incident has occurred, the steps to recover are similar for each incident, although experience with prior wells in the same prospect can have an effect in eliminating some waste of time.

TABLE VI

Operations Considered but not Included in the Analysis

1. Preventing or Recovering Lost Circulation Incidents.
2. Drilling Practice ("Making Hole").
3. Decision to Abandon or Develop Entire Prospect.
4. Directional Surveys (Crooked Holes and General Directional Drilling).
5. Estimation of Reserves, as input to regulatory policy decisions and regulation of production.
6. Information needed for Legal/Environmental aspects of reservoir development.

Drilling practice, or "making hole," is another facet of this business that has much room for improvement. Various decisions that affect drilling costs are currently made on the basis of the tool pusher's experience in the prospect. Decisions such as weight on bit, bit selection, when to pull the bit, are examples. Well logging does not provide the kinds of information that are useful for the real-time dynamics of these kinds of decisions. Since logging could not substantially contribute toward improving this aspect of drilling operations, it was omitted from detailed consideration.

The decision to abandon or develop an entire prospect was not considered for detailed analysis, because the complexity of the issues involved in such a decision make any estimates of the value of logging information highly speculative at best.

The value of directional surveys for use in directional drilling or straightening crooked holes was omitted from consideration, in part because there is no R&D project to which benefits might be ascribed, and partly because a lack of data on how frequently such surveys are needed would have made benefit estimates very speculative.

The last two items on the list, estimation of reserves, and legal/environmental inputs, are relatively global issues in the geothermal energy field, and both contain elements far outside the scope of this analysis. This, combined with the speculative

nature of connecting logging information to these decisions, prevents the treatment of these issues with the same degree of rigor as those discussed in Section 5.3. Therefore, they were omitted from the analysis.

5.2 Approach

Given the drilling operations of interest (Table V), each was carefully analyzed in terms of what kinds of logging information could contribute toward improvements in that operation, and the magnitude of the improvement that could be expected. These estimates were primarily based on three sources: (1) interviews with the logging instruments program manager and several others involved in the industry; (2) the available literature on the subject; (3) MITRE's understanding of the industry and its technology. Since the literature is rather scanty, and the analysts are at some distance from the problem (with no field experience), the estimates developed in this analysis should be viewed as subject to improvement and refinement.

Each operation was examined with respect to both its potential impact on the development of an entire field, and its potential impact on the drilling of a single well. This distinguishes between information needed while the well is being drilled and completed, and information that accrues after well completion and accumulates to contribute to the general longer-term development

of an entire field. As an example of this distinction, in the previous section it was stated that lost circulation incidents could not be recovered anymore effectively than current practice by use of well logging. That is, in this case logging cannot have a useful impact on the well as it is being drilled. However, as information accumulates about each geothermal prospect from both the logging of wells and the experience of the tool pushers, then appropriate planning of mud materials may reduce the occurrence of lost circulation incidents, at least those that would have been recovered by use of lost-circulation materials alone. This latter case is the one treated in Section 5.3.1.

After it was determined that a particular operation offered a potential economic benefit, then the mode of input to MITRE's geothermal development cost computer codes was selected. Two major codes were used. One, WELCST, is a simulation of the step-by-step costs incurred during the drilling and completion of a geothermal well. The well costs generated by this code are then used by another code, GEOBEN, which calculates the cumulative United States liquid-dominated geothermal development scenario for about 400 plants at 27 prospects, between the years 1978 and 2000 (inclusive). If a particular technological improvement could be tied to particular drilling parameters, as in a reduction of mud costs, or reduction frequency of lost circulation incidents, then the WELCST model was used to calculate the single well benefit and GEOBEN

would calculate the overall benefit. In the case of a benefit tagged to a whole field, as, for example, a reduction in number of wells needed to supply a given level of fluid production in a field, then this benefit would be calculated through GEOBEN alone. It is this benefit value, calculated by GEOBEN, that is described in Sections 4.1 and 4.2, and serves as the basis for ascribing a dollar benefit to each of the projects in the Well Logging R&D Program.

5.3 Analysis of Specific Operations

Each operation which was identified as having a potential for being improved by well logging is described below. Included with each description is a summary chart that provides a synopsis of the operation. The chart begins with the title of the operation and a list of the percentage impact of each sonde type on that operation. These are from Table III, described in Section 4.0. The next part of the chart summarizes the technical impacts of logging upon the operation as described in Section 5.2, as to whether the impact would be on a single well or a whole field, and what magnitude of change (cost or other) was estimated for that operation. Following that is a list of the variables from WELCST or GEOBEN, and the values used to enter the changes into the models. The next section shows the estimate of what factors other than logging might contribute to the calculated benefit, and with what share of the impact and benefit each is credited. The final entry shows the overall calculated benefit, and the share credited to the

logging program. It is this last number that is entered back into Table III.

5.3.1 Optimize Mud Formulation Plan					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature		20%	Fractures		
Fluid/Formation Temperature		20%	Lithology		
Wellbore Pressure		40%	Heat Flow		
Wellbore Flow			Porosity		
Caliper			Permeability		20%
Impact On:					
Entire Field	Single Well	EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
No		This is an additional prior experience input to the mud plan.			
Yes		Logs on previous holes contribute to optimizing well and mud plans.	Reduction in mud costs	-5%	-10%
			Reduce frequency of Lost Circulation Incidents in soft and medium rock prospects.	-5%	-10%
Inputs to WELCST				Pessi- mistic	Opti- mistic
Mud Cost = ENGVAR #17 (YCSMUD)				0.95	0.90
Freq. of L-C, recovered with mud = ENGVAR #20 (YFLCM)				0.95	0.90
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools		= 50%			
% of Benefits due to Prior Experience		= 50%			
% of Benefits due to		=			
TOTAL BENEFITS			Pessimistic	Optimistic	
			5.77M	11.75M	
TOTAL DUE TO LOGGING			2.89M	5.88M	

5.3.1 Optimize Mud Formulation Plan

One of the more complex and sophisticated aspects of well drilling is the proper formulation of the drilling mud. It is anticipated that with experience in a field, and information from logging previous holes, some noticeable savings could be made through appropriate planning of mud formulation. These savings would be of two kinds; reduced material costs, and less time lost in recovering lost circulation.

Four different types of logging information are seen as relevant; drilling temperature, fluid/formation temperature, well bore pressure, and formation permeability. This information, applied toward improving mud formulation, would not contribute toward reducing costs of a well as it was being drilled, but could lead to a 5 to 10 percent reduction in mud cost and a 5 to 10 percent reduction in lost circulation incidents averaged over the entire field. Half of the estimated savings are credited to experience factors, and half to the logging information. Thus, the potential benefit of logging in reducing L-C incidents ranges from \$2.9 million to \$5.9 million.

5.3.2 Maintain Optimal Mud Formulation While Drilling					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature		100%	Fractures		
Fluid/Formation Temperature			Lithology		
Wellbore Pressure			Heat Flow		
Wellbore Flow			Porosity		
Caliper			Permeability		
Impact On:					
Entire Field	Single Well	EXPLANATION	IMPACT	Pessi-mistic	Opti-mistic
No		Only immediate downhole conditions are useful here.			
Yes		Knowledge of down-hole mud temperature can optimize the on-site selection of the least expensive effective mud materials.	Reduction in mud cost	-5%	-10%
			Logging cost is increased by \$1000 per well	+3%	+3%
Inputs to WELCST				Pessi-mistic	Opti-mistic
Mud Cost = ENGVAR #17 (YCSMUD)				0.95	0.90
Logging Cost = ENGVAR #53 [YAC (20)]				1.03	1.03
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			=	33%	
% of Benefits due to current practice			=	67%	
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			5.20M	14.12M	
TOTAL DUE TO LOGGING			1.73M	4.71M	

5.3.2 Maintain Optimal Mud Formulation While Drilling

With effective knowledge of the downhole temperature while drilling, it appears that the on-site selection of mud materials to minimize their cost is feasible. This could result in savings of 5 to 10 percent in mud costs, but would incur a 3 percent increase in logging costs. Approximately two-thirds of the derived benefit would be due to current practices and experience factors, leaving a net logging benefit of \$1.7 million to \$4.7 million.

5.3.3 Preventing Twist-Offs					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures	25%	
Fluid/Formation Temperature			Lithology	75%	
Wellbore Pressure			Heat Flow		
Wellbore Flow			Porosity		
Caliper			Permeability		
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No		Experience has greatest impact on drilling practice.			
Yes		Lithology logs might produce advanced warning for next well.	Reduction in frequency of twist-offs	-5%	-10%
Inputs to WELCST				Pessi- mistic	Opti- mistic
ENGVAR 23 (YFPIPE) (80% is twist-off)				0.96	0.92
ENGVAR 24 (YFFAIL) (95% is twist-off)				0.9525	0.905
ENGVAR 26 (YSIDBT) (95% is twist-off)				0.9525	0.905
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			=	50%	
% of Benefits due to prior experience			=	50%	
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			26.17M	52.11M	
TOTAL DUE TO LOGGING			13.09M	26.06M	

5.3.3 Preventing Twist-Offs

Twist-offs occur for several reasons, weak pipe being the main one. Since geothermal drilling tends to be harder on equipment than oil and gas drilling, the drilling companies may prefer to use older hardware on geothermal wells, rather than risk newer equipment on these wells. But, even with good equipment, twist-offs will occur, and it is felt that appropriate foreknowledge of the fracture and lithology conditions downhole would allow experienced tool pushers to reduce the incidence of twist-offs. This would result in between a 5 and 10 percent reduction in the incidence of twist-offs, with the tool pusher's experience in that field being worth half of the benefit. The net logging benefit would then be from \$13.1 million to \$26.1 million.

5.3.4 Cement Volume and Time					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures		
Fluid/Formation Temperature 50%			Lithology		
Wellbore Pressure			Heat Flow		
Wellbore Flow			Porosity		
Caliper 50%			Permeability		
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No					
Yes		Sondes can give better control over cement retardation time and volume.	Reduced idle time; lower cement costs	-5%	-10%
Inputs to WELCST				Pessi- mistic	Opti- mistic
ENEVAR #7 (YCEMCS)				-5%	-10%
ENEVAR #8 (YCEMTM)				-10%	-40%
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools = 33%					
% of Benefits due to practices and materials = 67%					
% of Benefits due to =					
TOTAL BENEFITS			Pessimistic	Optimistic	
			37.80M	131.81M	
TOTAL DUE TO LOGGING			12.60M	43.94M	

5.3.4 Cement Volume and Time

Apart from the actual drilling, the most time-consuming aspect of drilling operations is waiting for cement to set when casing the well. The use of two sondes could reduce the costs associated with cementing operations. First, before the casing is run in, a caliper sonde could allow a more exact specification of the volume of cement needed for the particular segment to be cemented. Second, after the cement is run into the casing, a temperature probe could identify more more precisely the moment that the cement had hydrated sufficiently to be considered set.

The combination of these cost saving opportunities could lead to a 5 to 10 percent reduction in cost of cementing materials, and a 10 to 40 percent reduction in time spent waiting on the cement to set. Even when crediting two-thirds of the savings to better practices and materials, the logging benefit would be between \$12.6 million and \$43.9 million.

5.3.5 Cement Bond, Borehole-to-Casing					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures	10%	
Fluid/Formation Temperature 25%			Lithology	20%	
Wellbore Pressure			Heat Flow		
Wellbore Flow			Porosity		
Caliper 25%			Permeability	20%	
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No					
Yes		Better bond between casing and borehole with knowledge of T, fractures, caliper, rocks and permeability.	Longer well life (reduced cement failure during life of well)	+4.3% (-25%)	+9.1% -50%)
Inputs to GEOBEN (through RADFILJ)				Pessi- mistic	Opti- mistic
Record 8: 1-7 % change in Life Span of Prod Well } Low 8-14 % change in Life Span of Inj. Well } Salinity				+4.3%	+9.1%
Record 9: 1-7 % change in Life Span of Prod Well } High 8-14 % change in Life Span of Inj. Well } Salinity				+4.3%	+9.1%
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			= 33%		
% of Benefits due to improved materials			= 67%		
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			54.94M	128.27M	
TOTAL DUE TO LOGGING			18.31M	42.76M	

5.3.5 Cement Bond, Borehole-to-Casing

Apart from improving the cementing procedures, as above, there remains a problem of durability of the cement once it is in place. This is primarily a materials problem, but once new cement compositions have been developed, their effective deployment will depend on good information about the downhole conditions.

These considerations led to analytic estimates of 25 to 50 percent reduction in cement failure during the life of a well. Given the anticipated failure rates, as described elsewhere in this report, this translates to a 4.3 to 9.1 percent longer well life. According one-third of the benefit to the logging tools, this yields a net logging benefit of \$18.3 million to \$42.8 million.

5.3.6 Decision After Reaching Planned Depth					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures		
Fluid/Formation Temperature 50%			Lithology		
Wellbore Pressure 50%			Heat Flow		
Wellbore Flow			Porosity		
Caliper			Permeability		
Impact On:					
Entire Field	Single Well				
		EXPLANATION	IMPACT	Pessi-mistic	Opti-mistic
No					
Yes		Logging can improve the decision of what to do with a low quality or dry hole when the planned depth is reached.	Reduced well cost from logging only	-0.4%	
			Reduced well cost from logging and reservoir engineering		-4.6%
Inputs to GEOBEN				Pessi-mistic	Opti-mistic
RAFILJ: % reduction in production well cost				-0.4	-4.6
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			= 33%		
% of Benefits due to other input			= 67%		
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			12.80M	146.98M	
TOTAL DUE TO LOGGING			4.27M	48.99M	

5.3.6 Decision After Reaching Planned Depth

When drilling in a field to obtain producing wells, the depth to which the well is drilled is planned ahead of time. In the majority of cases, this depth will be appropriate and the well can be handled consistent with standard practices. In the remaining cases, after reaching planned depth, the well may be dry or only minimally producing. The choices at this point are assumed to be:

- Abandon the hole,
- Drill 2000 feet more,
- Step out and redrill a new bottom, or
- Stimulate the well.

In order to estimate the impact of logging on these choices, several decision trees were constructed. Figure 3 represents the base case, where no logging is done, and the hypothesized ratio of abandoned holes to producer holes appears at the bottom. Figure 4 presents the same tree, with variations introduced to show the effects of logging on each well as an independent event, with no feedback from other previously-drilled wells to influence the decision. This tree shows a small improvement in the success ratio. Figure 5 shows the same tree given the effects of information accumulated from prior local wells to enhance decisions made before drilling begins. The success ratio in this case is substantially improved over either of the first two cases.

FIGURE 3
DECISION TREE FOR WELL COMPLETION

SCENARIO: II. CASE 1 - Logging on Individual Well, No Reservoir Engineering

B-45

FIGURE 4
DECISION TREE FOR WELL COMPLETION

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FIGURE 5
DECISION TREE FOR WELL COMPLETION

Using the logging-only case (Scenario II) as the minimum estimate, and the reservoir engineering case (Scenario III) as the maximum, the net benefit to logging ranges from \$4.3 million to \$49.0 million.

5.3.7 Depth to Produce					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature Fluid/Formation Temperature Wellbore Pressure Wellbore Flow Caliper			100%	Fractures Lithology Heat Flow Porosity Permeability	
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No					
Yes		Detect thief zones, optimize flow from well.	Improved flow reduces number of producers needed in field.	10% of wells in- crease output 5%	30% of wells increase output 10%
Inputs to GEOBEN				Pessi- mistic	Opti- mistic
RADFILJ: RDFMPW: % change in number of production wells Record 3, column 1-7 (No change in injection wells)				-0.5%	-3.0%
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			= 100%		
% of Benefits due to			=		
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			10.61M	60.29M	
TOTAL DUE TO LOGGING			10.61M	60.29M	

5.3.7 Depth to Produce

Once the well is drilled, and it is seen to be producing sufficiently to be shut-in as a producing well, there remain some down-hole strategies that can result in improved productivity for that well. In particular, by logging to detect thief zones, and thus appropriately positioning and/or perforating the casing, the flow from the well often can be considerably enhanced.

The logging benefit attributed to this aspect of the operation ranges from \$10.6 million to \$60.3 million. This occurs through a net reduction in the number of producer wells needed for a field to operate a given size power plant. The number of injection wells would remain the same.

5.3.8 Stimulation of Well Flow					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures		
Fluid/Formation Temperature 10%			Lithology		
Wellbore Pressure			Heat Flow		
Wellbore Flow 50%			Porosity 20%		
Caliper			Permeability 20%		
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No		Handled well-by-well			
Yes		Need to know whether a fracture job will start or improve flow	Decreased cost of production wells	0.9%	-17.2%
Inputs to GEOBEN				Pessi- mistic	Opti- mistic
GEOBEN (through RADFILJ) % change in cost of production well				-2.3%	-4.4%
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			= 33%		
% of Benefits due to better tools & pro-			= 67%		
% of Benefits due to			cedures =		
TOTAL BENEFITS			Pessimistic	Optimistic	
			110.75M	177.24M	
TOTAL DUE TO LOGGING			36.92M	59.08M	

5.3.8 Stimulation of Well Flow

When a well has reached planned depth, but is not flowing sufficiently to be classed as a producer, then there is the possibility of stimulating the well. Appropriate logging will provide the information needed to improve the chances of a fracture job succeeding in starting or improving flow from a well.

The improved information for fracture jobs will result in fewer wells abandoned, and fewer unsuccessful fracture jobs undertaken. The net result is a reduction in the cost of production wells that ranges from 2.3% less to 4.4% less. Injection wells would not be affected. Crediting logging with one-third of the savings, the logging benefit is from \$36.9 million to \$59.1 million.

5.3.9 Site and Design for Next Well					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures		
Fluid/Formation Temperature 25%			Lithology 25%		
Wellbore Pressure 25%			Heat Flow		
Wellbore Flow			Porosity 25%		
Caliper			Permeability		
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
No					
Yes		Better knowledge of Lithology, Porosity, Temp., Pressure could yield improved field development.	Reduced number of wells needed to exploit a field.	-1%	-5%
Inputs to GEOBEN (RADFILJ)				Pessi- mistic	Opti- mistic
% reduction in number of production wells } % reduction in number of injection wells }				-1.0	-5.0
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools			= 50%		
% of Benefits due to analysis			= 50%		
% of Benefits due to			=		
TOTAL BENEFITS			Pessimistic	Optimistic	
			63.97M	208.93M	
TOTAL DUE TO LOGGING					
			31.99M	104.47M	

5.3.9 Site and Design For Next Well

With appropriate logging and interpretation, the development of a field could proceed more efficiently, requiring fewer wells to operate the power plants, than would be the case without reservoir engineering. At least half of the overall calculated benefit would be credited to the analysis needed to understand the field characteristics from the logging data. Even so, the logging benefit of this operation could range from \$32.0 million to \$104.5 million.

5.3.10 Well Operation Analysis					
PERCENTAGE OF IMPACTS DUE TO SONDE TYPE					
Drilling Temperature			Fractures		
Fluid/Formation Temperature 50%			Lithology		
Wellbore Pressure 50%			Heat Flow		
Wellbore Flow			Porosity		
Caliper			Permeability		
Impact On:		EXPLANATION	IMPACT	Pessi- mistic	Opti- mistic
Entire Field	Single Well				
Yes	Yes	Optimal flowing of well improves life of field and well	Extended well life and reser- voir life	+2.4% +5%	+4.8% +10%
Inputs to GEOBEN (RADFILJ)				Pessi- mistic	Opti- mistic
% increase in life of production well both low to high salinity				+2.4	+4.8
Distribution of Benefits to Other Information Inputs:					
% of Benefits due to Logging Tools = 50%					
% of Benefits due to Analysis of other factors = 50%					
% of Benefits due to =					
TOTAL BENEFITS			Pessimistic	Optimistic	
			21.67M	42.30M	
TOTAL DUE TO LOGGING			10.84M	21.15M	

5.3.10 Well Operation Analysis

Optimizing the flow from a given producing well has several potential benefits. The individual well itself is not damaged by improper flow, and the reservoir life is enhanced by proper draw-down through each of its wells. The effectiveness of this operation would be dependent on improved understanding of reservoir characteristics, as well as the appropriate logging tools. Giving the logging tools half the credit for the calculated benefit yields a benefit of \$10.8 million to \$21.2 million.

5.4 A Horse of a Different Color: Heat Flux and Thermal Gradient Probe

All of the well operations covered in Section 5.3 and the benefits derived for them are focused on the development and exploitation of known geothermal resources. It so happens that one of the geothermal logging R&D projects, the Geosciences, Inc. Heat Flux and Thermal Gradient Probe, is to develop a sonde that will have its primary use in exploration work. When this project was carried through the impact matrices during the first pass of the analysis, zero benefits were credited to the Geosciences Probe. Therefore an independent analysis, reported here, had to be made of the potential economic benefit from this probe.

MITRE recently completed a benefit/cost analysis of the Geothermal Exploration and Resource Assessment (GERA) R&D Program of DGE (4). The authors of that study were consulted to help estimate the cost saving impacts of the Geosciences Probe. The following estimates from that study were found to apply:

(1) First Method: Under the assumption of a 10% discount rate, the total benefit of the GERA program in the years 1978-2000 is estimated to be about \$300 million to \$500 million. Of this, about 20% is attributable to thermal methods, and 80% of the benefit of thermal methods is attributable to the use of thermal gradient methods (Range: \$48 million - \$80 million). If 10% of this latter amount is due to use of the Geoscience Probe, the range is \$4.8 million - \$8 million. If 20% of the amount is due to use of the

Geosciences Probe, the range is \$9.6 million - \$16 million (all values in 1978 dollars).

(2) Second Method: The average cost/effectiveness of thermal gradient methods is \$13 per \$1 spent. About \$160,000 must be spent for each 200 MW prospect discovery. About 130 discoveries are still needed. Therefore the potential costs of thermal methods is approximately $(13/1) \times (\$160,000) \times (130) = \270 million. If thermal methods are improved 10%, the cost-effectiveness ratio is improved to 14.3 : 1. The benefit of this would be a cost saving of about \$27 million. If thermal methods are improved 30%, the benefit due to cost savings is about \$81 million.

Again, as in Method 1, 80% of the benefit of thermal methods is accounted for by the use of thermal gradient methods (Range: \$22 million - \$65 million). If 10% of this latter amount is due to use of the Geosciences Probe, the (pessimistic) benefit range is \$2.2 million - \$6.5 million. If the Geosciences Probe accounts for 20%, the (optimistic) benefit range is \$4.4 - \$13.0 million.

(3) Combining the Results: The benefit values from Method 1 range from \$4.8 million - \$16 million, while those from Method 2 range from \$2.2 million to \$13.0 million. So there is reasonable agreement between the results of the two methods. When the extreme low (2.2 million) and extreme high (\$16 million) estimates are discarded, the resulting estimate of the benefit from the Geosciences Probe are \$4.4 million (pessimistic) and \$13.0 million (optimistic).

TABLE VII
RESULTS OF ANALYZING DRILLING OPERATIONS

		INPUT PARAMETERS CHANGED	AVERAGE PERCENT REDUCTION IN WELL COSTS ¹	TOTAL BENEFIT \$ x 10 ⁶	LOGGING BENEFIT \$ x 10 ⁶
5.3.1 Optimized Mud Formulation Plan	•Pess.	YCSMUD YRLCM	- 0.1	5.77	2.89
	Opt.		- 0.2	11.75	5.88
5.3.2 Maintain Optimal Mud Formulation While Drilling	Pess.	YCSMUD YAC(20)	- 0.1	5.20	1.73
	Opt.		- 0.3	14.12	4.71
5.3.3 Preventing Twist-offs	Pess.	YFPIPE YFFAIL YSIDBT	- 0.5	26.17	13.09
	Opt.		- 1.1	52.11	26.06
5.3.4 Cement Volume and Time	Pess.	YCEMCS YCEMTM	- 0.9	37.80	12.60
	Opt.		- 3.1	131.81	43.94
5.3.5 Cement Bond, Borehole to Casing	Pess.	% Change in Well Life	- 1.2	54.94	18.31
	Opt.		- 2.7	128.27	42.76
5.3.6 Decision After Reaching Planned Depth	Pess.	% Change in Prod. Well Cost	- 0.3	12.80	4.27
	Opt.		- 3.1	146.98	48.99
5.3.7 Depth to Produce	Pess.	% Change # Prod. Cells	- 0.2	10.61	10.61
	Opt.		- 1.3	60.29	60.29
5.3.8 Stimulation of Well Flow	Pess.	% Change Cost of Prod. Well	- 2.1	110.75	36.92
	Opt.		- 3.8	177.24	59.08
5.3.9 Site and Design for Next Well	Pess.	% Reduc- tion in # Wells	- 1.4	63.97	31.99
	Opt.		- 4.4	208.93	104.47
5.3.10 Well Operation Analysis	Pess.	% Increase in Life of Prod. Well	- 0.5	21.67	10.84
	Opt.		- 0.9	42.30	21.15
TOTAL	Pess.				143.27
	Opt.				417.3

¹For a field of production and injection wells sufficient to support a 50 MWe power plant at a liquid-dominated prospect.

These values were placed in the appropriate cells in the analysis matrices.

5.5 Results

The results of analyzing each well drilling operation are summarized in Table VII. For each operation, there is a pessimistic and optimistic entry. The first column shows the input parameters that were changed in WELCST or GEOBEN to calculate the benefit. Where there was a calculated change in the average cost of a well, it is shown in the second column. The third column shows the total benefit calculated for the particular operations, and the fourth is the share of that benefit that is credited to the logging program. The overall program represents a potential benefit of from \$143.3 million to \$417.3 million.

Some points of interest from these results are:

- About one-fifth of the savings accrue from changes in cementing practices.
- About two-fifth of the potential benefit comes from improved handling of the well once the hole is made (Operations 6, 7 and 8).
- Slightly less than one-third of the potential benefit is from improved reservoir planning and exploitation (Operation 9).

TABLE VIII
OVERALL BENEFIT OF SONDE PROJECTS

PROJECT	BENEFIT (\$x10 ⁶)		% OF TOTAL BENEFITS	% OF TOTAL SONDE PROJECTS BENEFITS
	PESS.	OPT.		
1-4-6: Mechanical Refrigerator for Sondes	38.3	112.2	27	----
[1-4-x: Cables and Connectors	30.4	97.7	23]	----
[1-4-x: General Purpose Log Interpretation	19.0	53.0	13]	----
1-4-2: Neutron Activation Analysis Sonde	17.7	51.0	12	34
1-4-5: Electromagnetic Borehold Telemetry System	15.8	44.8	11	30
1-4-1: Pressure and Temperature Sonde	10.8	37.5	9	25
1-4-3: Sensor for Acoustic Log	3.5	6.5	1.6	4
1-4-4: Heat Flow Transducer and Thermal Conductivity Probe	1.8	5.2	1.2	4
1-4-7: Borehole Maximum Temperature While Drilling	1.8	4.5	1.1	3
[1-4-x: Mechanical Caliper Device	1.1	3.4	0.8]	----
[1-4-x: Mud Pulse Telemetry	0.2	0.5	0.1]	----
TOTAL	140.4	416.3	100.0	100

¹ Brackets indicate the dummy projects.

6.0 DISCUSSION AND CONCLUSIONS

This section presents two summary tables which display the results in ranked order. Table VIII lists the projects in the DGE Well Logging R&D Program in order of decreasing benefit. The dummy projects (See Section 3.2) are marked parenthetically. The percent of total benefit listed is based on the optimistic estimate. These percentages differ only slightly if based on the pessimistic estimates.

The project for which the maximum benefit was found was the Mechanical Refrigerator project. If this project is successful, it would allow most existing oilfield sondes to be combined with a cooling package that would enable the conventional sonde to survive the higher temperatures with little alteration of conventional components. The other two next highest ranking projects (Cables and Connectors, and General Purpose Log Interpretation) resemble the Mechanical Refrigerator project in that they would apply to a large proportion of the logging information category needs.

This general trend applies to all the projects: the more types of information affected by the project, the greater the benefit.

The Borehole Maximum Temperature project (1-4-7) did not show a great deal of benefit, probably because the temperatures assumed to be found at the various prospects are not out of line with the mud chemistries currently available. More information is needed in this area.

TABLE IX
OVERALL BENEFITS DUE TO PARTICULAR
DRILLING OPERATIONS

Operation	Benefit (\$ x 10 ⁶)		% of Total
	Pess.	Opt.	
Site and Design for Next Well (Reservoir Engineering)	32.0	104.5	25
Depth to Produce	10.6	60.3	14
Stimulation of Well Flow	36.9	59.1	14
Decision After Reaching Planned Depth	4.3	49.0	12
Cement Volume and Time	12.6	43.9	11
Cement Bond, Borehole-to-casing	18.3	42.8	10
Preventing Twist-offs	13.1	26.1	6
Well Operation Analysis	10.8	21.2	5
Mud Formulation Plans	2.9	5.9	1.4
Mud Formulation While Drilling	1.7	4.7	1.1
TOTAL	143.2	417.3	100

Table IX lists the drilling operations in order of decreasing benefit, based upon the optimistic estimates. In this Table, there is some difference in the ranking of optimistic versus pessimistic estimates. The reason that the operations have different ranks for the high and low estimate is that there was more uncertainty in the range of benefits to be attributed to some operations than in others.

Nonetheless, the general trend is clear and conforms to common sense: The bulk of the economic benefits of well-logging sondes derive from effects that logging operations have on reservoir engineering and the completion of individual wells. The economic effects that sondes can have on drilling operations appear to be much smaller. This is probably because hole-making economics is dominated by the rate of penetration, which can be improved by better bits and perhaps by downhole instrumentation for drilling, but will probably be improved but little by the use of wire-line logging tools.

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